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Review

# Intentional and Undesirable Effects Related to the Interaction of Electromagnetic Fields with Major Living Tissues

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**Abstract:** The well-being and sociability of individuals have always been part of modernity. The development of new technologies that meet these aspirations is receiving increasing attention. Thus, strengthening the desired objectives of these tools and minimizing their undesirable side effects is the subject of a growing commitment. The present contribution aims, in this context, to evaluate and analyze the desired and undesirable effects of the interaction of electromagnetic fields with living tissues in general. This involves routines reinforcing expected functions as well as those controlling and protecting against undesirable effects. First, the interactions of electromagnetic fields with tissues are analyzed, involving their thermal biological effects of desired and undesired exposures. The roles of blood and sap fluids in bio-affected tissues are then analyzed. Secondly, the governing electromagnetic, bio-heat equations, and their coupled solution are studied. Third, the thermal behavior of tissues and the exposure adverse effects are examined. Next, monitoring and defending of the effects of exposures are discussed. This contribution illustrates and discusses mathematical modeling routines based on a generalized interaction of electromagnetic fields with living tissues.

**Keywords:** electromagnetic field; living tissues; thermal effects; blood and sap; bio-heat; mathematical models

## 1. Introduction

Throughout human history, the quest for modernity has never stopped. Nowadays, many daily processes and devices are part of modern human society. The association of these auxiliaries with humans leads, in addition to the desired purposes, to undesirable effects. These side effects can affect not only humans, but also wildlife and other objects. This is due to the proximity of humans' environments to those of others. It should be noted that human, fauna, and flora interact regularly. Each of them needs and helps others, for example; the first can feed others and needs to be fed by them. In addition, an activity necessary for any can interact positively or negatively with oneself or with others. Moreover, an external phenomenon can interact in the same way with any of them. Regardless, the effects of such exposures may be desired by some but undesirable by others.

One of the existing environmental issues today is linked to exposure to electromagnetic fields (EMFs). These exhibit large frequency spread including non-ionizing ( $10^3$ – $10^{14}$  Hz) and ionizing ( $10^{15}$ – $10^{22}$  Hz) ranges. The ionizing radiation is likely to have adverse health effects by generating molecular disturbances leading to tissue damage. The non-ionizing fields are used in daily activities of humans for communications, information transfer, processes supervision, food preparation, industrial processing, health care, etc. The connections between EMFs and humans in these activities certainly play an important role in human well-being. In addition to these desired dealings, there are undesirable effects on human tissues as well as those of fauna and flora [1–15]. These EMF exposures are due to two types of sources, near field (NF) as telephone cells [9], and far field (FF) as antenna towers for telephone cells [7,8]. These two types of exposure can produce biological effects (BEs) on the various exposed tissues of humans, fauna and flora. These BEs are related to induced fields in tissues and generally result in thermal effects depending on the characteristics of the EMF source, the features of the exposed material, and the conditions and duration of exposure [9,10]. The higher the

field strength and frequency are in the tissue and the longer the exposure interval, the greater the temperature rise will be. Such BEs can be desired as in healthcare hyperthermia treatments or microwave cooking [10]. Otherwise, BEs due to unwanted exposures are generally harmful and need to be supervised. Excessive induced EMFs or heating in tissues would cause an alteration in the molecular behavior of tissues, which denotes non-thermal BEs. These latter effects can cause tissue damage like ionizing frequency fields do.

The governing equations involved in determining the distribution of temperature rise in tissues consist of the EMF equations coupled, via the dissipated electric power distribution, to the tissue heat transfer equations. These are the bio heat (BH) equations in irrigated tissues. The blood fluids of humans and fauna generally irrigate them as well as the sap fluids of flora in general [16].

Thresholds are established to control tissues security, relative to induced EMF values and their thermal BEs. These are denoted by the specific absorption rate (SAR) and temperature rise  $\Delta T$ . The 3D distributions of these quantities obtained from the coupled solution of the EMF and the BH equations should be checked with thresholds to insure the tissues security [9,10,17]. These thresholds depend on, the tissue part of body or plant, the relation with exposure source, and the exposure conditions. Concerning tissue parts dependence, thresholds are related to the nature of tissue and the vital importance of the part e.g. the difference of head and members in bodies or of leaves, flower petal, stem, branch and trunk in plants. Relative to the relation with exposure, thresholds are different for e.g. between a device fabricator and user or between a plant occasionally exposed to phone cell or permanently to a fixed antenna. The exposure conditions are mainly related to type, NF or FF and the duration of exposure.

The protection of EMF exposures could be managed through design optimization of emitting sources, limiting of use of radiating devices in restricted zones, or establishing zones devoid of EMF radiation as public healthcare centers, public parks, city districts, whole towns, woods, petting zoos, zoological gardens, etc. [16].

This paper aims to evaluate and analyze the looked-for and unwanted consequences of the exposure to EMFs of living tissues of human, fauna and flora. This entails routines strengthening expected purposes as well as those monitoring and defending against undesirable outcomes. The second section is devoted to the analysis of the interactions of EMFs with tissues, involving their thermal BEs of wanted and unsolicited exposures. In the third section, the tasks of blood and plant sap fluids in bio-concerned tissues are analyzed. Section 4 relates to the investigation of the governing EMF, BH equations, and their coupled solution. In section 5, the tissues thermal conduct and their EMF exposure adverse effects are discussed. Section 6 explains checking and protecting of the exposures consequences. Section 7 gives conclusions and future recommendations.

