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Communication

Potential biological effects on living tissues of biodiversity subsequent to exposure to high-frequency electromagnetic fields

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Abstract: Exposure to high-frequency (HF) electromagnetic fields (EMF) has various effects on living tissues involved in biodiversity. Interactions between fields and exposed tissues are correlated with the characteristics of the exposure, tissue behavior, and field intensity and frequency. These interactions can produce mainly adverse thermal and possibly non-thermal effects. In fact, the most expected type of outcome is a thermal biological effect (BE), where tissues are materially heated by the dissipated electromagnetic energy due to HF-EMF exposure. In case of exposure at a disproportionate intensity and duration, HF-EMF can induce a potentially harmful non-thermal BE on living tissues contained within biodiversity. This paper aims to analyze the thermal BE on biodiversity living tissues and the associated EMF and bio-heat (BH) governing equations.

Keywords: HF-EMF; exposure adverse effects; living tissues; biodiversity

1. Introduction

Associates of biodiversity, including humans, animals, plants, etc., living in their environmental ecosystem, are interdependent and interact with each other and with the ecosystem. Humans have always sought to improve their well-being through the latest innovations. Recently, electromagnetic (EM) devices have made a significant contribution to these innovations. These devices have expected effects, beyond the unwanted side effects related to the electromagnetic fields (EMFs) involved. Exposure to stray and radiated EMFs, particularly in the HF range, involving radio and microwave (RF and MW) in the non-ionizing frequency range of $105 - 0.3 \times 1012$ Hz, can disrupt humans as well as other organisms associated with biodiversity. These alterations are concentrated in the living tissues concerned in the form of biological effects (BEs). Although these BEs can sometimes be usefully exploited, as in EM food processing [1], seed drying [2], or healthcare processes [3,4], they often lead to adverse effects [5,6]. The most common BEs are thermal in origin, produced by the dissipation of EM energy due to EMF exposure. Heated parts of living tissues can pose a risk, especially when they are poorly irrigated. In reality, living tissues are composed of solid or soft materials irrigated by specific fluids that ensure their function, such as blood in animals or sap in plants. Such thermal BEs in living tissues due to EMF exposure are governed by a bio-heat physical phenomenon. This is a heat transfer problem involving biological tissue mater. For a given external heat energy input, the output will be the corresponding temperature rise in the tissues [7].

The present contribution aims to analyze such BEs' physical phenomenon via its mathematical representation, thus a bio-heat equation involving the biological and thermal parameters of the tissues and convective heat transfer in irrigating fluid. The source of such an equation corresponds to the dissipated EM power for a given time interval. Such power is directly related to electric field E and the electric parameters of the tissues.

2. Interdependence and interactions in biodiversity

As mentioned earlier, an artificial device produces the desired results but also undesirable side effects on its environment. Thus, human well-being and potential biodiversity problems are linked, both resulting from artificial human activity. Moreover, these biodiversity damages can impact the ecosystem where its own habitats live. Thus, an artificial activity, aimed at human well-being, can be harmful to the human, his biodiversity partners, and their ecosystem. This sequence of impacts is reversible (bidirectional), illustrating the interdependent interactions between biodiversity partners and with their ecosystem.

Moreover, other instances of interdependencies could be observed in nature, for example, the coalition of certain viruses with their lodged organism (virus-host dealings). Thus, the viruses' genomes are constituted of genetic material borrowed from the entities they contaminate and can bring them the aptitude to fabricate a toxin to abolish their competitors (as in baker's yeast) [8]. Other instances are metabolic interactions concerning bacteria and phytoplankton [9] and the association of some microorganisms, plants, and nutrient sequences [10].

3. Expected and side effects outcomes in EMF devices

In the construction of an EMF device, it is most likely to upgrade the expected outcome and diminish the undesirable side effects. Thus, managing human well-being and adverse effects on biodiversity and ecosystems. Sustainable energy utilization implies, in addition to such optimized construction, the use of clean EM energy (conversion from clean energy). Such sustainability also impacts the biodiversity and ecosystem in an ecological context. Actually, this sustainably balances and protects the health of humans and their biodiversity partners and ecosystem, which are closely linked and behave reciprocally contingent.

