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Review

Assessment and Categorization of Biological Effects and Atypical Symptoms Owing to Exposure to RF Fields from Wireless Energy Devices

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Abstract: Nowadays, environmental electromagnetic fields exist everywhere and the whole population is exposed. The most widespread technologies engendering exposure to electromagnetic fields for the public and workers are radiofrequency wireless communication systems. Such exposure can have direct effects on living tissue involving biological problems or personal symptoms, as well as indirect effects restricting healthcare appliances. This assessment aims to analyze, examine and categorize the consequences of non-ionizing electromagnetic fields emitted by radiofrequency devices. This concerns biological effects in living tissues and atypical personal symptoms for short and long-term exposures. The evaluation methodology in this field of investigation is also discussed. In the article, these consequences as well as their evaluation techniques, in the case of wireless digital communication tools, are analyzed and reviewed. The categorization of exposure sources, the corresponding effects and their assessment methodologies are analyzed. The concept of systematic reviews and meta-analyses and their applications in various assessments of these effects and symptoms are reviewed and discussed.

Keywords: electromagnetic fields; radiofrequency exposure; biological effects; atypical symptom; categorization; evaluation methodologies

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Citation: Razek, A. Assessment and Categorization of Biological Effects and Atypical Symptoms Owing to Exposure to RF Fields from Wireless Energy Devices. *Appl. Sci.* **2023**, *13*, 1265. https://doi.org/10.3390/app13031265

Academic Editors: Demis Pandelidis, Roberto Zivieri and Katrzyna Wartalska

Received: 8 December 2022
Revised: 15 January 2023
Accepted: 16 January 2023
Published: 17 January 2023

1. Introduction

The interaction of electromagnetic fields (EMF) with living tissues or manufactured objects can produce different effects on these exposed entities. In different circumstances, these fields are used daily in various friendly applications. Moreover, they are utilized safely in healthcare, either directly on the human body or in the operation of medical instruments. However, when exposure to these fields occurs incidentally or accidentally, it can produce adverse effects. Thus, the increase in the daily use of EMF has prompted studies concerning their effects in various domains and in particular that of public health. This inquest was devoted to the effects of electromagnetic (EM) exposures at the frequency and power of the emitting source on the various tissues of the human body to assess the potential effects in accordance with international health-safety standards [1–3]. These effects are closely related to the nature of the EMF and the exposed matter. The intensity of the field and its frequency characterize EMF, while the biological and geometric properties of the different parts and tissues of the body characterize matter. Devices emitting EMF used daily mainly expend frequencies producing non-ionizing radiation. However, in specific healthcare procedures, the frequencies may be in the range of ionizing radiation; in this case, exposure is restricted and controlled.

In fact, the consequences due to exposure to EMF can be separated into two distinct categories concerning the frequency ranges, and the corresponding wavelengths. The first concerns the range of 10^3–10^{14} Hz where EM waves can be split into radio, microwaves and infrared that produce non-ionizing radiation. The second regards the range of 10^{15}–10^{22} Hz divided into ultraviolet, X and gamma rays, which generate ionizing radiation. In the case of ionization, the radiated energy is high enough to cause the release of electrons, which are expelled from the atoms; the consequence is the materialization of pairs of ions, which are ionization. This is likely to have adverse health effects by generating molecular disturbances leading to tissue damage. On the contrary, the non-ionizing case is distinguished by the fact that the radiated energy is too weak to cause the release of electrons from their orbits in the atoms. Thus, non-ionizing radiation signifies that its conforming excitation energy level infers that electrons even with a changed energy state remain in their atoms avoiding the creation of charged ions. EMF of different frequencies, in the range of non-ionizing category, operate in several circumstances and can disrupt human society. The research followed in this contribution falls into this category of frequency range.

In general, the apparatuses most involved in EMF non-ionizing exposure are those exerting significant stray fields such as wireless energy devices embracing wide power and frequency ranges. A typical class is the case of digital communications comprising ordinary sources of radiofrequency (RF), 10^5–3×10^{11} Hz, emissions by, e.g., antennas, Wi-Fi points, smartphones, Bluetooth tools. In this case, moderate field strength but relatively high frequencies RF characterize the exposure of the human body to emissions from these devices. Such RF-EMF implies rigorous control of the safety conditions; see for example [4–9]. Humans exposed to RF-EMF endure biological effects (BE) which, with common use of RF tools, are primarily thermal due to energy dissipation. These BE must not exceed the limits set by the safety standards. By respecting these standards, the exposed subjects do not normally risk any inconvenience. These thermal BE due RF-EMF exposure are the most common with usual use of digital communication devices. Moreover, there are also lesser frequently effects that are non-thermal. In addition, other special cases relate to rarer people who show dissimilar effects due to such exposure. These will present with atypical symptoms (AS). This is the case of two different categories of people. The first presents various non-specific symptoms due to insignificant exposures even for a negligible duration. The second displays cognitive disturbances for long-term exposure to RF-EMF. Considering the case of people showing non-specific symptoms, even with exposures well below the limits set by safety standards, those are supposed hypersensitive to EMF for different frequencies in general. Electromagnetic hypersensitivity (EHS) involves symptomatic intolerance to EMF environments. Such intolerance concerns more particularly the RF range EMF. The cause of these symptoms is obviously unfounded. Several studies have been accomplished to comprehend this enigmatic circumstance, see for example, [10–16]. Regarding the case of long-term effects of exposure to RF-EMF on cognitive functioning (CF), several investigations have been reported in literature, e.g., [17–19].

Regarding the assessment of the different effects mentioned above due to exposure to RF-EMF, we might encounter difficulties mainly in situations of irregular outcomes or a very high number of published investigations. In both cases, we need specific tools to assess a given subject.

This contribution aims to analyze, review and categorize the consequences of non-ionizing EMF emitted by RF devices, on BE in human tissues and on AS for short and long-terms exposures. The assessment methodology in this investigation field is also targeted.

In the article, these consequences in the case of wireless digital communication tools will be analyzed and reviewed. This goes through the characteristics of sources and their interactions with tissues, BE and health safety standards, the discussion of AS for EHS and CF and the evaluation of these effects and symptoms due to exposure. Next, we discuss the categorization of BE and AS and examine their assessment methodologies. These include illustrating the concept of systematic reviews and meta-analyses and its application in various evaluations of these effects and symptoms including recent world health organization (WHO) assessments.

