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Effects of Electromagnetic Field Pollution on Human Health: Current Evidence

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ABSTRACT

The rapid expansion of technologies emitting electromagnetic fields (EMFs), including mobile communication systems, wireless networks, household electronics, and industrial equipment, has markedly increased human exposure to artificial EMFs. This review aims to provide an updated synthesis of current scientific evidence regarding the potential health effects of electromagnetic field pollution. While the thermal effects of high-intensity EMFs are well established, growing attention has focused on non-thermal biological interactions within the extremely low frequency (ELF) and radiofrequency (RF) ranges. Reported effects include oxidative stress, alterations in cellular signaling pathways, gene expression changes, sleep disturbances, and possible links to cancer and reproductive dysfunction. However, study findings remain heterogeneous due to differences in exposure parameters, experimental designs, and study populations. This review critically examines epidemiological, in vivo, and in vitro research to identify areas of consensus, knowledge gaps, and emerging mechanisms of action. Improving the understanding of EMF-related biological effects is crucial for informed risk assessment and the development of evidence-based public health guidelines. Given the ubiquity of EMF-emitting technologies, clarifying their long-term health implications is essential to ensure adequate protection of public health and to guide future research directions. The study places special emphasis on the effects of electromagnetic fields on human health, particularly the short- and long-term consequences of exposure on biological systems, and provides a detailed discussion.

Keywords: Electromagnetic fields (EMF), Thermal effects, Low frequency (ELF), Oxidative stress, Radiofrequency (RF).

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Introduction

With the development of technology, the level of electromagnetic fields (EMFs) around us has increased. In nature, there are always EMFs coming from natural sources such as stars and the sun. Today, however, electronic devices also contribute to these fields, disrupting the natural electromagnetic balance and causing electromagnetic pollution [1].

Especially in recent years, the widespread use of wireless communication devices has exacerbated this problem. The biological effects of electromagnetic fields emitted by these devices on human health have become an important issue. Children and individuals in poor health are more vulnerable to these effects [2].

Although international guidelines provide some recommendations for protection from electromagnetic fields, these measures apply only to humans. However, the effects on plants and animals should not be ignored. Indeed, some sources of EMFs are classified as “probable carcinogens” for humans, which means that they can be associated with certain types of cancer. Because EMFs are invisible to the eye, people often fail to recognize this risk. But while it is not possible to completely avoid exposure to these fields, limiting exposure can prevent health problems [3].

Although many scientific researches have been conducted on this subject today, the subject is still not fully elucidated due to the rapid development of technology. Therefore, it is of great importance to continue research on the effects of EMFs [4].

EMF is a combination of electric and magnetic fields. The electric field depends on voltage and the magnetic field depends on current [5].

The electric field consists of the force exerted by electric charges on each other and each charge creates an electric field around it. This field is defined by the direction of the force acting on the positive test charge and weakens with increasing distance. The electric field, whose unit is volt/meter (V/m), is directed from positive to negative and can be weakened by insulating materials [6].

The magnetic field generated by electric current occurs when electrical devices operate. Its intensity increases with current and decreases with distance. Unlike the electric field, the magnetic field, whose unit is tesla (T) or gauss (G), cannot be easily blocked by matter. All living things have a magnetic field, even if it is weak [7].

