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REVIEW ARTICLE

Thermal effects of electromagnetic origin from heating processes to biological disturbances due to field exposure—A review

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ABSTRACT

This contribution aims to appraise, analyze and evaluate the literature relating to the interaction of electromagnetic fields (EMF) with matter and the resulting thermal effects. This relates to the wanted thermal effects via the application of fields as well as those uninvited resulting from exposure to the field. In the paper, the most popular EMF heating technologies are analyzed. This involves on the one hand high frequency induction heating (HFIH) and on the other hand microwave heating (MWH), including microwave ovens and hyperthermia medical treatment. Then, the problem of EMF exposure is examined and the resulting biological thermal effects are illuminated. Thus, the two most common cases of wireless EMF devices, namely digital communication tools and inductive power transfer appliances are analyzed and evaluated. The last part of the paper concerns the determination of the different thermal effects, which are studied and discussed, by considering the governing EMF and heat transfer (or bio heat) equations and their solution methodologies.

Keywords: Electromagnetic Fields; Heat Transfer; Induction Heating; Microwave Heating; Field Exposure Thermal Effect; Digital Communication; Inductive Power Transfer; Electromagnetic-Thermal Modeling

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1. Introduction

Throughout the development of modern society, many devices using electromagnetic fields (EMF) of different frequencies and intensities have been created. These devices have been used for many specific applications, generally enabling human well-being but sometimes accompanied by undesirable side effects that disturb society in general. An important class of applications using EMF is related to heat production. The corresponding thermal energy is used in various industrial and societal fields, e.g., heat treatment and melting of metals, food industry, and health. In these applications, the production of heat in materials by EMF is advantageously characterized by the absence of contact with a heat source. On the other hand, there are other applications using EMF but which can present needless or undesirable thermal effects. The needless case corresponds to typical unavoidable losses in most of electric devices. The undesirable effects are generally relative to perturbing and harmful consequences. An important category in this case is that of wireless EMF devices intended for communication[1–4] and energy transfer[5–7], which can produce dangerous biological thermal effects.

The various mentioned thermal effects are induced by EMF using frequencies in the non-ionizing range. They are linked to EMF by a loss of power or dissipation in the matter involved, resulting in a rise of temperature. The rules in play relate to electromagnetics (EM) and heat transfer (HT). The EM phenomenon[8] behaves via magnetic, induction and field (related by magnetic permeability), electric, induction and field (related by electric permittivity) and current density, which is related to the electric field by electrical conductivity. The HT phenomenon behaves through temperature, specific heat and thermal conductivity. Its density plus its mentioned EM and HT parameters characterize the matter involved. It should be noted that, the behaviors of the EM and HT parameters, each depend on its involved phenomenon and may be interdependent on the other phenomenon.

The most common techniques of heat production mentioned are induction heating (IH) and microwave heating (MWH). The efficacy of IH is mainly affected by the matter electric conductivity (and permeability in ferromagnetic materials) while MWH is related mainly to the matter electric permittivity (and conductivity for lower frequencies). Typically, IH is used for relatively high conductive matter as metals[9–11] and MWH is employed in dielectric matters as living tissues[12,13]. These two techniques employ different EMF frequencies and strengths. The IH displays high frequency (in the range of kHz), that is high frequency induction heating (HFIH), enough to permit reasonable skin effect, and high strength allowing high temperature on the surface layer of the conducting material; this permits metal surface treatment or melting. The MWH utilizes microwave (MW) frequency (300 MHz–300 GHz) and moderate strength allowing heating in the depth of matter. The matter parameters in these procedures are generally temperature dependent which need supervision protocols.

Concerning the case of wireless EMF devices that can produce harmful biological thermal effects, two classes are commonly used in many everyday applications. These are wireless communication tools (WCT), e.g., mobile phones, Wi-Fi access points, and antennas, which use radiofrequency (RF) (100 kHz–300 GHz) EMF with moderate strengths and inductive power transfer (IPT) devices, e.g., wireless charging devices that use moderate frequencies (less than 200 kHz) and relatively higher strengths depending on the application. These devices can induce biological effects (BE) due to the exposure of tissues to EMF. The most common is thermal BE (TBE)[1–7].

The two mentioned types of favored and undesirable thermal effects produced by EMF can be evaluated by solving both of the EM and the HT equations[14]. This can be done in a coupled manner due to the interdependence of parameters behaviors. This coupling could be of a weak nature (successive iterations) due to the high difference of time constants of EM and thermal behaviors[15].

In this contribution, the interaction of EMF with matters and the resulted thermal effects will be examined, analyzed and discussed through an evaluation of the literature. Interaction here means all influences, effects of EMF and matters changes resulting therefrom. After a general introduction of the subject in the first section, the second section will be devoted to the analysis of the most popular EMF heating technologies. This involves HFIH and MWH including MW ovens and hyperthermia treatment. In the third section, the problem of EMF exposure will be examined and the resulting TBE will be illuminated. The two most common cases relative to wireless EMF devices, namely WCT and IPT apparatuses, will be analyzed and assessed. The fourth section is concerned with the evaluation of thermal effects considering the governing equations and their solution.