2. Energy of EMF

As indicated in the introduction, the two categories of non-ionizing and ionizing radiation (see Figure 1a), which have different frequency ranges, are distinguished by their energy levels, which produce differentiated atomic states; respectively, without or with creation of charged ions. Both types of radiation produce undesirable effects under different circumstances.

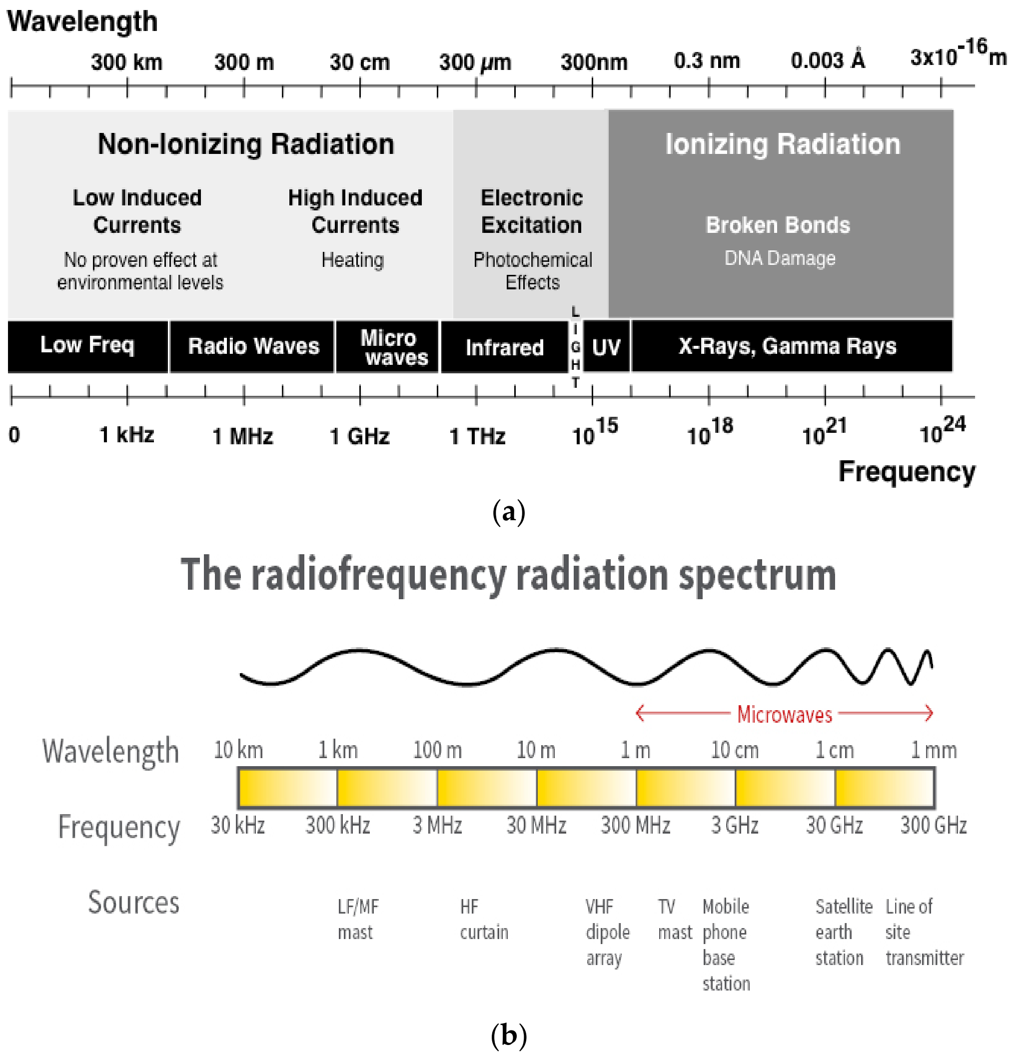

Figure 1. EMF frequency and wavelength ranges (**a**) ionizing and non-ionizing, (**b**) RF.

Indeed, EMF in the frequency range of the non-ionizing category can disturb human society. On the one hand, thermal and non-thermal BE, of EMF in body tissues, as well as AS can directly harm human beings. In addition, high frequency EMF can disrupt the operation of electronic and communication devices, including medical equipment, which affects several areas of societal development. Ionizing EMF are arguably the best-known category of radiation due to their wide use in medical therapies, e.g., X-rays. This use is limited to specific health safety conditions for patients and medical personnel. These emissions are similar to sunlight but have a higher energy level. The amount of energy can vary from very little, as in dental X-rays, to particularly large amounts in irradiators used to sterilize medical utensils.

3. RF-EMF Exposure

Applications of non-ionizing RF-EMF, frequencies from 100 kHz to 300 GHz (see Figure 1b) have continuously increased for almost six decades. This involves medicine (e.g., magnetic resonance imaging and RF ablation), manufacturing (e.g., heaters and solders), home usages (e.g., child video display unit and Wi-Fi), protection and navigation (e.g., radar and RFID) and particularly in telecommunications (e.g., TV transmitting and mobile phones). This growth signifies that great amounts of the population are undergoing exposure to RF-EMF and worry has been inflated concerning public health concerns due to such exposure.

3.1. Characteristics of Sources and Interactions

The sources of RF-EMF are of two categories, devices functioning nearby the human body, occasionally a near field exposure interacting highly constrained in a part of the body, and sources functioning distantly from the body that create an entire-body uniform exposure. Approximately, far field corresponds to transmitter-receiver distance greater than a wavelength and its strength diminishes quickly with distance. Classic near field sources are mobile and cordless phones. Characteristic far field sources include TV posts, mobile and cordless phones base stations, Wi-Fi access points or neighboring mobile phones.

Interaction of RF-EMF with a human body is affected by the frequency, the field intensity, the exposure interval, the field polarization and the dielectric properties of absorbing matters. Moreover, in case of simultaneous activation of several EMF radiating sources nearby the body we have to account for such complex interactions. The nature of interactions can produce different BE. These effects can be due to short or long-term exposure. The most common effect is the thermal short-term one. There are also lesser frequent short and long-terms effects. The non-thermal complex effects fall in this category, as well as the cases exposing atypical symptoms.