## 2. Interactions of EMFs with Tissues

As mentioned earlier, humans' connections with EMFs may be desired for human well-being and his social communication. These fields are primarily in the non-ionizing frequency range and mostly in the radio frequency (RF) and microwave (MW) scales. Exposure of these EMFs to living tissues can produce different effects. In the case of a focused confined space as in MW hyperthermia medical interventions, or closed cavities, as in MW ovens, exposures in these applications result in the desired thermal BEs [10]. In the case of different telecommunication and transmission tools, the connections and contacts sought result from the connection of RF EMF with humans. Affected devices typically use wireless wave transmission, which exhibit stray fields characterized by field exposure radiation in open space. These unwanted exposures can affect the exposed materials by disrupting their normal functioning [9,17]. In the case of living tissues, RF EMF exposures would create unwanted thermal BEs [10]. As we see, the effects of EMF exposures might be desired in one case but undesirable in the other. Note that the relationship between EMFs and tissues may have particular handlings allowing tissues to interact via radiation. For example, several types of ornamental plants have the ability to absorb EMF radiation, thereby protecting other surrounding living tissues; see e.g. [18]. At this point, highlighting the notion of interaction would be hailed. Two or more entities can interact, that is, one can affect the other. The outcome may be desired, indifferent or undesirable. The number of interaction possibilities will be greater as the entities are more numerous. Considering human, fauna and flora, these three living entities could be exposed to external phenomena (entities) which can interact with them in unwanted manner. These phenomena

could be divided into two categories of exposure, natural and artificial. The most common natural exposures are lightning, storms, seismic and volcanic activities. Artificial exposures are mainly due to human activities. Such artificial unwanted exposures are considered as pollutions to the normal functioning of the three living entities. This is linked to the exposure of living tissues of man, fauna and flora that can produce unwanted thermal BEs. In this case, human creates pollution, which interacts with the tissues of the man, fauna and flora.

The practice of mathematical modeling seems essential in the design and analysis of devices and processes involved in thermal BEs. Thus, we can better understand the physical phenomena involved. The thermal BEs affected by desired and undesired EMFs are governed by the EMF equations and the BH equation, as will be discussed in Section 4.

### 2.1. *Desired EMF Thermal BEs*

Different applications employ EMF as a production mode of thermal BEs. The most common are related to two categories [10]. The first concerns food cooking and drying of different matters as fruits, wood, paper, etc. using induction (range kHz) and MW heating. The second relates to medical tissues treatments as hyperthermia for tumor destruction using different frequencies heating.

#### 2.1.1. Induction and MW Heating

Induction heating uses wireless induction to induce eddy currents in a cooking or drying vessel constructed of conductive material, without direct contact with a heat source [19–23]. A high frequency excitation coil accomplishes this. The resulting flux induces an electromotive force in the conductive metal of the vessel, which induces electric current to flow. The interior vessel surface will be heated in agreement with Faraday's law and the Joule effect, producing a power dissipation loss directing to a temperature rise. This heating mode is mainly used for cooking, conservation and sterilization of food. It could be applied also for different dielectric matters treatments and disinfection of medical instruments. For the cooking action, the involved process behaves, as a thermal-BE, comprising H<sub>2</sub>O extraction plus chemical reaction, which transform raw matters into consumable food.

MW industrial and domestic ovens use a frequency of 2.45 GHz allowing good penetration into food or other materials, so that the heat produced is uniformly distributed in the volume concerned [24–27]. During the heating process, the radiated energy in MW is converted into heat thanks to intermolecular friction forces. The corresponding ovens are used for drying materials by providing energy to water molecules. This thermal energy will be conducted from the interior towards the surface of the material; the water will evaporate through diffusion and dry once the energy exceeds the level needed to completely, remove the moisture. As in induction heating, thermal-BE will transform raw materials into consumables. Note that MW industrial ovens are also used for drying processes of wood, paper and other materials.

Note that humans besides feeding both domestic fauna and flora, they use desired EMF thermal BEs to cook these two elements for his food.

#### 2.1.2. Hyperthermia Tissues Medical Therapies

Minimally invasive tissue treatments, which require thin MW antennas, small RF probes or laser fibers introduced directly through the skin or natural pathways for local tissue therapy by thermal damage. Hyperthermia uses the BE of tracked induced heat to adversely disturb tumor evolution. This is done via an artificial increase of temperature of 40–44 °C for a duration of 1–1.5 hours. For example, MW hyperthermia aims to raise the temperature of the tumor in a selective manner via a dedicated arrangement of antennas with applicators functioning at 434–915 MHz frequency. Thus, such applicators reflect a capacity of tissues penetration creating a regulated concentrate of heat in the region of tumor. Again, this thermal-BE permits a benefic selective destruction of tumors without damage to healthy adjacent areas [28–33].

### 2.2. *Unwanted EMF BEs*



The exposure of EMFs to objects generally produces various effects, which depend on the nature of the exposure source and the exposed elements. Daily used wireless devices working in the non-ionizing frequency range (mainly RF and MW) produce the involved fields. When such exposure occurs accidentally or unintentionally, it can have disruptive effects. This may disrupt the operation of a device, such as an electronic appliance, or a medical instrument, such as an imager. As well, this may affect different living tissues.