4. Thermal BEs in living tissues

As mentioned above, tissue BEs due to HF-EMF exposure are mostly thermal. The behavior of such thermal BEs and their likely outcomes on living tissues are analyzed in this section.

As mentioned earlier, living tissues are composed of solid or soft materials irrigated by fluids that ensure their function. They are generally protected by an outer epidermal tissue, which covers the inner layers, against natural external aggressions such as wind, sun, cold, etc. Natural heating is characterized by heat transfer by conduction through the epidermal surface of the tissue and by convection in its fluid. Natural tissue self-protection is characterized by a relatively thin epidermis and low fluid flow, well adapted to natural external aggressions. Such self-protection may prove ineffective due to artificial external exposure for which the tissue is not prepared. Exposure of tissues to HF-EMFs is a typical artificial external exposure.

Two specific physical features are related to HF-EMF exposures. They focus on interior tissues, provoking dissipated EM energy heating, and exhibit a robust capacity to swiftly heat tissues [11,12]. The main way to deal with excessive interior heating of living tissues lies in their degree of irrigation by fluids such as blood or sap. Thus, tissue parts exhibiting deficient fluid flow would show feebleness to endure the disproportionate temperature upsurge.

5. Ruling physical and mathematical analyses

Following the mechanism described in the last section relative to HF-EMF exposure focusing on interior tissues and exhibiting swift heating of tissues, the corresponding heat EM energy source and its dissipation in living tissues will be analyzed in this section.

Actually, such physical phenomena relate to a bio-heat (BH) occurrence involving heat transfer in living tissues, including tissue matter and irrigating fluid. Such occurrence includes, in addition to tissue intrinsic source and convective heat in fluid, an external heat source. This last, in the case of EMF exposure, corresponds to the EM dissipated energy governed by EMF physical phenomena. These two physical phenomena, BH and EMF, behave coupled through the external heat source of the first, occasioned from the second, thus the dissipated EM power for a given duration (energy). These physical phenomena interactions can be mathematically represented by the following equations related to EMF harmonic formulation (adapted for exposure instance), BH, and EM tissue dissipated power P_{td}:

$$\nabla \times \boldsymbol{H} = \boldsymbol{J} \tag{1}$$

$$\boldsymbol{J} = \boldsymbol{J}_e + \sigma \, \boldsymbol{E} + j \, \omega \, \boldsymbol{D} \tag{2}$$

$$\boldsymbol{E} = -\nabla \, V - j \, \omega \, \boldsymbol{A} \tag{3}$$

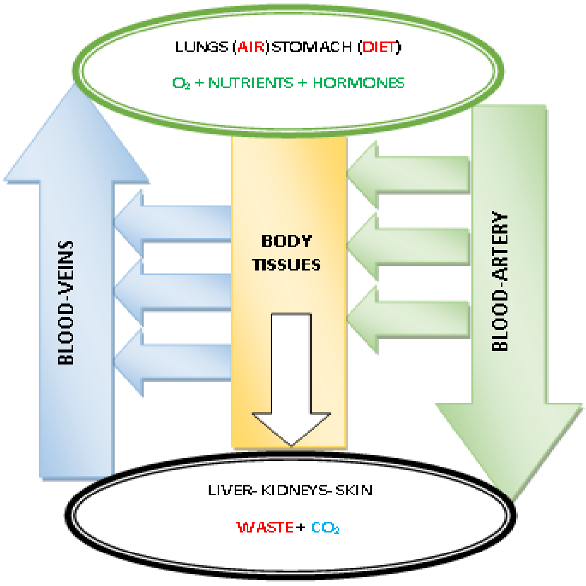
$$\boldsymbol{B} = \nabla \times \boldsymbol{A} \text{ with } \nabla \cdot \boldsymbol{A} = 0 \text{ (gauge)} \tag{4}$$

$$c \, \rho \, \partial T/\partial t = \nabla \cdot (k \, \nabla T) + P_{td} + P_{ti} + c_f \, \rho_f \, p_f \, (T_f - T) \tag{5}$$