The thermal effects and the cases exposing atypical symptoms will be detailed in the next subsections while the non-thermal effects will be discussed later in Section 4.

3.2. Thermal BE Due to RF-EMF

Regarding the thermal effects, exposure to relatively high RF-EMF (strength and duration) can be hazardous to living organisms. Such exposure may lead to body heating resulting in an increase in temperature, which may cause tissue damage. Two characteristics reinforce this occurrence. The first relates to the aptitude of RF energy to, rapidly heat biological tissues, similarly to how microwave ovens that cook food. The second concerns the body's incapability to withstand or dissipate the disproportionate heat that can be produced. Note that the parts of the body least protected from RF-EMF heating are those that lack accessible blood circulation, which is the primary means of dealing with extreme heat. The magnitude of such heating is correlated to several circumstances involving the field intensity, 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.

Note that excessive strength fields can display non-thermal effects. One of the most popular BE in this case is the interruption of brain electro-wave due to the important external EMF that causes altered cell secretion. In addition, EM-induced membrane electroporation also affects cell activation. This will be discussed later in Section 4.1 on non-thermal effects.

3.3. Health Safety Standards

The thermal customary biological effect induced by exposure to EMF can be quantified by the specific absorption rate (SAR) which evaluates the energy absorbed by an element of the tissue. The SAR if multiplied by the exposure interval signifies the EMF entire-body or part of the tissue-specific absorbed energy amount. This energy generates a rise in tissue temperature, which can increase health risks. The SAR and corresponding temperature rise for given frequency and exposure time can be represented by, see [20] for more details:

$$\mathrm{SAR} = \mathrm{P}/\rho = \sigma\, \mathrm{E}^2/(2\,\rho) \quad (1)$$

$$\Delta \mathrm{T} = \sigma\, \mathrm{E}^2\, \Delta \mathrm{t}/(2\, \mathrm{c}\, \rho) \quad (2)$$

In (1) and (2), SAR is the specific absorption rate in (W/kg). P is the power loss density in (W/m3), E is the electric field strength in (V/m), ΔT is the temperature rise in (°C) and Δt is the exposure time in (s). The tissue properties parameters ρ, σ, c are the density in (kg/m^3), the conductivity in (S/m) and the specific heat in J/(kg °C), respectively. Note that the conductivity σ of human tissues depends not only on matter but also on frequency. It is mostly constant with growing frequency up to megahertz and then rises, often nearly linearly.

Expressions (1–2) indicate that the higher the SAR and the longer the exposure time, the greater and more dangerous the increase in temperature will be. This behavior will be affected in addition to the field (intensity and frequency) and the exposure time by the density of the tissue and its thermo-electric properties. Thus, the SAR limits imposed by health safety depend on the part of the body considered and the nature of the subject exposed as well as the exposure conditions. Exposed subjects can be adult humans, children or animals. The exposed parts of the body are the head, trunk and limbs. Exposure conditions include different categories of exposed subjects (allied to the liaison with the source of exposure): workers involved in manufacturing, testing, and installing devices, users of the device, and nearby subjects. For all these situations, health safety standards set thresholds relating to SAR, ΔT and fields triggered in the human body: magnetic flux density B, electric field E and current density J. Figure 2 summarizes the different input parameters, nature and condition of exposure and there effects on tissue. These effects must comply with the corresponding thresholds.

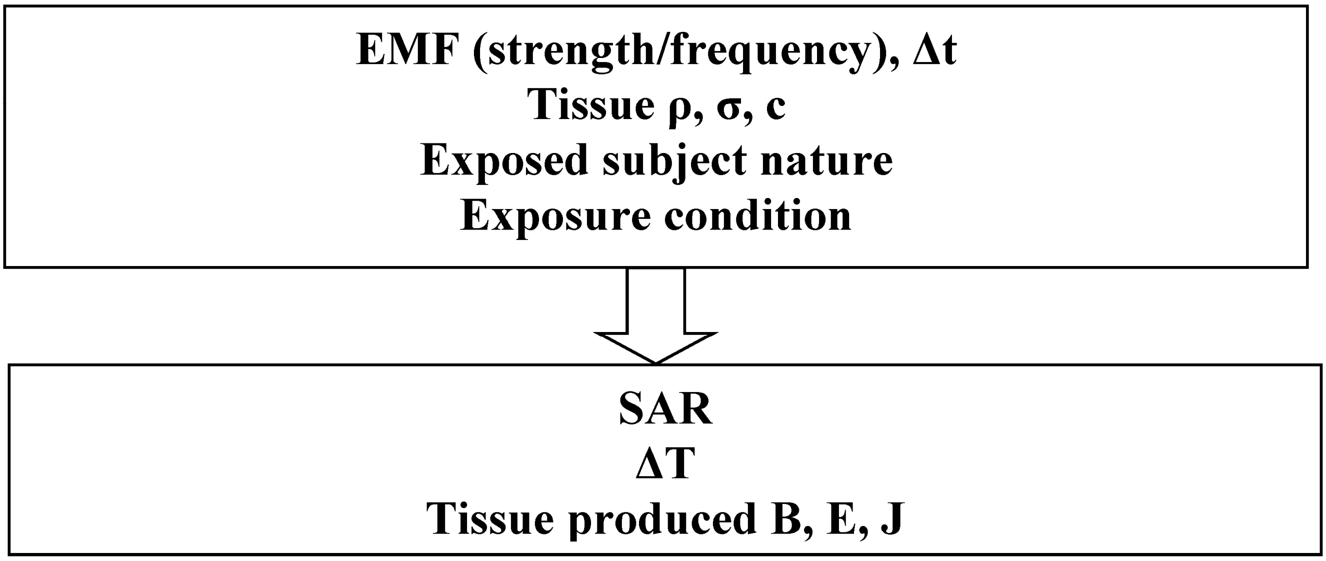

Figure 2. Input EMF exposure (parameters, nature and condition) and output effects on tissue.