### 2.2.1. Common Thermal BEs

Wide varieties of exposures affect living tissues. Exposure of such tissues to non-ionizing EMF may produce undesirable BEs related to tissue-induced fields, such as electric field  $E$ , magnetic induction  $B$  or current density  $J$  and temperature rise  $\Delta T$ . Too high values of such induced fields could be dangerous and should be monitored by checking their harmony with the thresholds set by safety standards [34–38]. These BEs are closely linked to the characteristics of the EMF source and the exposed material. The frequency and intensity of the field characterize the source, while the biological and geometric characteristics of the tissues characterize the matter. It may be noted that the needed conditions for desired thermal BEs that are caused indirectly by induction heating or directly by MW heating, are these to be avoided for unwanted exposures.

### 2.2.2. Uncommon EMF Tissues-Effects

The above-discussed thermal BEs due EMF exposure are the utmost frequent in relation with habitual practice of digital communication tools. These BEs do not represent any risk if the tissues induced fields are in harmony with the thresholds set by safety standards.

Other special personal effects concern fewer people who experience different unusual effects due to such exposure. These will present atypical symptoms, which correspond to two different categories. The first presents several nonspecific signs due to minor exposures with an insignificant interval, well below the limits of safety standards. The second exposes cognitive disorders for long-term exposures. Regarding the first category of people, they are presumed to be hypersensitive to different frequencies of EMF in general. Such electromagnetic hypersensitivity (EHS) includes a characteristic intolerance to EMF atmospheres. The origin of these signs is obviously not proven. A number of investigations have been published to understand this inexplicable situation, see for example [39–45]. For the second category of disorders of cognitive functioning, the origin of these is also unfounded and different examinations have been mentioned in the literature, for example [46–48]. At this point, from these investigations, these two categories of atypical symptoms that seem real, their occurrence is really connected with EMF although their BE looks non-present. Thus, the exposure brings obliquely through an unknown liaison (for the instant) with the special effects, which are the cause of the signs. Constantly with such a conflict, one can meditate that EMF effects unseen now could possibly arise and clarify these symptoms. Definitely, it is scientifically problematic to contest the existence of a menace. Such doubt can always rationalize a cautious approach [49]. Due to this challenging circumstance, and awaiting further investigation and better evaluation, individuals with these warning sign could rationally be considered clinically as a chronic sickness, acknowledging that the main origin stays the EMF environment.

Additionally, there are lesser, special tissue effects that are not thermal. This can occur due to excessive tissue-induced EMF values and increased temperature. These can cause molecular disruptions leading to tissue damage [50–61]. Moreover, accidental exposures to EMFs in the ionizing frequency range can result in dangerous adverse health effects associated with molecular disorders involving tissue damage. However, this class of radiation can be used in medical treatments, for example X-rays, whose energy level varies from very low as for dental X-rays, to particularly high in irradiators intended to sterilize medical utensils. Particular health safety environments condition this type of routine for patients and medical staff.

## 3. Roles of Blood and Sap Fluids in Tissues

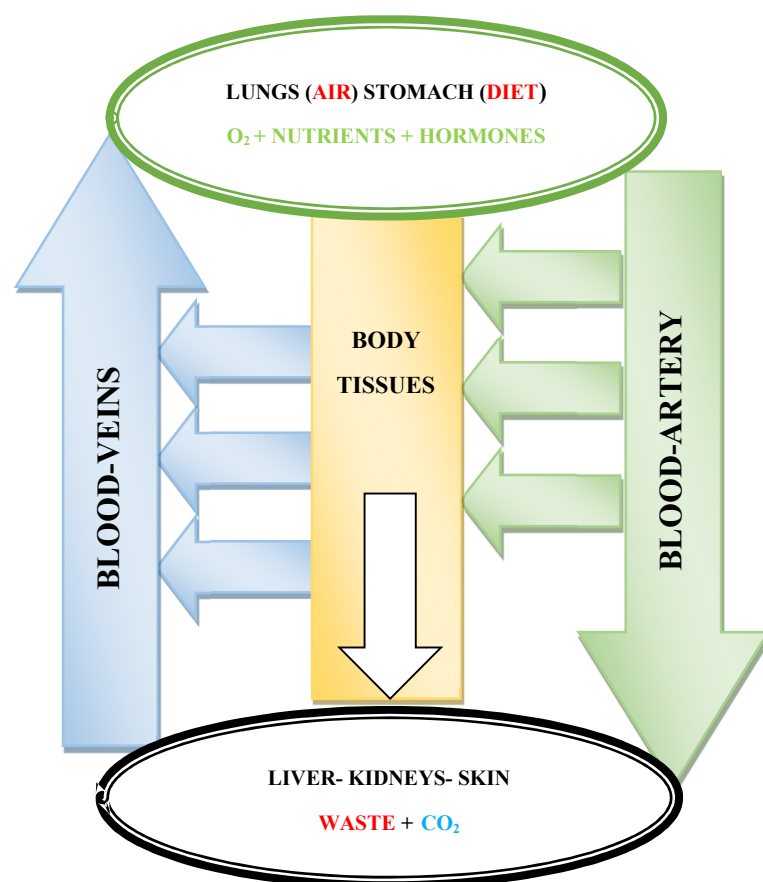
Man, fauna and flora need a circulation of fluids in their tissues allowing their irrigation to continue to live. This includes the blood fluid of humans and wildlife, as well as the sap of flora. The

study of BE due to exposure to EMF is closely linked to these fluid circulations. In this section, we will analyze the role of blood and sap circulation in living tissues.