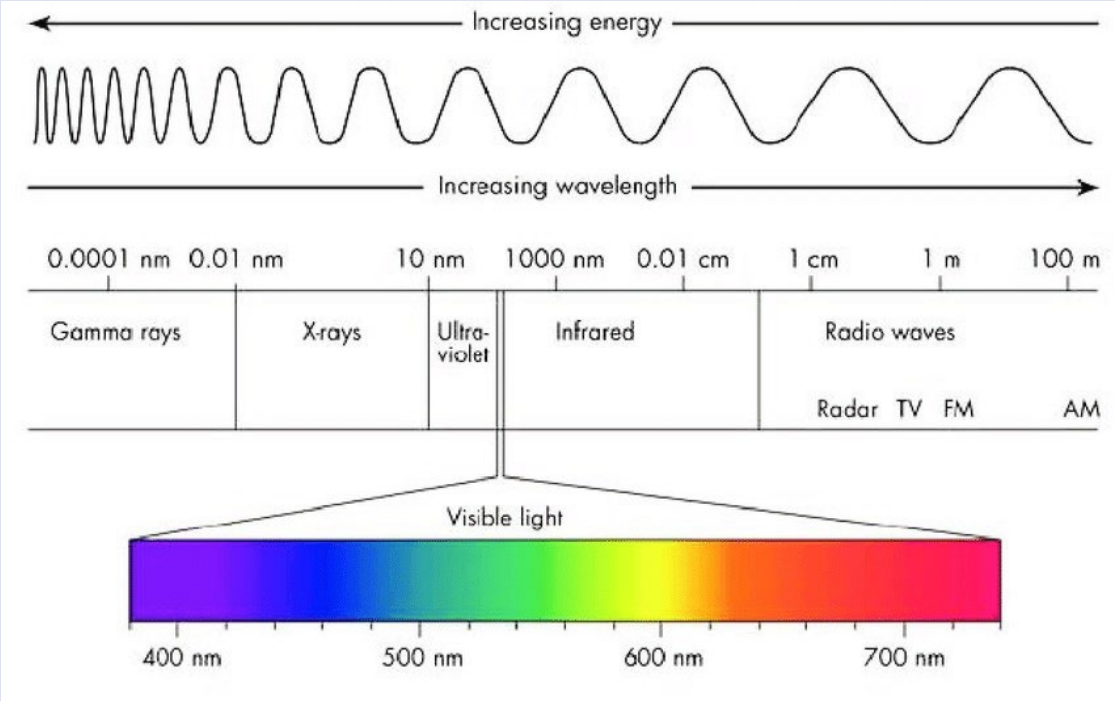

Figure 1. An electromagnetic wave consists of oscillating electric and magnetic fields that are perpendicular to each other and to the direction of wave propagation [8].

Electromagnetic waves, generated by the combination of electric and magnetic fields, are generated by the accelerated motion of charged particles and propagate at the speed of light. These waves exhibit both wave and particle properties and undergo various physical interactions (e.g. reflection and refraction) [9].

The motion of charges creates electric current; these motions create a field around them and vary according to their position.

Basic Physical Concepts:

Frequency (f): The number of vibrations per second (Hz).

Wavelength (λ): The distance traveled by a wave in one oscillation.

Power Density (I): The amount of energy passing through a unit area (W/m²).

Spectrum: The range in which electromagnetic waves are classified according to their frequency [10,11].

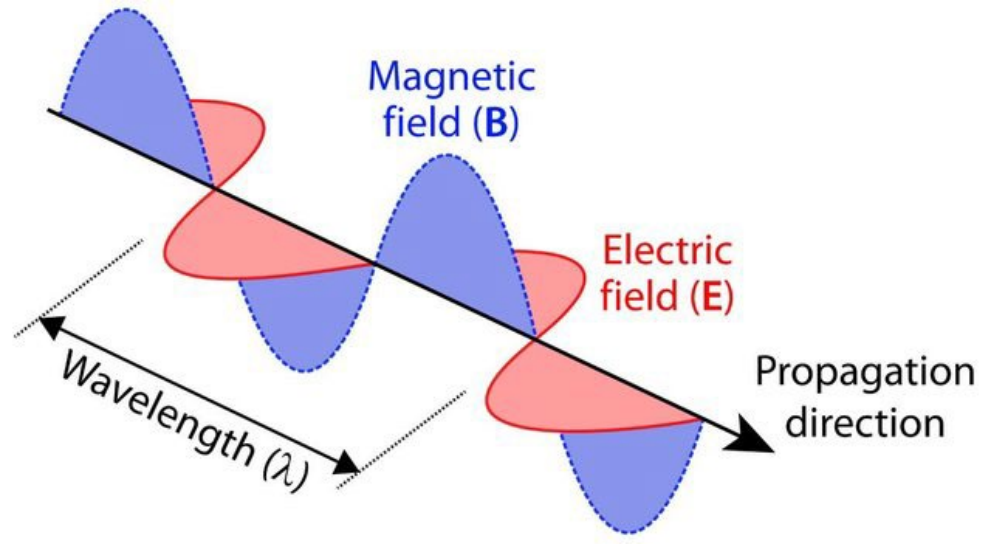

Figure 2. Diagram of electromagnetic spectrum [11].

Basics of Electromagnetic Fields and Radiation

EMFs are composed of electric and magnetic components resulting from the movement of electric charges.

The electromagnetic spectrum divides radiation into two groups:

Ionizing radiation (alpha, beta, gamma, X-ray, neutron): Can cause permanent damage to DNA and cell structures.

Non-ionizing radiation (ELF (extremely low frequency), RF (high frequency), microwave): Lower energy but can cause biological effects with prolonged exposure [11].

The World Health Organization (WHO) recognizes EMFs as an important environmental contaminant for human health. Pregnant women and developing fetuses are particularly vulnerable to these fields. Short-wavelength EM waves can damage the placental barrier and adversely affect embryo development. It is therefore recommended to limit cell phone use during pregnancy as much as possible [12,13].