2. EMF heating

EMF heating exists under diverse forms differing owing to the heated matter nature, heating purpose and the used source strength and frequency. We will examine the most common cases concerning heating of electric conducting and dielectric matters. This corresponds to respectively HFIH (range of kHz) and MWH (MW frequencies). As mentioned before, these heating procedures are linked to EMF by a loss of power or dissipation in the matter involved. The density of this power per volume for conducting or dielectric materials is respectively given by:

$P_d = \sigma \cdot E^2/2$, low ω such that $\sigma >> \omega\varepsilon$, mainly conductor (1)

$P_d = \omega \cdot \varepsilon'' \cdot E^2/2$, high ω such that $\sigma << \omega\varepsilon$, mainly dielectric (2)

The corresponding specific absorption rate (SAR) is given by:

$$SAR = P_d/\rho = \sigma \cdot E^2/(2\rho) \text{ or } = \omega \cdot \varepsilon'' \cdot E^2/(2\rho)$$

(3)

In equations (1–3), the parameters: σ is the electric conductivity of the heated material, ε'' is the imaginary part of the complex permittivity of the absorbing material and ρ is the material density. The variables ω is the angular frequency = $2\pi f$, f is the frequency (Hz) of the exciting EMF, E the absolute peak value of the electric field strength (V/m) and SAR (W/kg).

The power dissipation given by equation (1) corresponds to dominant Joule heating of EMF energy loss relative to HFIH, while this given by equation (2) relates to foremost dielectric heating of EMF energy loss relative to MWH. Note that the imaginary part ε'' of the (frequency-dependent) permittivity ε is a measure for the ability of a dielectric material to convert EMF energy into heat, also named dielectric loss. The real part ε' of the permittivity is the normal effect of capacitance and results in non-dissipative reactive power.

The power dissipations given by equations (1) and (2) as well as the SAR given by equation (3), will be used in the coupling of EM and HT equations in section 4.

2.1 HFIH

HFIH is a process using the principle of EM induction to generate heat inside electrically conductive materials, by induced current without direct contact with a heat source. An AC excitation coil encircling the material accomplishes this. The flux from this coil induces an electromotive force in the material, which causes the electric current to flow. Normally, IH can work at any frequency range, but the process examined here uses high frequency sources (in the range of kHz frequencies)—HFIH, permitting to induce current inside material. It aims to heat the material surface, in compliance with Faraday's law and the Joule effect, inducing a power dissipation leading to a rise of temperature. Indeed, in high frequency operation according to Lenz's law, the induced current density due to the skin effect will be concentrated near the surface of the material. The induced current density will have its maximum value on the surface and decays exponentially deeper towards the center. A corresponding penetration depth δ of the induced current is often used to estimate the dissipated power and the heat produced. The value of δ is inversely proportional to the electrical conductivity σ, the permeability μ and the frequency f. The more important these parameters are, the smaller the depth of penetration will be and therefore the higher the apparent resistance of the material will be. Note that δ is temperature dependent (σ and μ are temperature dependent). Moreover, δ is also frequency dependent, so variable frequency sources allow the process to be optimized. Heat producing power dissipation is proportional to field strength (a function of current and number of coil turns), frequency, permeability, and resistance in the conductive heating material. Numerous investigations have been done for the design and optimization of HFIH systems[16–19].

In typical heating installation using HFIH, the heated object can have different forms, cylinder, billet, sheet, beam, bar, etc. The heating coil is necessary close to the heated object for better efficiency and hence has the same configuration. On the other hand, HFIH systems are fed generally via resonant circuit. Indeed, an inverter is used to feed the high frequency AC current to the heating coil. However, the coil reactance may prevent the inverter from supplying a large enough AC current to the heater coil. Actually, the coil resistance is relatively small while its reactance under high frequency can be very high. Moreover, this last consumes reactive power (bad power factor). A capacitor is usually joined to the heater coil and both are energized at their resonant frequency, thus the capacitor cancels the inductance of the heating coil. Therefore, inverters that typically operate at the resonant frequency, allowing a large AC current to flow through the heating coil, power these systems[20,21].

HFIH systems offer several advantages: reliable surface treatment thanks to the concentration of heat, fast, efficient, non-polluting heating, allowing temperature control, etc. Several applications are well suited to such technology: cooking without loss of surrounding heat, metal melting, metal (annealing, forging, brazing, welding, and quenching), sterilization of medical instruments, etc.[22–29].