Blood carries oxygen from the lungs and nutrients from the digestive system to all tissues in body parts so they can continue to function and carries carbon dioxide from the tissues back to the lungs. It carries oxygen in the form of an unstable compound – oxyhemoglobin, from the lungs to tissues and fights infections by delivering the hormones throughout the body. Moreover, it carries excretory materials from tissues to the liver, kidneys or skin and other wastes from the digestive system for elimination from the body. The vessels that leave the lungs with oxygen are arteries and those that arrive at the lungs with carbon dioxide are veins. Figure 1 illustrates a schematic representation of the role of blood circulation in body tissues.

The sap fluid circulating in plant tissues plays the role of blood fluid circulating in animal tissues. Two types of sap fluids flowing through two corresponding types of plant vessels in opposite directions (from leaves to roots and vice versa). Phloem primarily transports sugars and hormones from leaves to roots through plant tissues and xylem primarily transports water and minerals in the opposite direction. They act as arteries and veins for blood fluids in animal tissues. Note that sugars and hormones are produced by the exchange of nourished leaves of water and minerals with sunlight, while water and minerals are filtered and absorbed by roots from the soil. Figure 2 schematically shows the role of sap fluids in plant tissues corresponding to blood in the body shown in Figure 1.

It should be noted that in both human-fauna and flora, the arterial, venous, phloem and xylem vessels, including their circulating fluids, blood and sap, shown in Figures 1 and 2, are strongly linked to good functioning of different parts of bodies and plants. In addition, they play an important role in living tissues protection against thermal assaults, particularly thermal BE due to exposure to EMF. Therefore, their representation in the BH equation must be realistic and faithful [16].



**Figure 1.** Schematic representation of the role of blood circulation in body tissues.

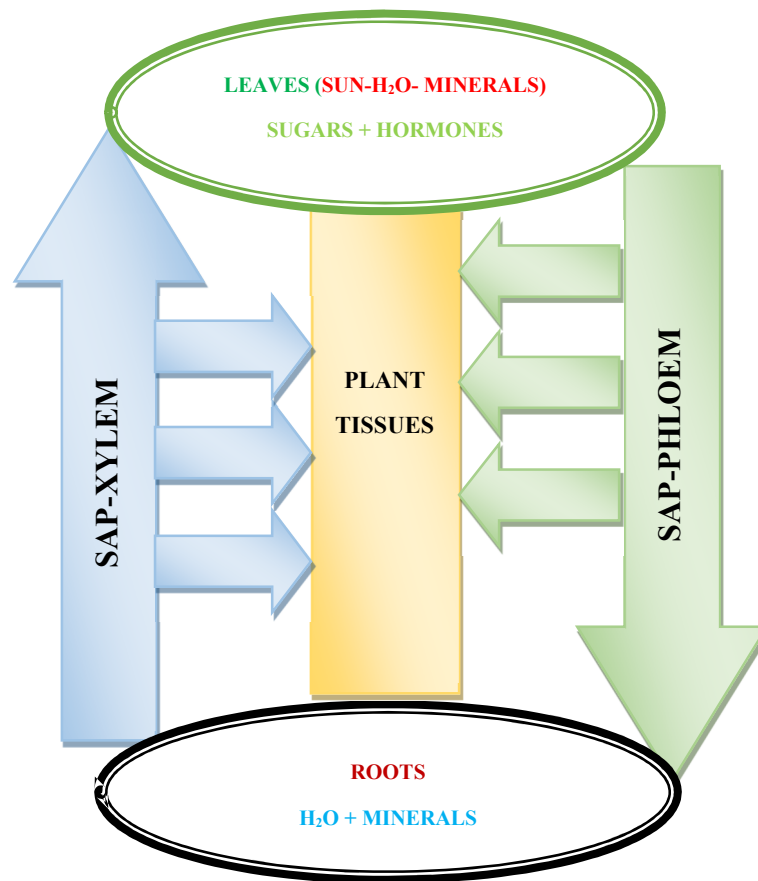


Figure 2. Schematic illustration of the role of sap fluids in plant tissues.

#### 4. Governing Equations

This section is dedicated to mathematical investigation of the EMFs exposure thermal effects. The electromagnetic (EM) and heat transfer (HT) phenomena run EMF exposure thermal effect. In the case of living tissues, the HT will be occur in a BH representation. The tissue temperature rise will be determined by the BH phenomenon initiated by a heat source corresponding to the EM power dissipated in the material concerned, which can be determined by the EM phenomenon. The EMF and BH equations govern thermal desired and unwanted BEs due to EMF exposure.