3.4. AS Due to RF-EMF

As stated earlier, EMF exposure has two categories of effects on human health. The first is related to short-term exposure to EMF, and the second is result of long-term exposure. Short-term effects are those relative to usual thermal effects as well as that result in AS for EHS people showing non-specific symptoms mentioned earlier. Long-term ones are those related to non-thermal effects as well as AS long-term effects on CF.

As mentioned previously, in rare cases people present AS owing to exposure to RF-EMF. Among these persons are subjects with EHS that present with non-specific symptoms. These range widely between people and include headaches, weakness, anxiety, trouble sleeping, skin tingling, burning sensations, muscle problems with agony and pain and other different symptoms. Historically, this phenomenon appeared a few decades ago and in particular with the advent of modern digital communication technologies [21–32].

These non-specific symptoms were presented for a wide range of frequencies and different types of sources, but the vast majority involved RF sources. Even those EMF in the RF range act to the greatest danger to humans if the field strength and SAR are relatively high; EHS symptoms can be present for non-significant values of these measures. For example, the SAR activated in such sources could reach in certain uses about ten W/kg depending on the intensity of the field and its frequency. For a short time, this is enough to cause a temperature rise of 1 °C in body tissues, which in a normal healthy case is completely safe. At the same time, for SARs less than 0.1 W/kg, symptoms may be present in an EHS subject. This negligible level of exposure seems surprising given the many radiating RF-EMF tools in the everyday environment. Indeed, EHS subjects often fall into the category of users nearby and relatively far from the tools for which the field decreases as the square of the distance. In addition, these tools are generally subject to electromagnetic compatibility rules and adapted to avoid BE in the body tissues of users [1–3]. The EHS symptoms seem real and their presence is associated with EMF even if the biological effect of the latter seems non-existent. Most investigations only consider EMF-induced BE that are acknowledged by the scientific medical organization. In fact, health agencies are gradually admitting RF EHS. Subjects enduring EHS expose symptoms in cases of field insignificant enough not to create perceptible BE. The term hypersensivity (HS) may introduce a misinterpretation and one may use idiopathic environmental intolerance (IEI), which signify better the state of sickness. Thus, it can be used in case of EM, EHS or EIEI. According to patients and often verified by double blind (patient and supervisor) experiences, these symptoms appear only occasionally at first, but then they become more prominent and more persistent. Even with such an insignificant level of exposure, one can think that electromagnetic effects ignored today may perhaps emerge below the established exposure intensities and elucidate the EHS symptoms. Decidedly, it is scientifically difficult to refute the presence of a danger. Such uncertainty can constantly justify a cautious attitude [33].

As in the case of subjects with EHS, we have another similar case of AS relative to the same type of exposure but for longer duration. This is the case of long-term effects of exposure to RF-EMF on CF. As in the case of EHS, this problem appeared with the advent of modern digital communication technologies and in particular the use of mobile cell phones. The RF-EMF exposure from these devices affects directly the brain tissues and consequently the cognitive function that involve diverse cerebral abilities. These can be weighed in a sort of spheres, for instance understanding, remembrance, rationalizing, trouble explaining, judgement acting and concentration capacity. Observation assessments can be used to analyze these problems even that only instant effects can be observed while the needed results could only be obtained after at least small or long-term exposure.

Different reviews involving analysis of results have been realized concerning RF-EMF exposures in both EHS non-specific symptoms and CF long-term effects symptoms, see, e.g., [34–36].

3.5. Evaluation of RF-EMF BE and AS

The evaluation of BE and AS can be performed by modeling, experience or observational studies. In the case of evaluation through modeling, the governing mathematical equations can be solved locally in the body tissues concerned by the effects or symptoms. This can be performed by using numerical discretized techniques or other methods permitting local evaluation, e.g., [37–45]. This involves the EM equations and the bio-heat tissue equation [46]. In the case using measurements for evaluation, sensors can be placed in tissues (when possible) to detect the needed fields (electric, magnetic, thermal). In addition, imagers can be utilized for the revealing of tissue comportment concerning a stated symptom. Concerning observational assessment, this involves mainly, as mentioned earlier, tests in the case of AS practiced on patients exhibiting these symptoms. Such tests are generally performed in a double-blind manner on a group suffering from the same symptom.

3.6. Governing Mathematical Equations

The governing equations are the Maxwell EMF equations and the Penne's bio-heat tissue equation [46]. The external source in the bio-heat equation corresponds to the SAR, which is determined from the EMF equations. These governing equations can be given by:

$$\nabla \times \mathbf{H} = \mathbf{J} \tag{3}$$

$$\mathbf{J} = \sigma\, \mathbf{E} + \mathbf{j}\, \omega\, \mathbf{D} + \mathbf{Je} \tag{4}$$

$$\mathbf{E} = -\nabla\, V - \mathbf{j}\, \omega\, \mathbf{A} \tag{5}$$

$$\mathbf{B} = \nabla \times \mathbf{A} \tag{6}$$

$$c\, \rho\, \partial T/\partial t = \nabla\, (k\, \nabla T) + \rho\, (SAR) + q^{met} - c_b\, \rho_b\, \omega_b\, (T - T_b) \tag{7}$$

In the EM Equations (3)–(6), **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 **Je** are the total and source current densities, σ is the electric conductivity and ω is the frequency pulsation. 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 between **B/H** and **D/E** are represented by the permeability μ and the permittivity ε, respectively.

As well in the Penne's bio-heat Equation (7), k is tissue thermal conductivity, T is local temperature of tissue, 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), T_b blood temperature. $\nabla \cdot (k\, \nabla T)$ represents simple heat equation in differential form and ρ (SAR) represents the influence of electromagnetic energy absorbed in the human tissues.

The solution of Equations (3)–(6) allows us to determine the induced EMF, for a given frequency pulsation, in the body tissues. As well, the SAR (1) can be computed using the fields resulting from such solution. Additionally, the EMC analysis checking the perturbations due to EMF exposers of instruments (embedded or not) can be verified from such solution. Penne's bio-heat equation [46] given by (7) is usually used to determine heat transfer in living tissues. Thermal behavior in tissues due to EMF exposure through the SAR is governed by Equations (1), (3)–(7). The EMF equations and the heat transfer equation must be solved in a coupled fashion. Due to slow thermal time behavior compared to fast EM time behavior, weak coupling with successive solution can be used.