2.2 MWH

The range of MW radiation in the EM spectrum is between infrared and radio waves and has wavelengths from 1 m to 1 mm (0.3 to 300 GHz). In industrial and household MW devices, a frequency of 2.45 GHz is used, which corresponds to a wavelength of 12.25 cm with hotspots at half-wave points, or every 6.125 cm. In medical treatments as hyperthermia, the operated frequency is in the range of 434–915 MHz. In MWH, intermolecular frictional forces due to MW radiation mainly generate heat. In fact, such heating is initiated by the rotation of the molecular dipole in the material (usually a dielectric). The process by which matter absorbs MW energy is called dielectric heating. The dielectric heating mechanism under MW impact is called dipole polarization, which is triggered by the molecular friction produced by the alignment of the dipole moments of matter. Thus, the molecules move from a disordered state moving rapidly to an ordered aligned state and the friction generated during these movements produces heat. Thus, the MW radiation energy is converted into heat via intermolecular frictional forces.

2.2.1 MW ovens

In industrial and household MW ovens, as mentioned before, waves of 2.45 GHz frequency penetrate well into foods of realistic size so that the heating is relatively uniform all through the foods. MW heating in ovens is often used to dry food. The effect of MW radiation on water molecules provides energy in the water, which will be directed from inside the materials to the surface. The drying process can be summarized as follows: exciting the moving molecules with MW energy, which is converted into heat, the water rapidly evaporates by diffusion and dries when the thermal energy exceeds the energy needed to completely vaporize the moisture.

The MWH is affected by various factors, which are related to MW radiation and heated materials. Those of MW include power, duration of exposure, frequency, and power density. While those of materials include dielectric properties, humidity, depth of penetration and geometry. These factors interact with each other to affect the heating effect per MW and they are closely linked to the adjusting of the magnetron output, matter size, or oven cavity size.

Numerous investigations relative to this technology and its applications can be found in literature[30,31].

2.2.2 Hyperthermia treatments

Hyperthermia treatments, indicated as an artificially produced temperature increase of 40–44 °C normally for an interval of 60–90 minutes. Thus, using the biological effect of pursued induced heat to negatively impact tumor evolution. The central aim of a MW hyperthermia action resides in selectively raising the tumor temperature through an appropriate antenna arrangement, while maintaining the heat in the neighboring healthy areas in an allowable extent. The temperature rise within a tumor in the actions of MW hyperthermia is usually triggered by MW radiation emitted by applicators with antenna system surrounding the area under treatment. Applicators functioning at 434–915 MHz are most common for treatments of, e.g., cancer of the head and neck by hyperthermia, due to their capacity to penetrate tissue and engender a controlled focus of heat in the tumor region. Note that the capacity of an applicator to deposit EM energy into a target depends on the operating frequency, the number of antennae, and target position and size. Various investigations on hyperthermia techniques and systems have been published[32,33].

The efficacy of a hyperthermia conduct is strongly reliant on the feature of the heating procedure; this has encouraged developments in treatment forecasting to situate optimally the amplitudes and phases of the applied signals. Amplifying the temperature inmost the tumor is the decisive objective of a hyperthermia treatment; still, a temperature-centered optimization necessitates an excessive computational problem at each step. Owing to this, treatment forecasting usually depends on the optimization of the SAR related to deposited EM energy corresponding to the heat source. Many works have been done in the evaluation, planning and optimization of hyperthermia treatment[34–37].

2.3 Secondary effect overheating

This heat side effect is present in most of EM devices and auxiliaries. This involves conductors, magnetic and dielectric materials present in electric machines, transformers, cables, transmission lines, electronic devices, etc. All these EM systems suffer of functioning losses, which are specific to each matter. These superfluous losses trigger several useless problems. One of the most important is related to the conversion of these EM losses into heat. The proper functioning of these EM systems hence necessitates cooling, which consume additional energy. This loss spurious energy could only be reduced or/and detoured. The reduction of these losses could be achieved by optimizing the design, materials, control and functioning of systems, which results in improving the efficiency including losses and cooling. Detouring these losses could be done by using the produced heat in a useful purpose, like heating houses, offices, and transport.

3. EMF exposure

Interaction of EMF with objects in general crops diverse effects that depend on the nature of the exposed articles. Interaction here means all influences, effects and resulting changes. This can perturb the function of an apparatus, e.g., an electronic device, or a healthcare instrument, e.g., an imager. An important category of interactions concerns living tissues. In various situations, these fields are operated quotidian in several welcoming purposes. Furthermore, they are employed securely in healthcare, either straight on the body tissues or in the function of medical devices. Nevertheless, when exposed to these fields happens parenthetically or unintentionally, it can crop unfavorable effects. Thus, the growth in the regular use of EMF has encouraged investigations regarding their effects in several domains and in specific that of public health. This enquiry was keen to the effects of EMF exposures at the frequency and power of the source, on the human body tissues to evaluate the likely effects in harmony with international health-safety standards[38–40]. These effects are intimately linked to the type of the EMF and the exposed substance. The strength of the field as well as its frequency typify EMF, whereas the biological and geometric belongings of the diverse segments and tissues of the body describe matter. Devices producing EMF used every day mostly use frequencies creating non-ionizing radiation. Nevertheless, in particular healthcare actions, the frequencies may be in the scale of ionizing emission; in this case, exposure is constrained and managed.