##### 4.1. EMF Equations

The general EMF four equations, in their differential form, based on the Maxwell's microscopic local equations [62] are given by:

$\nabla \times \mathbf{E} = -\partial_t \mathbf{B}$  (Maxwell – Faraday),  $\nabla \times \mathbf{H} = \sigma \mathbf{E} + \partial_t \mathbf{D}$  (Maxwell – Ampère),  $\nabla \cdot \mathbf{D} = \rho_e$  (Maxwell – Gauss), and  $\nabla \cdot \mathbf{B} = 0$  (Maxwell – Thomson).

For harmonic fields, the EMF equations can be given by:

$$\nabla \times \mathbf{H} = \mathbf{J} \quad (1)$$

$$\mathbf{J} = \mathbf{J}_e + \sigma \mathbf{E} + j \omega \mathbf{D} \quad (2)$$

$$\mathbf{E} = -\nabla V - j \omega \mathbf{A} \quad (3)$$

$$\mathbf{B} = \nabla \times \mathbf{A} \quad (4)$$

In the above EMF equations,  $\mathbf{H}$  and  $\mathbf{E}$  are the vectors of the magnetic and electric fields in A/m and V/m,  $\mathbf{B}$  and  $\mathbf{D}$  are the vectors of the magnetic and electric inductions in T and C/m<sup>2</sup>,  $\mathbf{A}$  and  $V$  are the magnetic vector and electric scalar potentials in W/m and volt.  $\mathbf{J}$  and  $\mathbf{J}_e$  are the vectors of the total and source current densities in A/m<sup>2</sup>,  $\sigma$  is the electric conductivity in S/m,  $\rho_e$  is the volume

density of electric charges in  $C/m^3$ , and  $\omega$  is the angular frequency  $= 2\pi f$ ,  $f$  is the frequency in Hz of the exciting EMF. The symbol  $\nabla$  is a vector of partial derivative operators, and its three possible implications are gradient (product with a scalar field), divergence and curl (dot and cross products respectively, with a vector field). The symbol  $\partial$  is the operator of partial time derivative. The magnetic and electric compartment laws respectively between  $B/H$  and  $D/E$  are represented by the permeability  $\mu$  and the permittivity  $\epsilon$  in H/m and F/m.

The source term in the EMF equations (1-4) is the excitation current density  $J_e = \sigma E_e = j \omega D_e = j \omega \epsilon E_e$ . The choice of the form of the source term depends on the nature of the exposure, NF, FF, etc. and the exposed material nature.

The volume density of the dissipated power  $P_d$  in dielectric materials (biological tissues) and the corresponding specific absorption rate (SAR) are given by:

$$P_d = \omega \cdot \epsilon'' \cdot E^2/2 \quad (5)$$

$$SAR = P_d / \rho = \omega \cdot \epsilon'' \cdot E^2 / (2\rho) \quad (6)$$

In (5, 6), the parameters:  $\epsilon''$  is the imaginary part of the complex permittivity of the absorbing material and  $\rho$  is the material density in  $kg/m^3$ .  $E$  is the absolute peak value of the electric field strength in V/m and SAR is in W/kg. The power dissipation in  $W/m^3$  given by equation (5) relates to foremost dielectric heating of EMF energy loss. Notice that the imaginary part  $\epsilon''$  of the (frequency-dependent) permittivity  $\epsilon$  is a measure for the ability of a dielectric material to convert EMF energy into heat, also termed dielectric loss. The real part  $\epsilon'$  of the permittivity is the effect of capacitance and results in non-dissipative reactive power.

The volume density of power dissipations given by equation (5) will be used in the coupling of EMF and BH equations.

#### 4.2. BH Equation

Concerning the HT problem, generally the heat flux corresponding to the rate of thermal energy flowing across a surface in a given medium is produced by a temperature difference gradient. Such a gradient can generate heat fluxes in solids (by conduction), in gases or liquids (by convection) and via space waves (by radiation). Heat is often, transferred in a combination of these three modes and occurs irregularly. For example, heat flows through the ground (conduction) and the body envelope (mainly convection and radiation) affect the thermal environment of a standing body. Generally, the quantity of heat absorbed by an element of tissue or more largely of a lossy dielectric can be given as:

$$\Delta Q = c m_s \Delta T \quad (7)$$

In (7),  $Q$  is the heat energy dissipated in joule (J),  $m_s$  is the mass of the substance in kg,  $\Delta T$  is the change in substance temperature in  $^{\circ}C$ ,  $c$  is the specific heat of the substance in  $J/(kg \cdot ^{\circ}C)$ . The corresponding power will be  $\Delta P = \Delta Q / \Delta t$ . The volume specific power will be:

$$\Delta P_v = \Delta P / v = c (m_s / v) (\Delta T / \Delta t) = c \rho (\Delta T / \Delta t) \quad (8)$$

In (8),  $P$  is the power in watt (W),  $t$  is the time in (s),  $P_v$  is the power per unit volume in  $W/m^3$ ,  $v$  is the volume in  $m^3$ , and  $\rho$  is the density in  $kg/m^3$ .