4. RF-EMF Effects Categorization

4.1. Direct Simple Effects on Biological Tissues

There are different effects owing to exposure to RF-EMF. Biological interactions of RF-EMF and the exposed body are related to the nature of exposure and to tissue comportment that depends on the signal frequency. These interactions can produce different effects.

- The most common category of such effects is the thermal effect where tissues are physically heated by absorbed electromagnetic energy produced by an EMF.
- Other types of these interactions can also be more complex, producing non-thermal effects involving various biochemical or bioelectrical consequences that affect cellular, molecular and chemical structures in living tissues [47–58]. These effects can be produced due to long-term exposures or excessive short-term exposure involving high SAR values. Indeed, electromagnetic fields of moderate intensity generally have no non-thermal effects on living tissue cells. On the other hand, excessive strength 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 strength (100–200 V/m) without risk. It can be noted that the mechanisms of the non-thermal effects remain undetermined [51].

- The last category of effects owing to exposure to RF-EMF concerns exposed people endangering AS.

4.2. Intricate Effects

In addition, as mentioned before the widespread use of wireless communication devices in the same application obliges evaluation of interactions considering all these devices accounting for possible exposure effects on each. Thus, we need to consider, on the one hand, the potential malfunctions of nearby electronic devices triggered by RF-EMF exposures, and on the other hand the combination of all nearby wireless communication devices. The case of combined devices needs a global SAR estimation in the different tissues for the corresponding implicated scenario involving tissue feature behaviors and properties of the different sources [59,60]. Examples of malfunction and combined effects can be found in [61–70].

4.3. Indirect Effects

Moreover, there are other secondary indirect types of interactions relative to EMF exposure on healthcare instruments and devices [20,71–79]. These include imagers, interventional tools, embedded apparatuses and wearable devices. The effects of such interactions can cause serious consequences for health safety and can be evaluated through EM compatibility (EMC).

4.4. Evaluation of Different Effect Categories

The different effects mentioned, namely the usual thermal biological effects, the non-thermal effects, the effects exposing atypical symptoms, the dysfunctions and the combined effects and the indirect effects on health devices, these effects require methods of assessment and management different account. Note that these effects are related to the source nature and the exposure duration. The categorization of sources, exposure duration, effects and evaluation tools are illustrated in Figure 3.

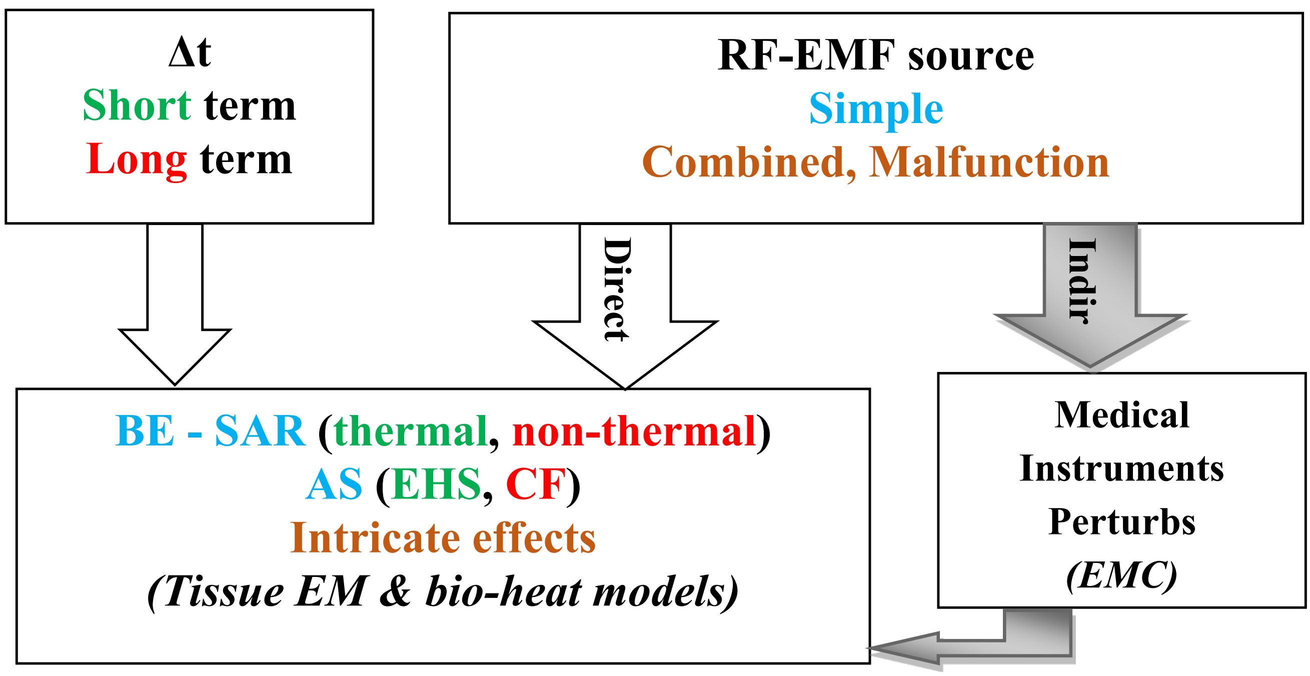

Figure 3. Schematic illustration of different categories of sources, exposure terms, effects and evaluation tools.

The ruling mathematical equations in the case involving biological tissues are those of EM [20], the bio-heat tissue equation [46] and the SAR, Equation (1). These equations can be solved simultaneously and locally in the appropriate element of the body tissue.

Thus, the solution gives the local distributions in the tissue of the SAR, ΔT as well as the produced EMF, which are the electric field E, the magnetic induction B, and the current density J. The source term in such solution corresponds to the RF EM exposure source accounting for the exposure conditions. The involved parameters are those relative to tissue properties (matter, electric and bio-thermal). The concerned geometry considers the nature of the exposed subject. Figure 4 illustrates the modeling of exposure involving source input, tissue parameters, exposure duration and local distributions outcomes.