Actually, the outcomes due to exposure to EMF can be disjointed into two different classes regarding the frequency ranges, and the conforming wavelengths. The first involves the range of 10^3–10^{14} Hz where EM waves can be divided into radio, microwaves and infrared that yield non-ionizing radiation. The second concerns the range of 10^{15}–10^{22} Hz shared into ultraviolet, X and gamma rays, which engender ionizing radiation. In the situation of ionization, the radiated energy is great sufficient to origin the liberation of electrons, which are ejected from the atoms; the result is the realization of duos of ions, which are ionization. It is possible in this case to have adverse health effects by creating molecular disorders leading to tissue damage. Quite the reverse, the non-ionizing circumstance is differentiated by the fact that the emitted energy is too low to trigger the liberation of electrons from their revolutions in the atoms. Thus, non-ionizing radiation indicates that its following excitation energy degree implies that electrons yet with an altered energy situation stay in their atoms averting the formation of charged ions. EMF of diverse frequencies, in the range of non-ionizing class, work in several conditions and can disturb human society.

In general, the apparatuses most involved in non-ionizing EMF exposure are those using important stray fields such as wireless energy devices containing wide power and frequency ranges. Two typical classes of such devices are WCT and IPT apparatuses. The case of WCT comprising ordinary sources of radiofrequency (RF), 10^5–3×10^{11} Hz, emissions by, e.g., antennas, Wi-Fi access points, smartphones, tablets, portable phones and Bluetooth devices. As the exercised frequencies in these devices are high and the exposed entity interests the human head and body, the security conditions of these devices have to be controlled. The second situation of IPT reports to wireless inductive charging techniques for uses extending from minor applications, e.g., phone sets and electric toothbrushes to great power apparatuses, e.g., electric vehicles and other industrial mobility arrangements. The exposure to EMF has dissimilar effects in these two cases. These effects, as mentioned before, are intensely linked to both characters of the EMF and the substance exposed. In WCT, the field strength is modest; however, the functioned frequency is elevated, and the exposed part is mostly the head zone, the BE is focused on brain. In the case of IPT, the field intensity could be great with elevated stray level, and the frequency is relatively small (generally less than 200 kHz) and the exposure affects bodies nearby the mechanism.

Such EMF exposures infer precise management of the safety conditions. Humans or animals exposed to EMF undergo BE which, with ordinary use of the concerned tools and apparatuses, are principally thermal due to energy dissipation. These BE must not surpass the bounds set by the safety standards. By obeying these standards, the exposed subjects do not ordinarily risk any problem. These TBE due to EMF exposure are the most popular with normal use of WCT and IPT devices. Moreover, there are also smaller frequently effects that are non-thermal.

3.1 Energy of EMF

As indicated before, the two classes of non-ionizing and ionizing radiation (see **Figure 1**), which hold dissimilar frequency ranges, are characterized by their energy heights, which crop distinguished atomic conditions, respectively without or with formation of charged ions. Both categories of radiation produce unwanted effects under diverse conditions.

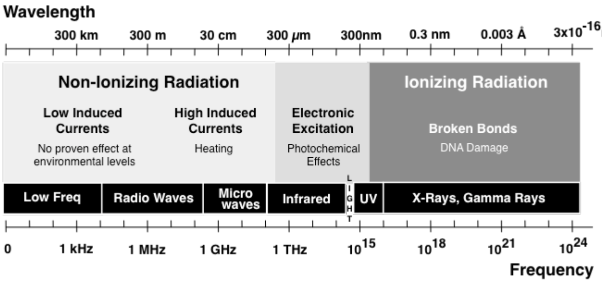

Figure 1. EMF frequency and wavelength of ionizing and non-ionizing ranges.

Indeed, EMF in the frequency range of the non-ionizing class can produce thermal and non-thermal BE in body tissues, which can directly harm human beings and animals. Moreover, high frequency EMF can disturb the working of electronic and communication devices, comprising medical apparatus, which touches numerous areas of societal progress. Ionizing EMF are perhaps the best-known class of radiation due to their broad use in medical treatments, e.g., X-rays. This usage is restricted to specific health safety circumstances for patients and medical staffs. The quantity of energy can differ from very little, as in dental X-rays, to especially large quantities in sterilizing medical utensils irradiators.

3.2 Features of WCT EMF

Applications of non-ionizing RF-EMF constantly augmented since nearly 6 decades. This contains medicine (e.g., magnetic resonance imaging and RF ablation), manufacturing (e.g., heaters and welding), home usages (e.g., Wi-Fi), defense and navigation (e.g., radar and RFID) and especially in communications (e.g., TV transmitting and mobile phones). These expansions signify that large quantities of people go through exposure to RF-EMF and burden has been escalated concerning public health alarms due to such exposure.