The HT equation providing the volume specific power of (8) in its differential form is given by:

$$c \rho \partial T / \partial t = \nabla \cdot (k \nabla T) \quad (9)$$

In (9)  $k$  is thermal conductivity in  $W / (m \cdot ^{\circ}C)$

Considering the case of living tissues, we have to consider in (9) a self tissue heat source  $P_t$  and the involved convective heat transfer via irrigating fluid corresponding to the considered part of tissue. The convective heat transfer coefficient in the fluid  $h_f$  in  $W / (m^2 \cdot ^{\circ}C)$  can be defined through the heat flux in  $(W/m^2) = h_f \cdot \Delta T$  or through the power  $\Delta P$  in (W)  $= h_f S \Delta T$ , from (8):



$$\Delta P_v = h_f (S/v) \Delta T = (h_f / \chi) \Delta T = c_f q_f (\Delta T / \Delta t) \quad (10)$$

Then

$$h_f = c_f q_f p_f \chi \quad (11)$$

In (10, 11)  $S$  is the surface of tissue part concerned in  $m^2$ ,  $\chi$  is the thickness of the tissue part in  $m$ . Also  $c_f$ ,  $q_f$ ,  $p_f$  are respectively fluid, specific heat in  $J/(kg \text{ } ^\circ C)$ , density in  $kg/m^3$ , perfusion rate in  $1/s$ .

On the other hand, we have to consider in (9) the external heat source related to the EMF exposure,  $P_d$  or SAR given by (5 or 6).

Under these conditions, (9) will be extended to a tissue BH equation, which can be presented as follows:

$$c \rho \partial T / \partial t = \nabla \cdot (k \nabla T) + P_d + P_t + c_f q_f p_f (T_f - T) \quad (12)$$

In (12)  $P_t$  is the tissue self-heat source in  $W/m^3$ ,  $T_f$  and  $T$  are respectively the fluid temperature and the local temperature of tissue in  $^\circ C$ . Equation (12) corresponds to a bio-heat tissues accounting for EMF exposure. This equation has a form similar to the Pennes's bio-heat equation [9,10,17,63] related to human tissues and convective heat transfer in blood. As mentioned earlier, plant sap plays the role of blood in animals. In addition, Phloems and Xylems for sap play the role of arteries and veins for blood. Note that in the Pennes's bio-heat equation the term  $P_t$  in (12) is related to tissues metabolic heat and corresponds to plant tissues internal heat. As well, the last term in (12) representing convection fluid heat transfer correspond to animal blood or plant sap. The orders of magnitude of the relative values of the parameters related to animal and plant tissues as well as blood and sap are obviously different due to the different nature of animal and plant tissues. The different values of parameters involved in (12) relative to  $P_t$ ,  $c_f$ ,  $q_f$ , and  $p_f$  depend on the tissue type and the specific part of this tissue. Note that the contribution of  $P_d$  is much important relative to  $P_t$  (see section 5).

#### 4.3. Coupled Solution of EMF and BH Equations

Equations (1–4 and 12) can be solved in a coupled way. Given the geometric complexity and inhomogeneity of tissue, the solution must be local in the tissue using discretized 3D techniques as finite elements [64–71] in the appropriate element of the tissue. The discretized 3D elements are volume parts enclosed in surface elements, each encircled by edge elements, each ended by two nodes. For example, a tetrahedral element involves four triangular faces, six straight edges, and four nodes. The fields could be defined at nodes, edges, faces or volume depending on the nature of the field as requirements of continuity, etc. The coupling of the EMF and BH equations is weak in nature due to the distant values of their time constants [9,10,17]. Thus, an iterative solution provides in the tissue the local distributions of the induced values of the fields  $E_i$ ,  $B_i$ , and  $J_i$ , and hence  $P_{di}$ ,  $SAR_i$ , and  $\Delta T_i$ . The parameters concerned are those of the tissue properties,  $\epsilon$ ,  $P_t$ ,  $c_f$ ,  $q_f$ ,  $p_f$ , etc. The geometry involved is that related to the shape of the portion of tissue concerned. Exposure conditions are taken into account via the nature of the EMF source (strength and frequency) and the exposure interval. Note that consideration of the exposure source is different for near or far field cases. For NF radiation, the source is generally involved in the solution domain as a focused field. In the case of FF, which is generally of homogeneous value, the source is imposed uniformly over the entire exposed surface of the object. The different parameters in equations (1–4 and 12) could be found in literature or measured [72–76].

### 5. Tissues Heating Adverse Effects

In this section, we will analyze the thermal behavior of BE and summarize the possible adverse consequences on tissues due to such effect. As mentioned previously, heating by high frequency EMFs focuses directly inside tissues, as in MW heating [10]. Additionally, high frequencies such as in the RF and MW range exhibit energetic ability to rapidly heat tissues [9]. Added to this, is the

weakness of the tissues to resist the uneven increase in temperature, which can occur mainly in those parts of the tissues where the flow of fluid (blood or sap) is deficient, which establishes the main ways of deal with excessive heat. . These three characteristics, internal concentration, rapid heating and low fluid flow, are not integrated into the natural self-protection of the tissue, which depends on heat transfer by conduction and convection in relation to sunlight and the hot environment. Therefore, the main detrimental consequence on tissues exposed to high frequency EMF would be rapid heating inside the defenseless parts of the tissues, without proper self-preservation perspective to defend the key functions of the tissues [9,13]. Note that in addition to possibly damaging parts of tissue, excessive and permanent fields can trigger non-thermal effects, which could disrupt molecular arrangements similar to those in the case of ionizing radiation.