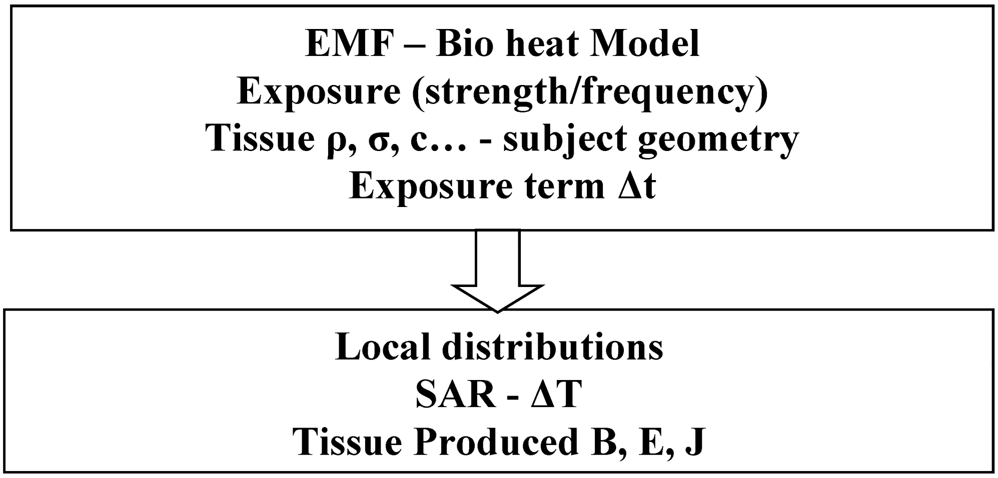

Figure 4. Schematic of modeling of exposure involving the model, input parameters and local distributed outputs.

The last local field distributions make it possible to evaluate the common thermal effect. They can also contribute to assessments of non-thermal and AS effects in addition to experimental or observational means. The case of complex combined effects is difficult to assess by modeling especially if it involves distinct frequencies, but still experimental approaches can be used. In the case involving indirect effects on healthcare instruments and devices, the governing equations are those of EM associated with EMC analysis. The reduction in the consequences of exposure by RF-EMF could be achieved by shielding equipment used on the exposed medical devices and instruments. The checking of the shield impact on the exposed objects can be carried out by EMC analysis [20].

5. Assessment of Effects and AS Due to Exposure to RF-EMF

Most of the effects discussed in the last section have been evaluated in the literature, as indicated in the different sections of this manuscript. In some particular situations, the assessment can be difficult, e.g., irregular outcomes or very high number of published investigations. In both examples, we need specific tools to assess a given topic. Typically, the case of AS due to exposure to RF-EMF that is relatively complex. As mentioned earlier, these AS are displayed by subjects with EHS who exhibit nonspecific symptoms and subjects exhibiting long-term exposure effects on cognitive functioning. The literature in this field is relatively rich but characterized in more or less cases by contradictory, conflicting, divergent and temporary outcomes. The challenge is that the patients themselves often describe the symptoms of these effects. Even though some of these feelings can be verified by, biological sensing and imaging as well as double-blind placebo testing. In many of these situations, the likely misjudgment can lead to a questionable conclusion. The evaluation in this case may consist of reviewing the various works published on the subject, examining the various results and selecting the most relevant. Another option concerns the evaluation of the methodologies used in the various works and the maintenance of the most plausible ones. Effectual tools make it possible to achieve such intentions such as systematic reviews and meta-analyses, see, e.g., [80,81]. These can provide an effective solution for assessing the effects of EMF exposures in general.

5.1. Concept of Systematic Reviews and Meta-Analysis

The quality of accessible and valued research should inform health care advice for individual patients and for society's health strategies. The practice of medicine is based in general on clinical expertise with clinical evidence from systematic research for public health decision making. This evidence comes from scientific journals that are a synthesis on a given research topic. Given the explosion of medical literature and the short time available, we need more condensed and comprehensive reviews. So-called systematic review (SR) and meta-analysis (MA) resources can play this role. They are essential for decision-making in medical practice. Thus, healthcare professionals need resources and clinical practice guidelines that can be their best source of evidence. The concept of SR and MA can provide important support for clinical practice and scientific research. These tools identify, appraise and summarize the results of all relevant studies on a health topic, making the available evidence more accessible to decision makers. In short, an SR is about the processes of collecting, reviewing and presenting all the available evidence while MA uses the statistical technique to extract and combine data to come up with a summary result.

There are two main types of medical research: initial research and subsequent research. Initial research is the assembly of direct patient-related data, while subsequent research is the evaluation of data already collected during the initial research. A review summarizes a number of research investigations (initial and/or subsequent) and allows conclusions to be drawn about the issue of concern, which may be conventional (non-systematic) or systematic. A conventional review is any action aimed at merging the results and conclusions of two or more published research on a specified topic. A systematic review combines the results of several researches related to each other by applying approaches that reduce arbitrary biases and inaccuracies. It is supposed to be guided according to a clear and reproducible practice. It may or may not include a combined statistical meta-analysis, depending on whether the surveys are sufficiently similar for the merging of their results to be meaningful. Meta-analysis is a particular statistical approach to bring together results from multiple surveys that deal with the same survey with similar assumptions to provide a single estimate such as, e.g., the risk factor.

Virtuous SRs and MAs focus on tracing all pertinent research, accurately evaluating each investigation, integrating the outcomes from different investigations in an unbiased way, and giving impartial synopses of outcomes taking due account of any weaknesses in the proof. SR and MA are manners of recapitulating research proof, which is usually the finest mold of substantiation. Alternatively, in the accomplishment of SR or MA, if the feature of the investigations is not properly assessed or if the appropriate approach is not rigorously operated, the outcomes may be biased and consequently the arises will be erroneous. Different works related to the SR and MA tools have been reported in literature; see, e.g., [82–93].

5.2. SR and MA Applications

The concept of SR and MA has been used for observational and experimental studies to review and make the suggestion available in the form of protocols. In general, such use relates to different effects contributing to reducing threats to the establishment of sustainability [94]. The applications related to the different effects of exposure to EMF are numerous; see, e.g., [13,14,17,19,34,95–113].