The sources of RF-EMF involving WCT are of two sorts, devices working neighboring the human body, causing a near field exposure interacting greatly confined in a part of the body, and sources operating far away from the body that create a whole-body uniform exposure. Approximately, far field relates to transmitter-receiver gap superior than a wavelength and its force reduces fast with distance. Typical near field sources are mobile and cordless phones. Normal far field sources contain TV posts, mobile and cordless phones base stations, Wi-Fi access points or adjacent mobile phones.

Interaction of RF-EMF with living tissues is influenced by the frequency, the field strength, the exposure duration and the dielectric properties of absorbing tissues. Furthermore, in case of simultaneous triggering of several RF-EMF radiating sources close to the body, we have to account for such intricate interaction. The nature of interactions can crop diverse BE. These effects can be due to short or long-terms exposures. The most familiar effect is the thermal short-term one. There are also slight regular short- and long-term effects. The non-thermal complex effects fall in this category.

3.3 Features of IPT EMF

The two concepts underlying IPT are Ampere's Law of 1820 and Faraday's Principle of Magnetic Induction of 1831. These foundations later allowed Nikola Tesla to introduce wireless energy transfer for the first time in the 1890s. The technique of wireless energy transfer was first initiated for the propagation of power over long distances expending microwave rays. It is only recently that near-field short-range IPT technology has been widely used to charge the batteries of many devices such as cell phones, home appliances, drones and electric vehicles. IPT, inductive coupling, and resonant power transfer generally refer to wireless power transfer (WPT). These various terms refer to the same process—the contactless transfer of energy from a power source to a load across an air gap. An IPT system consists of two coils—a transmitter and a receiver. The input power source to the transmitter coil is generally a resonant power inverter. The use of resonance permits the same advantage as in the case HFIH (see section 2.1).

3.4 BE produced by wireless devices

An important consideration motivates investigations on the interactions between wireless structures and living tissues. That is to evaluate the EMF provoked in the human body. These fields are magnetic flux density, electric field and current density. This makes it possible to assess the likely effects on health and to verify the agreement with safety health standard.

3.4.1 BE due to interaction with WCT

EMF exposure in RF range, as mentioned before, is measured by the SAR. In the case of WCT, the absorbed energy is focused near to the head zone of human body. Safety standards limit the SAR in this case to a value of 0.5–2.0 W/kg. Note that the SAR limits are 2.0 for the head and body and 4.0 W/kg for the limbs. These values guarantee to limit thermal effects for normal use exposure durations. Regarding the thermal effects, exposure to fairly great RF-EMF (strength and duration) can be hazardous to living organisms. Such exposure may steer to body heating occasioning a rise of temperature, which may origin tissue damage. Two features strengthen this event. The first relates to the capacity of RF energy to fast heat biological tissues, much as MW ovens discussed in section 2. The second relates to the incapability of body to endure or dissipate the conflicting heat that can be produced. Note that the portions of the body least protected from RF-EMF heating are those that lack available blood circulation, which is the principal way of dealing with extreme heat. The scale of such heating is associated to several conditions involving the field strength, the frequency of the waves, the exposure interval, the heat dissipation capacity of the tissues, the surrounding environment and the size, shape and positioning of the exposed body[1–4].

Note that, disproportionate strength fields can exhibit non-thermal effects. One of the most common BE in this circumstance is the break of brain electro-wave due to the significant external EMF that leads to changed cell secretion. In addition, EM-induced membrane electroporation also disturbs cell activation.

3.4.2 BE due to interaction with IPT

IPT is used as inductive battery charging in many devices of different powers. An important future use of IPT is for recharging electric vehicle (EV) batteries. In this case, due to electromagnetic compatibility (EMC) and power efficiency, the IPT in EV normally operates in a lower frequency scale (from a few kilohertz to about 200 kHz). Regarding the thermal effects, as in the last WCT case, EMF exposure may steer to body heating occasioning a rise of temperature, which may origin tissue damage.

The evaluation of EMF exposure of human tissues from the IPT generally includes the IPT assembly, the vehicle and the human body (in the vehicle or located on the side). The electromagnetic exposure assessment should be performed for the worst-case body configurations[6].

3.5 Health safety standards

The SAR, equation (3), which values the energy absorbed by an element of a matter, can quantify the thermal effect induced by exposure to EMF. If the SAR is multiplied by the exposure interval, it signifies the specific absorbed energy amount. This energy produces a rise in matter temperature.

Generally, the quantity of heat absorbed by a lossy dielectric can be given as:

$$\Delta Q = c \cdot m \cdot \Delta T \tag{4}$$

where Q is the heat energy absorbed or dissipated in joule (J), m is the mass of the substance (kg), ΔT is the change in substance temperature (°C), c is the specific heat of the substance (the heat required to change a substance unit mass by one degree) in J/(kg · °C).