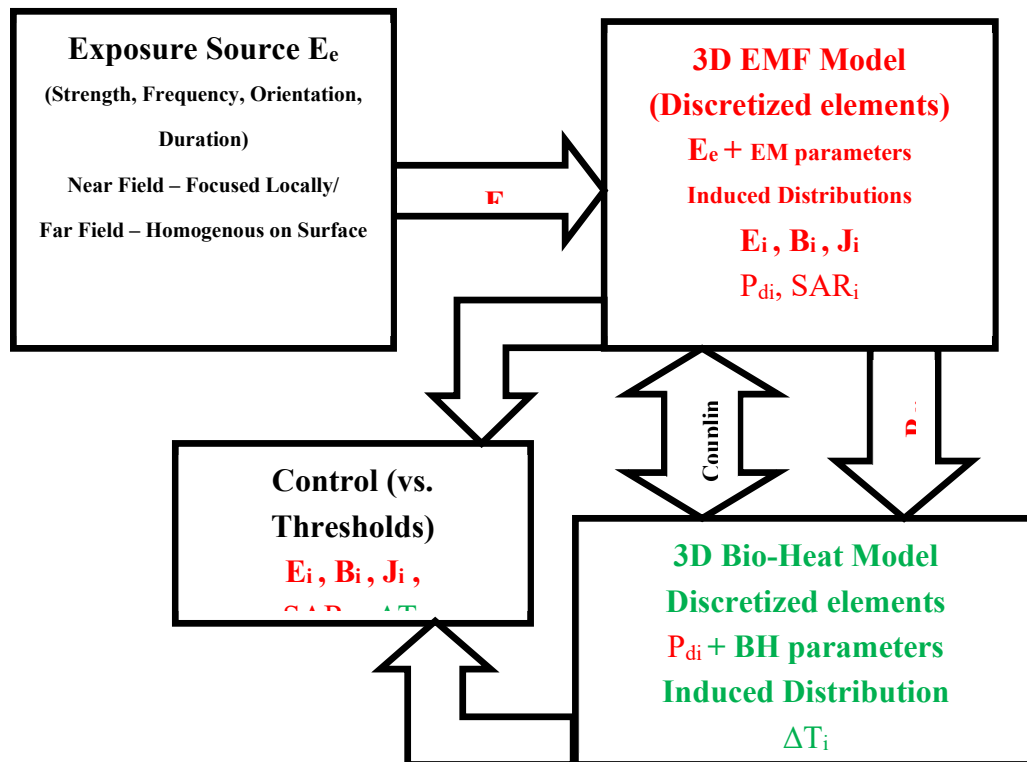
The SAR given by equation (6) and the exposure interval  $\Delta t$  characterize the behavior of EMF exposures. SAR is directly related to frequency, field strength and tissue parameters. See section 7 for more details on how different parameters affect temperature rise. Common SAR values for adverse effects of tissue exposure are 4 to 10 W/kg. The affected frequency range involving RF and MW is  $10^3 - 0.3 \cdot 10^{12}$  Hz, which produce non-ionizing radiation. Function of the nature of the tissues, long exposure intervals could cause temperature rises exceeding thresholds (see next section) fixed by standards and resulting in adverse BE.

## 6. Monitoring and Defense of EMF Effects

The obtained local 3D distributions regarding the induced EMFs and  $\Delta T$  make it possible to accomplish two main actions, which are the control of the unwanted effects (see figure 3) as well as the protection strategies concerning unwanted radiated fields.

### 6.1. Control Methodology of Unwanted Radiation

In the case of human and animal tissues, the different unwanted predicted field distributions are checked by comparison to thresholds [9,10,17,34–36]. These thresholds are fixed in function of nature of the exposed tissue (body part, adult, child, animal, etc.), the relation of source to exposed subject (fabrication, installation, user, etc.), and the exposure condition (distance, concentration, duration, etc.). In the case of plant tissues, these thresholds correspond to the safety limits of public exposure, e.g. [37,38]. Such thresholds could be set for different, kinds of plants, parts of a plant, atmospheric circumstances of the plant location and corroborated exposure duration and conditions. Figure 3 summarizes the EMF-BH models, weak coupled solution strategy accounting for the nature of the exposure source and the tissue parameters. The induced fields, in the case of unwanted exposure, are controlled vs. thresholds in the whole tissue.



**Figure 3.** Schematic illustration of the EMF-BH models weak coupled solution strategy accounting for the exposure conditions and the control of different unwanted predicted field distributions.

## 6.2. Protection Strategies Against Unwanted Exposures

As mentioned previously, the most significant disruptions to terrestrial biodiversity are caused by human-to-nature relationships. This involves, in addition to man, fauna and flora: birds, animals, insects and plants. Protection of these species from RF-EMF could be achieved by two main protection strategies: source shielding and restricting of exposure zones. The first is directly linked to radiation sources by reducing their stray fields via shielding technologies [77–82]. This concerns the entire environment, including humans, animals, electronic devices, etc. This protection strategy is not obvious because it is limited by the operating principle of RF wireless devices based on the radiation of electromagnetic waves. The only way to implement such protection is to limit their emission capacity and therefore their performance in restricted protected areas. Thus, the mention of this strategy brings us to the second protection option. This involves the management of restricted areas devoid of radiating devices. This can concern public parks, urban neighborhoods or entire cities [83–85]. This protection option focuses largely on anthropogenic innovations and their links with biodiversity and nature.