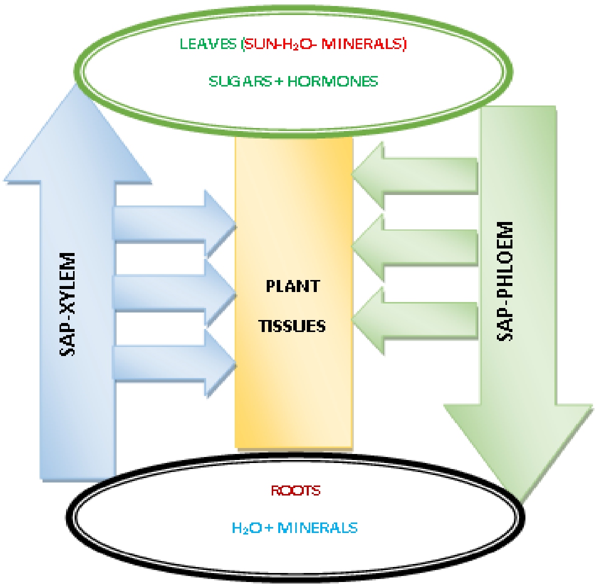
$$P_{td} = \omega \, \varepsilon'' \, E^2/2 \text{ or } \sigma \, E^2/2 \tag{6}$$

where $\boldsymbol{H}$ and $\boldsymbol{E}$ are the magnetic and electric field vectors in A/m and V/m. $\boldsymbol{B}$ and $\boldsymbol{D}$ are the magnetic and electric induction vectors in T and C/m^{2,} and $\boldsymbol{A}$ and V are the magnetic vector potential and electric scalar potential in Wb/m and volt. $\boldsymbol{J}$ and $\boldsymbol{Je}$ are the total and source current density vectors in A/m^2. The electric conductivity is denoted by σ in S/m, and the angular frequency by $\omega = 2\pi f$, with the frequency f in Hz. The character ∇ is a partial derivative vector operator. The behavior's magnetic and electric laws, respectively, given by $\boldsymbol{B}/\boldsymbol{H}$ and $\boldsymbol{D}/\boldsymbol{E}$, are signified by the permeability μ in H/m and the permittivity ε in F/m. The symbol ε'' denotes the imaginary part of the complex permittivity ($j \, \omega \, \boldsymbol{D} = j \, \omega \, (\varepsilon' - j \, \varepsilon'') \, \mathbf{E}$), and ρ represents the material density in kg/m^3. E represents the electric field strength (absolute peak value) in V/m; c represents the substance-specific heat (at constant pressure) in J/(kg °C), with k the thermal conductivity in W/(m °C) and T the temperature in °C. The dissipated power volume density in W/m^3 given by Equation (6) links to the principal dielectric (or conducting) EMF loss (depending on frequency) and will be used in the coupling of EMF and BH equations. The BH Equation (5), related to living tissues, involves a self-tissue intrinsic heat source P_{ti}, convective heat transfer via irrigating fluid (last term of 5), and an external heat source related to the EMF exposure P_{td}, all in W/m^3. T_f is the fluid temperature in °C, and c_f, ρ_f, and p_f are, respectively, fluid, specific heat in J/(kg °C), density in kg/m^3, and perfusion rate in 1/*s*.

Note that the concerned living tissues in the upper equations correspond to global biodiversity with irrigating fluid, which can be blood for animals or sap for plants. As well, self-tissue intrinsic heat source P_{ti} can be animal metabolic heat or internal heat in plant tissues. The correspondence of phloem and xylem encircling the sap in plants and veins and arteries enfolding the blood in animals is illustrated in **Figure 1**.



(a)



(b)

Figure 1. (a) Illustration of correspondence of veins and arteries, enfolding the blood in animals; and **(b)** phloem and xylems encircling the sap in plants.

The solution of the upper equations related to the EMF and BH, Equations (1)–(4) and (5), respectively, should take into consideration the particular features of the implicated structures. These are complexity of geometry, matter inhomogeneity, variables' nonlinear behaviors, and interdependence of physical phenomena, which indicate refined computational approaches. Fulfilling such features imposes structure on local answers, advocating the use of discretized 3D methods as a finite-element method (FEM) or comparable approaches (BEM, FDTD, etc.) [13–20] associated with suitable schemes for equation coupling. In the present case, a weak coupling (iterative) of EMF and BH equations due to their distant time constants would be practiced through Equation (6).