The power absorbed per unit mass of substance exposed to EMF, SAR (W/kg), which corresponds to the time derivative of the energy (J) absorbed per unit mass (kg) of substance can be given for an exposure time Δt (s) by:

$$\mathrm{SAR} = \Delta Q/(m \cdot \Delta t) = c \cdot \Delta T/\Delta t = \sigma \cdot E^2/(2\rho) \text{ or } = \omega \cdot \varepsilon'' \cdot E^2/(2\rho) \tag{5}$$

Equation (5) implies that SAR value of

substance varies with the induced electric field intensity, the exposure time, and the matter electrical-thermal properties. The energy absorbed by the substance is converted to thermal energy, triggering increase the temperature.

The temperature increase ΔT due to power dissipated by an electric field interacting with a lossy dielectric material specimen given for an exposure time Δt is given by:

$$\Delta T = \omega \cdot \varepsilon'' \cdot E^2 \cdot \Delta t/(2c \cdot \rho) \tag{6}$$

Note that equation (6) gives the temperature rise in an element of a dielectric. For a living tissue, the heat transfer is usually represented by Penne's bio-heat equation[41] as will be shown in section 4.

3.5.1 Safety thresholds

Equations (4–6) denote that the greatest the SAR and the more the exposure time is, the higher and further dangerous the elevation in temperature will be. This behavior will be influenced, in addition to the field (intensity and frequency) and the exposure interval, by the density of the tissue and its thermoelectric properties. Thus, the SAR limits imposed by health safety depend on the element of the body portion and the nature of the material exposed as well as the circumstances of exposure. Exposed themes can be adults, children or animals. The exposed elements of the body are the head, trunk and limbs. Exposure conditions comprise different classes of exposed themes (linked to the liaison with the source of exposure): workers implicated in manufacture, testing, and placing devices, consumers using the device, and neighboring subjects. For all these situations, health safety standards set thresholds corresponding to SAR, ΔT and fields produced in the human body: magnetic flux density B, electric field E and current density J.

4. Evaluation of thermal effects

4.1 Evaluation methods

The evaluation of thermal effects can be performed by modeling or experience studies. In the case of evaluation through modeling, the governing mathematical equations can be solved locally in the object or body tissues concerned by the effects. This can be performed by using numerical discretized techniques or other methods permitting local evaluation[6,42–47]. This involves the EM equations and the general heat or bio-heat tissue equation[41]. In the case of using measurements for evaluation, sensors can be placed in the subject (when possible) to detect the needed fields (electric, magnetic, and thermal).

4.2 Governing equations and solution

4.2.1 Governing equations

The governing equations are the Maxwell EMF equations and the heat transfer general equation or the Penne's bio-heat tissue equation.

The junction between EMF and heat equations is Pd or SAR, which can be obtained from EMF equations and used as input to the heat equation.

The EMF equations can be given by:

$$\nabla \times \mathbf{H} = \mathbf{J} \tag{7}$$

$$\mathbf{J} = \sigma\, \mathbf{E} + j\, \omega\, \mathbf{D} + \mathbf{Je} \tag{8}$$

$$\mathbf{E} = -\nabla\, V - j\, \omega\, \mathbf{A} \tag{9}$$

$$\mathbf{B} = \nabla \times \mathbf{A} \tag{10}$$

In the EMF equations (7–10), **H** and **E** are the magnetic and electric fields, **B** and **D** are the magnetic and electric inductions, **A** and V are the magnetic vector and electric scalar potentials. **J** and $\mathbf{J}_e$ are the total and source current densities, σ is the electric conductivity and ω is the angular frequency. The symbol ∇ 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 magnetic and electric comportment laws respectively between **B**/**H** and **D**/**E** are represented by the permeability μ and the permittivity ε.

Generally, in EM systems, the current is delivered by a voltage source via an external circuit. The general following relation of the voltage v and the current i in the external circuit (coil) governs this current:

$$v = 1/C \cdot \int i\, dt + r\, i + L \cdot di/dt + d\Psi/dt + \text{ɤ} \tag{11}$$

In this equation, r is the total resistance of the circuit, L a linear inductance, C a capacitance, ɤ a non-linear voltage drop (typically a semiconductor component, e.g., a diode) in the electrical circuit and Ψ the flux linkage in the coil.

The input source term in EM equations (7–10) is $\mathbf{J}_e$ or its equivalent electric field σ $\mathbf{E}_e$. In case of HFIH and IPT, the source $\mathbf{J}_e$ is related to "i" of equation (11) and the EM equations to solve will be equations (7–11). In the case of MWH and WCT EMF exposure, the source will be σ $\mathbf{E}_e$, which corresponds to ω ε″ $\mathbf{E}_e$ in living tissue and the EM equations to solve will be equations (7–10).

The dissipated power Pd is given by equation (1) or (2) depending on material respectively, conductor or dielectric; equation (3) gives the SAR. The P_d and SAR can be determined from the solution of equations (7–10 or 11).