Case of WHO Assessments

Recently, the WHO has supported research and managed a special issue involving SRs on health effects of exposure to RF-EMF: WHO assessment of health effects of exposure to radiofrequency electromagnetic fields: systematic reviews, 2022, [114–123]. The WHO had a project to assess prospective health effects of exposure to RF-EMF in the broad and working population. To rank potential risky health consequences from exposure to these fields, WHO piloted an ample international survey within RF experts in 2018. The results of this survey distinguished major areas [114] (cancer, difficult reproductive outcomes, cognitive deficiency, EHS, oxidative stress, and heat correlated effects) for which the WHO has engaged SRs of observational and experimental studies to examine and make the suggestion available in the form of protocols for SRs. These SRs contributions involved different effects. There are ten SRs, the one on surveying and ranking of health effects, which are involved in those of the other nine SRs. Of these, four involving AS [115–118], three regarding cancers and oxidative stress [119–121], two on male fertility and pregnancy outcomes [122,123]. The following points summarize these categories.

- SR on Surveying and Ranking of Health Effects [114]

In this SR, the authors developed a survey list of all health effects described in the literature and requested 300 RF-EMF specialists and investigators to rank these health effects for systematic review as serious, important, or insignificant. They too requested these experts to specify the foundation for their ranking. Half of these experts answered. They graded cancer, heat-related effects, adverse birth outcomes, EHS, cognitive troubles, adverse pregnancy outcomes, and oxidative stress as the greatest serious consequences of exposure to RF-EMF. For heat-related results, experts founded their grading of dangerous consequences on what is recognized from human or animal investigations, and concerning cancer and other outcomes, they built their evaluation on public concerns. Reliably assessing the health risks of exposure requires an essential classification of health effects that must be methodically investigated. It was clearly agreed that there was a need to develop SRs for each of the topics categorized by this SR [114]. It should be noted that the classification result of this SR initiated the other SRs and confirmed the importance of the effects concerned.

- SR on AS [115–118]

The first SR [115] examined the effects of long-term or repeated exposure to local and whole-body human RF-EMF on symptom onset by assessing migraine, tinnitus, headache, sleep disturbance, and non-specific symptoms.

The second SR [116] used human experimental studies of the effects of RF-EMF exposure on self-reported human symptoms by evaluating these effects (relative to no or lower exposure levels) on symptoms in human subjects. It also evaluates the accuracy of perception of the presence of exposure in volunteers with and without idiopathic environmental intolerance attributed to EMF (IEI-EMF).

The third SR [117] used observational studies to assess the long-term effects of local and whole-body exposure to RF-EMF, compared to no or lower level of exposure, on indicators of cognition. This includes complex attention, executive function, learning and memory, perceptual motor ability and social cognition and to assess whether there is evidence for a dose-response relationship.

The fourth SR [118] evaluated the effect of RF-EMF exposure on cognitive performance in human experimental studies by assessing associations between short-term RF-EMF exposure and cognitive performance. The assessment techniques used allow the grouping of cognitive performance tests into the following cognitive domains: orientation and attention, perception, memory, verbal functions and language skills, construction and motor performance, concept formation and reasoning and executive functions.

- SR on Cancers and Oxidative Stress [119–121]

The first SR [119] aimed to assess the literature regarding the possibility that RF fields can induce cellular oxidative stress. Such stress is accompanied by an amplified creation of oxidizing species or a substantial decrease in the ability of antioxidant defenses. The consequences of oxidative stress depend on the magnitude of these deviations. Since a cell is capable of obstructing slight disturbances and returning to its initial condition, but medium oxidation can generate apoptosis, while more strong stresses can produce necrosis. Such a disorder can cause different diseases and can be caused by different external exposures. In the SR, the authors presented a protocol of experimental studies on exposure to the fields and biomarkers of oxidative stress. The authors assessed the relationships between RF-EMF exposure and oxidative stress through in vivo and in vitro laboratory studies managed to evaluate the exposure effects on valid markers of oxidative stress compared to a null or impostor exposure.

The second SR [120] used observational studies to assess the effect of exposure to RF fields on cancer risk in the general and working population. Thus, to assess the quality and strength of evidence provided by these human studies for a causal association between RF-EMF exposure and the risk of different cancers. The third SR assessed the effects of RF-EMF on cancer in laboratory animal studies [121].

- SR on Male Fertility and Pregnancy Outcomes [122,123]

The first SR [122] aimed to assess the effects of RF-EMF exposure on male fertility and pregnancy outcomes by an SR of experimental studies, conducted according to international guidelines. The evidence is organized into three strands: (1) studies evaluating the impact of RF-EMF on the male reproductive system of experimental mammals; (2) studies evaluating the impact of RF-EMF on human sperm exposed in vitro; (3) studies evaluating the impact of RF-EMF on unwanted pregnancies, birth outcomes and delayed effects in experimental mammals exposed in utero.

The second SR [123] examined the effect of RF-EMF exposure on male fertility and adverse pregnancy outcomes in human observational studies with meta-analysis.

6. Discussion

In this contribution, the pursued analysis and evaluation of the influence of non-ionizing RF-EMF emitted by energy devices have displayed that such an impact cannot be ignored and must be forecasted and monitored to reduce its effects. At this point, various points are worth remarking on:

- As conferred in the article, various biological effects due to RF-EMF exposure are related to the interactions of these fields and the exposed body, which are associated with the features of the exposure and the behavior of the tissues. The most common category of such interactions is that producing a thermal effect where tissues are physically heated by absorbed electromagnetic energy produced by a single source of emitted EMF. This corresponds to daily use of a device with stray fields that normally restricted by fabricators. Health and safety authorities specify the regular use of such a device through SAR thresholds. This is performed for different personal situations: manufacturers, users, and people nearby, as well as for different parts of a given living being. By respecting these thresholds recommendations for normal and not excessive use, the subjects concerned do not risk any danger. The control of these thresholds can be conducted through the evaluation, mainly by modeling, of these thermal effects, considering the nature of the exposed subject and the exposure conditions.
- The extensive use of wireless communication devices in the same consequence, as, e.g., in healthcare assistances, obliges evaluation of interactions reflecting all these devices accounting for possible exposure effects on each. Thus, we need to consider, on the one hand, the potential malfunctions of nearby electronic devices triggered by RF-EMF exposures, and on the other hand the combination of all nearby wireless communication devices. The case of combined devices requires a global SAR estimation in the different tissues for the corresponding implicated scenario involving the behaviors of the tissue characteristics and properties of the different sources. This problematic seems not trivial especially if the frequencies of these sources are distinct. Thus, the evaluation by mathematical modeling of this type of problem poses multifaceted hitches; see, e.g., [124–128]. Additionally, various approaches can be used to assess the effects of exposure to complex RF-EMF sources in indoor atmospheres. This can be based on measurement means and simulations. Punctual and long-term measurements by exposimeters located at fixed positions for a certain exposure time permit measuring in the frequency selective mode. This allows more detailed investigations of RF-EMF effects in selected positions, which covers both far-field, and near-field