## 7. Discussion

In this manuscript, the investigation of BEs due to the interaction of EMFs with living tissues of humans, fauna and flora, have illustrated that such a topic is thoroughly beneficial. At this stage, various questions deserve to be commented:

**Behavior of tissues temperature rise:** In the tissue bio-heat equation (12), the terms  $P_t$  and  $P_d$ , denoting tissue self-heat and external-heat volume power densities sources. Multiplied by the concerned tissue volume and the exposure time interval, these will give the total heat internal-external energy source  $\Delta Q = (P_t + P_d) \cdot v_t \cdot \Delta t$  in J. Considering the case of human, mammals, other animals and fauna in general this energy corresponds to tissue, metabolic and absorbed EMF exposure parts. The first is characterized generally by the basal metabolic rate (BMR) in J/s and the second by the SAR in W/kg. BMR is the energy needed by a body to perform elementary functions as breathing, temperature regulation, blood circulation, cellular development, hair growth, and hormone fabrication. These functions correspond to what the body does at rest. BMR is a part of

metabolism (converting food + O<sub>2</sub> into energy). BMR is almost 75% of burned energy at rest, which is almost 50 calories per hour (0.05815 J/s) for average human. Burned energy relative to day activity of human is between 100 and 800 calories (1 cl = 4.1868 J) including 10% to digest food. Noting that the average values of tissue parameters are ( $c = 3 \cdot 10^3$ ,  $Q = 10^3$ ,  $k = 0.5$ ), and approximately ( $\Delta Q = c m_s \Delta T$ ). The temperature rise due to EMF exposure will be  $\Delta T_d = SAR \cdot \Delta t / c$  and the temperature rise due to internal metabolism  $\Delta T_t = BMR \cdot \Delta t / (c M)$ , with M is the body mass. This indicates that contribution to temperature rise is much higher due to EMF exposure than internal metabolism. The case of plants relative to the internal tissue self-heat reflects the same observation. The total general tissue temperature rise will be approximately:

$$\Delta T = \omega \cdot \epsilon'' \cdot \Delta t \cdot E^2 / (2qc) \quad (13)$$

Equation (13) illustrates that the temperature rise  $\Delta T$  increase as the frequency  $f$ , the imaginary part of the tissue complex permittivity  $\epsilon''$ , the exposure duration  $\Delta t$ , the electric field as  $E^2 / 2$  and inversely as the product of the tissue density  $q$  and the tissue specific heat  $c$ .

**Reduction of EMF radiations for small sources:** In Section 6.2, strategies for protecting against unwanted exposures through radiation reduction were explored. A lesser universal strategy to reduce EMF radiation for small sources could be the use of EMF absorbers [86,87]. Moreover, an example of such strategy involves reducing radiation emitted by household portable electronic devices or home Wi-Fi sources, using several types of ornamental plants. In addition to beautifying the interior and exterior, these plants can absorb part of the radiation, thus reducing possible harmful effects. Such an act may be helpful in the case of those with EHS mentioned in section 2.2.2. One of the most effective plants in this area is the snake plant (*Dracaena trifasciata*), when placed near the radiation source; it reflects a radiation absorption capacity reducing its value by almost 30% [18,88].

**Complexity and living tissues behavior:** In theory, when living tissues are exposed to EMFs, the effects occur in real time. The mathematical modeling carried out to evaluate these effects is supposed to account for the real-time behavior of tissues. This problem faces various difficulties, the main ones being computational complexities, and tedious tasks linked to calculation time. The main cause of these difficulties is the nonlinearity of biological tissues reflecting complex constitutive laws representing the deformation and displacement behaviors of elastic tissues. Complexity often occur in a set of compound processes and could be encountered in various areas, e.g. neuroscience [89], Earth climate [90], space vehicles [91], computer vision [92], economics of fair division [93], game theory of strategic interactions [94], political science [95] and history [96,97]. These compound processes interact in complex actions according to nonlinear interdependent spatiotemporal behaviors. Such processes could form a non-complex action when they interact in a simple way. Returning to the complex behavior of living tissues, more realistic approximate constitutive laws, adapted computational techniques or combined methodology could solve this open research problem.

## 8. Conclusions

In this manuscript, the analysis and evaluation carried out on the biological effects due to the interaction of electromagnetic fields with the living tissues have shown that such a subject is quite valuable fact. The contribution focused on the evaluation and analysis of the desired and unsolicited effects of such relation with living tissues in general. Routines supporting expected functions as well as those controlling and protecting against unwanted effects have been proposed. The governing electromagnetic, bio-heat equations, and their coupled solution were analyzed. Monitoring and defending the adverse effects of exposures were discussed.

The following various recommendations for further investigation may be encouraged: Explore the different categories of living tissues in their environments likely to be radiated by near or far fields. Establish experimentally the bio-thermal-electromagnetic parameters necessary for models of different parts of tissues accounting for their environments. Setting thresholds for electromagnetic

and thermal fields for the main vulnerable parts of living tissues. Explore complex behavior of living tissues through constitutive laws, adapted computational techniques, or a combined methodology.

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