The general heat transfer equation can be given by:

$$c\,\rho\,\partial T/\partial t = \nabla \cdot (k\,\nabla T) + P_d \tag{12}$$

The bio-heat tissue equation can be given by:

$$c\,\rho\,\partial T/\partial t = \nabla \cdot (k\,\nabla T) + \rho\,(SAR) + qmet - c_b\,\rho_b\,\omega_b\,(T - T_b) \tag{13}$$

Pd in equation (12) is the power loss (dissipated) density in W/m^3. In the general heat transfer and the Penne's bio-heat equations respectively equations (12) and (13), k is thermal conductivity, T local temperature in °C, qmet is the basal metabolic heat source in W/m^3, c_b is blood specific heat in J/(kg · °C), ρ_b is blood density in kg/m^3, ω_b is blood perfusion rate (1/s), Tb blood temperature in °C. $\nabla \cdot (k\,\nabla T)$ represents simple heat equation in differential form and ρ (SAR) represents the influence of electromagnetic energy absorbed in the human tissues.

4.2.2 Solution methodology

The solution of EM equations (7–10 or 11) allows to calculate the induced EMF, for a specific frequency, in the object or tissues. The SAR can be determined from the fields resulting of this solution. Also, the EMC analysis controlling the disturbances due to EMF exposers of devices (embedded or not) can be controlled by this solution. Thermal conduct in objects due to EMF through the dissipated power is governed by equations (7–11, 1 or 2, 12). Pennes bioheat equation given by equation (13) is generally employed for heat transfer determination in living tissues. Thermal conduct in tissues due to EMF exposure via SAR is ruled by equations (2, 3, 7–10, and 13).

Concerning the solution of equations (7–13) that correspond to EM, external circuit and thermal behaviors, note that the strategy of solution depends on the relative time constants of the involved phenomena. When these time constants are near, the equations of concerned phenomena need to be solved through a strong (simultaneous) coupling; this is the case of EM and external circuit equations. Opposing, with far time constants, the corresponding equations can be solved in a weak coupling manner (iteratively); this is the case of EMF and thermal equations[15].

The equations can be solved in a coupled manner (strong or weak) and locally (by discretized techniques) in the appropriate element of the object or the body tissue. Thus, the solution gives the local distributions in the object or the tissue of respectively Pd or SAR, ΔT as well as the produced EMF, which are the electric field E, the magnetic induction B, and the current density J. The involved parameters are those relative to object or tissue properties. The concerned geometry considers the nature of the involved subject. **Figure 2** illustrates the modeling in case of exposure involving source input, tissue parameters, exposure duration and local distributions outcomes.

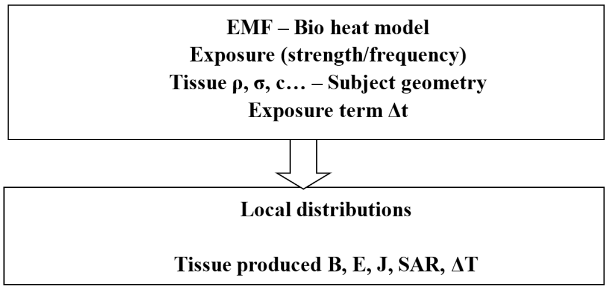

Figure 2. Schematic of modeling, input parameters and local distributed outputs.

The local field distributions make it possible to evaluate the thermal effects. In instance, relating to indirect effects on medical devices, the ruling equations are those of EMF linked to EMC analysis. The lowering of the causes of exposure to RF-EMF could be attained by shielding articles employed on the exposed medical tools. The control of the shield effect on the exposed elements can be achieved by EMC analysis.

4.3 Body models

Important research has been spent into construction of models of human bodies. At large, the practice of numerical simulations to compute EMF in human body demands suitable computer models of the human body and complete data of the dielectric belongings of human tissues at the effective frequency. These models are normally classified into homogeneous and non-homogeneous. For the first, the dielectric belongings of the human body are regularly labeled as a 2/3 equivalent muscle model[48]. For the second ones, layered tissue phantom models are adjusted on data attained from MRI, computed tomography and digital imaging techniques, proposing tissue shape accuracy on the order of mm[49]. **Figure 3** shows an anatomical whole body model and its diverse tissues and organs of concern. Such a high-resolution human model is well-suited with the numerical approaches expended for the calculation of induced fields in human's tissues. The dielectric properties of biological tissues are widely presented in the study by Gabriel *et al.*[50]. A comprehensive picture of accessible measurement data for dielectric permittivity and electrical conductivity for a specified frequency is also delivered in this reference.