6. Non-thermal BEs

In the last section, the most frequent thermal BEs due to EMF exposure have been discussed. They do not signify any danger in case the tissue-induced fields are coherent with safety standards thresholds. In case of excessive and durable tissue-induced EMF values, the corresponding tissue-dissipated energy will steer disproportionate temperature rise. The consequent effects reflect non-thermal behavior, which can stimulate muscles, nerves, and generally excitable structures, as well as trigger molecular disturbances leading to tissue injury [21–24]. Likewise, unintentional EMF exposure to frequencies in the ionizing range can occasion hazardous, hostile consequences accompanied by molecular disturbances engaging tissue harm and destruction, owing to photons or particles of high energy. In both cases of excessive and durable tissue-induced EMF values and exposure to ionizing frequencies, molecular damage could be produced.

7. Discussion

In the above analyses, potential BEs on biodiversity in living tissues consequent to exposure to HF-EMFs have been investigated and discussed. At this point, different problems deserve to be commented on:

- In the above analysis, BEs have been discussed. The corresponding tissue security is controlled by established thresholds related to tissue-induced EMF values and its thermal state. These are assigned by the tissue-specific absorption rate (SAR) and temperature surge ΔT. Thus, the 3D local distributions of these amounts attained from the solution of the coupled EMF and the BH equations should be checked against standard thresholds to guarantee the tissue's sanctuary [11,12]. These thresholds hinge on the body or plant part of tissue (e.g., head, members, etc. in bodies or leaves, flower petals, stems, branches, and trunks in plants), the relationship with the source of exposure (e.g., device fabricator, user, etc. or plants occasionally exposed to a cellphone or permanently to a fixed antenna), and the conditions of exposure mainly related to near- or far-field exposure and the duration.
- The guard of EMF exposures can be achieved via outline optimization of radiating sources, use of confining emitting devices in constrained zones, or founding areas without EMF emission as public centers of healthcare, free parks, urban quarters, entire municipalities, woodlands, zoological spaces, botanical

gardens, etc. [6]. In fact, the most important disturbances to biodiversity are triggered by human-nature interactions. Safeguarding biodiversity species, including humans, from HF-EMF could be accomplished by three principal policies: emitting device shielding, reducing their stray fields, and restricting device usage zones. Shielding devices is not evident since it is antagonistic to their functioning principle, in particular RF wireless devices established on EM wave scattering. The reduction of their stray fields could partially limit the risk, and the users of receiver devices would be impacted by low-performance tools. Thus, the only way to fulfill such a safeguard is to regulate device emission capability and hence performance or restrict its use. The option of founding areas without EMF emission concerns the organization of constrained areas empty of radiating tools [25–27]. This safeguard alternative centers mainly on anthropogenic advances and their associations with nature and biodiversity, thus reflecting the One Health concept [28].

- In the coupled solution of EMF and BH equations, the tissue local discretized 3D techniques, such as FEM, use volume walled-in surface elements, each bordered by edge elements, each finished by a couple of nodes. The different fields can be expressed at volumes, faces, edges, or nodes, contingent on the field character as requests of, e.g., continuity. Thus, the iterative weak solution of the equations delivers the local induced field distributions as well as those of the SAR and ΔT in the tissue. The diverse parameters involved in the equations could be found in literature or measured, e.g., [29]. The imposed source in the EMF equations is related to near- or far-field exposure. In the first, it is a focused field in a point or a small surface in the solution domain, while in the second, it is a uniform field imposed on the whole surface of the exposed volume.
- The 3D computations of induced fields in living tissues require models representing such tissues. These last are often taken as static representations, which match many real-instance assessments. In case we need an evaluation of the real-time EMF exposure impact on tissue, the tissue model should account as well for real-time behavior. This is a convoluted task due to the tissues' behavior nonlinearity reflecting complex mechanical constitutive laws denoting the deformation and displacement of elastic tissues.
- The effects of HF-EMF, in addition to human living tissues, on other organisms, such as small animals and plants, have also been investigated. In the case of animals, the effects are the same as those of humans. In the case of plants, including flowering plants, vegetables, trees, nutritional (for humans and animals) plants, etc., different works could be found, for example, in [30–34]. Also, general benefits and threats of these effects could be found in [35].

Conflict of interest: The author declares no conflict of interest.

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