exposures [61,64]. Thus, the exposure of tissues obtained by portable exposimeters makes it possible to obtain information at different places and at different times and hence to estimate SAR related to the whole body and organs.

- The review of indirect types of interactions, relative to EMF exposure of healthcare instruments and devices, illustrated the importance of the risk for the operational functioning and for the devices associated with the patient's body. These mainly involve imagers and interventional tools in the one hand and patients embedded apparatuses and wearable devices in the other. The effects of such interactions that can lead to serious health safety consequences can be assessed using EMC. Thus, the reduction of these effects can be achieved by using adequate shielding technologies.
- Considering the case of atypical symptoms involving the two different categories of people: those with various non-specific symptoms due to insignificant exposures, even of negligible duration, and those with cognitive troubles for long-term exposure to RF-EMF. The literature in this field is relatively rich and characterized by sporadic and conditional results. Conclusions relating to this case can vary in unpredictable ways, for example: research in the field is still immature, it is a phobia explained by the mechanisms of the anxiety disorder, it shows no modification in physiological parameters, it corresponds to a physio pathological change . . . ; see, e.g., [10–12,15,16]. In such a case, the assessment can be difficult and we need specific tools to carry out the evaluation. At this stage, in these two categories of atypical symptoms, which seem real, their presence is actually associated with EMF even if their biological effect seems non-existent. Thus, the exposure induces indirectly via an unidentified relationship (for the moment) with the effects at the origin of the symptoms. Always with such an inconsistency, one can think that electromagnetic effects ignored today could perhaps emerge and elucidate these symptoms. Decidedly, it is scientifically difficult to refute the presence of a danger. Such uncertainty can constantly justify a cautious attitude [33]. Because of this difficult condition, and pending further research and better assessment, people with these symptoms could reasonably be treated clinically as a chronic disease, recognizing that the primary cause remains the EMF atmosphere.
- Mathematical modeling can be a potential tool to determine the direct effects due to exposure to electromagnetic fields. The governing EMF equations can be solved locally in the body tissues or in the medical instruments concerned. This can be achieved using 3D discretized numerical techniques such as finite elements, finite differences or finite volumes. Thus, the solution gives the local distributions of the electric field E, of the magnetic induction B and of the current density J. The source term in the EMF model corresponds to the field emitted by the radiating device. The different distributions of fields in the tissues allow the control of the safety field thresholds and the analysis of the different effects. Additionally, the field distributions in the instruments allow EMC analysis that is needed for shielding design. The governing mathematical equations in the case of thermal effects in biological tissues are those of EMF associated to the tissue bio-heat equation. This ensemble can be solved simultaneously and locally in the appropriate element of body tissue. Thus, the solution gives the local distributions in the tissue of the EMF produced E, B and J as well as the SAR and the temperature rise. The parameters involved are those relating to the properties of the tissues (matter, electrical and bio-thermal).

It should be noted that one of the main fields of expertise of the author of this contribution corresponds to the mathematical modeling of electromagnetic systems. Part of this activity is in the field of interactions of EMF with objects in general including tissues. With regard to BE due to EMF in general, examples can be found in, e.g., [20,45,129]. Additionally, with regard to EMC analysis, in, e.g., image-guided medical interventions, see, e.g., [72]. The treatment by techniques of microwave hyperthermia is also involved, see, e.g., [130] and heating in microwave ovens, see, e.g., [131]. For more information, the author's expertise is given in [132] and his published contributions can be accessed in [133].

- Given the outburst of medical literature on specific topics and the limited time available, more condensed and comprehensive reviews are needed. The concept of so-called systematic review and meta-analysis resources can play this role. These tools are essential for decision-making in medical practice by identifying, evaluating and synthesizing the results of all relevant studies on a health topic.

7. Conclusions

The intentions of this contribution were the analysis, evaluation and categorization of the consequences for short and long-term exposures of EMF emitted by RF devices, on biological effects in human tissues and on personal atypical symptoms. In addition, valuation mythologies allowing analysis that is more accurate in this area were also targeted. The next points summarize the outcome of the paper:

- The different consequences of exposures in the case of wireless digital communication tools have been analyzed and reviewed.
- The evaluation of the thermal effects considering the nature of the exposed subject and the conditions of exposure seems well mastered either by modeling or experimentally.
- The case of atypical symptoms of people presenting various non-specific symptoms due to insignificant exposures and those presenting cognitive disorders for long-term exposure to RF-EMF, involves relatively rich literature that typified, as discussed in the last section, by irregular, divergent and temporary outcomes. In such a case, the evaluation can be difficult and we need specific tools to carry out the evaluation.
- The concept of systematic reviews and meta-analyses and its application in various evaluations have been reported in literature. The review and analysis carried out in this contribution relating to the applications of these tools to the various effects of exposure to electromagnetic exposure, including recent WHO assessments, have illustrated the potential of such a concept. This also demonstrated the possibility of solving challenging cases such as those of atypical symptoms, mentioned in the last point.
- The categorization of the sources of exposure and the durations of exposure linked to those of the effects and symptoms has been analyzed and discussed. It illuminated the difficulties of evaluating these consequences in certain situations. The example of the case of combined exposure devices involved in a single exposure is a typical case. As discussed in the last section, the evaluation of these intricate effects does not seem obvious, in particular when the radiating sources have distinct frequencies. A comprehensive assessment of these effects requires further investigation in future work.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The author declares no conflict of interest.

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