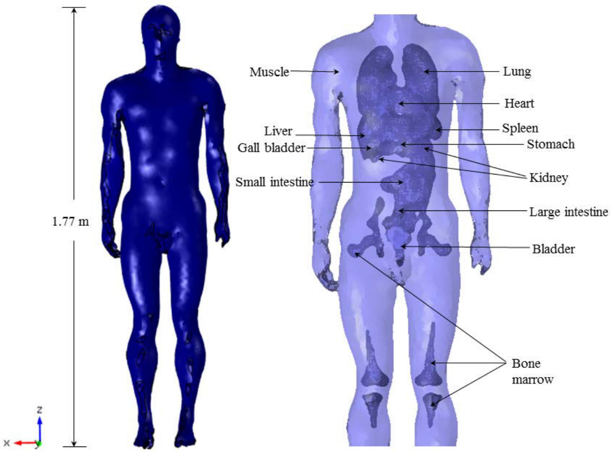

Figure 3. High-resolution anatomical whole body model and its different tissues and organs.

5. Discussion

In the analysis followed in this contribution, the thermal effects owing to EMF assistance or exposure have been discussed and assessed. At this point, various attentions are worth remarking on:

- In this contribution, thermal effects were investigated with temperature rise as output of applied or exposure EMF. In the concerned applications, the final outputs are beyond temperature rise. In HFIH, the purpose was, e.g., metal surface treatment or melting, which are related to chemical, metallurgic and magneto-hydrodynamic phenomena. In the case of MWH, the purpose was cooking, drying or tissue destroying, which are related to chemical, physical and biological phenomena. In the case of EMF exposures, the SAR and temperature rise were used to control safety thresholds. However, for excessive SAR and temperature rise, the corresponding effects (non-thermal) are related to molecular damages that relate to biology. In all these cases, the full investigations are beyond EM and HT coupled phenomena and need explorations that are more complicated.
- Regarding the notion of resonance, encountered in this contribution, allowing better performance and greater efficiency, e.g., the cases of HFIH and IPT, note that the cavities of the MW ovens on the contrary, they are not resonant (a lot of people thought the opposite). In fact, resonant MW cavities exist and are used in several applications for the reason mentioned above but are not used for MW ovens. In fact, the frequency used in MW ovens (2.45 GHz) has waves that penetrate reasonably sized foods well, so the heating is relatively even throughout the food. Using a frequency for which the water molecules react strongly (as in a resonance) would be a big miscalculation—the water molecules on the surface of the food would absorb all the microwaves and none would be able to reach the molecules deeper in the food. Therefore, in this case the oven will not be able to perform its function.
- In this contribution, the thermal effects due to the interaction of EMF with living tissues have been analyzed. Other types of interactions between EMF and living tissues can be more complex, producing non-thermal effects involving various biochemical or bioelectrical consequences that affect the cellular, molecular and chemical structures of living tissues[51,52]. These effects can be produced due to long-term exposures or excessive short-term

exposure involving high SAR values. Indeed, EMF of moderate intensity generally have no non-thermal effects on living tissue cells. On the other hand, excessive fields can display non-thermal effects such as membrane electroporation. Note that non-thermal effects can be used clinically for tumor treatment by applying RF-EMF with moderate force (100–200 V/m) without risk. It should be noted that the mechanisms of the non-thermal effects remain partially undetermined[52].

The EMF-thermal link can be found in many circumstances in the universe. For example, stellar effects where EMF are directly related to the management of internal chemical reactions in stars and planets (magnetized ones) that are associated with corresponding thermal behaviors. Additionally, natural effects exist, where EMF can affect the temperature of elements in fauna and flora, e.g., lightning.

6. Conclusions

The intentions of this contribution were to examine, analyze and evaluate the literature relating to the interaction of EMF with matter and the resulting thermal effects in the two cases: effect sought by the application of fields and unsolicited effect resulting from exposure to the field.

The following points summarize the conclusions of the article:

- Both cases of HFIH and MWH were analyzed and evaluated.
- The situation of EMF exposure and its biological thermal effects have been illuminated in the everyday-use cases of both WCT and IPT devices.
- A detailed modeling strategy was described and discussed, concerning the relevant phenomena of electromagnetism, external electrical circuits and bio heat transfer. The various specific couplings necessary for these phenomena have been specified.

The relationship between EMF and their thermal effects characterized by temperature rise was the main issue of this contribution. The ultimate purposes of the cases treated, heating by the field and exposure to the field, involve chemical, physical and biological phenomena. Specialists in these fields, thanks to the elements provided in this contribution, could more easily investigate these purposes.

List of used abbreviations

EMF: electromagnetic field(s)
IH: induction heating
HFIH: high frequency induction heating
MW: microwave
MWH: microwave heating
EM: electromagnetic
HT: heat transfer
WCT: wireless communication tool(s)
RF: radiofrequency
IPT: induction power transfer
BE: biological effect(s)
TBE: thermal biological effect(s)
RFID: radio frequency identification
SAR: specific absorption rate
MRI: magnetic resonance imager
EMC: electromagnetic compatibility

Conflict of interest

The author declares that he has no conflict of interest.

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