Biological Effects of EMF

ELF: Nerve and muscle stimulation can lead to uncontrolled neuronal activity with muscle contraction and involuntary muscle contractions [14].

RF: May cause localized heating and hyperthermia in the body [15].

Mobile device vs. base station: Mobile phones emit lower power but absorb more energy because they are used close to the head. Base stations emit a high power signal, but the effect decreases rapidly with distance [16].

Static and low frequency effects: Head movement during exposure to static magnetic fields can result in vestibular and somatic effects such as dizziness, nausea and metallic taste. In low-frequency magnetic fields (1-400 Hz) retinal phosphene formation is observed, while sensory effects such as auditory clicks can occur in the mid- and high-frequency range (300 Hz-6 GHz) [17].

Relay antennas: Base stations near homes can emit persistent electromagnetic fields throughout the day, posing potential hazards to living organisms [18].

Anthropogenic Sources of Electromagnetic Fields and Their Emergence as Pollution

Since the beginning of the 20th century, developments in electricity, household appliances, industry and telecommunications have continuously exposed people to artificial EMFs. The effects of these anthropogenic EMFs, which can be much stronger than natural sources, on living organisms were brought to the agenda in 1979 in a study by Wertheimer and Leeper [19].

it was suggested that the risk of leukemia increased in children exposed to high magnetic fields. EMFs are classified by frequency and wavelength, and each range interacts with biological systems in different ways. Understanding these interactions is important for assessing the potential health effects of EMFs [20].

Harmful Effects of Electromagnetic Fields

In addition to natural electromagnetic fields (EMF), anthropogenic (anthropogenic) electromagnetic pollution is also thought to have effects on the human body and especially on circadian rhythm. With the proliferation of electricity, internet and wireless communication technologies, our exposure to non-ionizing electromagnetic radiation has increased significantly. For example, RFs at around 1 GHz, used mainly in wireless devices, have increased about 10^{18} times compared to natural base levels. While modern devices such as smartphones, laptops, Wi-Fi routers and LED lights have become indispensable in everyday life, more and more scientists and citizens are questioning the potential health risks of the EMFs emitted by these devices [21].

Long-term use of wireless systems such as cell phones and Wi-Fi has been linked to various health problems such as attention deficit hyperactivity disorders, neurodegenerative diseases, infertility, cellular damage and cancer. Current safety standards are based only on the thermal effects of short-term exposure, while the biological effects of long-term, low-intensity exposure are still under-researched. Some findings suggest that cells respond to weak electromagnetic signals through cryptochrome proteins and that biological clock mechanisms such as circadian rhythms may be affected by EMFs [22].

Parameters such as continuous exposure to RFs from multiple sources, signal polarization, different sensitivity levels according to organ and age are ignored in most studies. However, numerous studies have shown that even low-intensity RFs can affect cellular functions. These effects include DNA damage, oxidative stress, mitochondrial dysfunction, activation of voltage-dependent calcium channels, induction of heat shock proteins and increased permeability of the blood-brain barrier ().In particular, voltage-dependent calcium channels have emerged as an important mechanism to explain the non-thermal effects of wireless EMFs. However, some studies have not observed harmful effects under certain conditions, delaying the general acceptance of the harms of EMF exposure [23].

Effects of Electromagnetic Fields on Health: History and Current Status

Although electricity has been in our lives for many years, attention to the potential health effects of low-frequency electric and magnetic fields, especially at frequencies of 50-60 Hz, has only begun since the 1970s. Research in these areas has revealed a variety of effects of public health importance and increased government interest in the subject [24].

EMFs underpin the devices and technologies used to transmit information. In particular, the use of mobile phones is rapidly expanding and users are not sufficiently taking into account the potential health risks. According to 2019 data, the International Telecommunication Union (ITU) and the Canadian Association for Wireless Telecommunications (ACTS) reported that there are more

than 6 billion cell phone subscriptions worldwide. In the same year, nearly 75% of Canadian households had access to wireless phone service, representing more than 26 million subscribers [25].

The health effects of EMFs emitted by RF and high voltage (HV) transmission networks have also been investigated in recent years. The growing concerns of the population and the proliferation of new wireless technologies have increased research interest. International health organizations, such as the World Health Organization (WHO), have initiated extensive research programs to address public concerns, and the number of studies on electromagnetic pollution has increased significantly [26].

Many studies on laboratory animals have shown that RF fields have potential effects on the brain and nervous system. Effects on the endocrine, hearing, cardiovascular and ocular systems, as well as immunological, hematological and blood-brain barrier effects have also been investigated. According to reports from the INRS (French National Institute for Health and Safety), workers exposed to EMFs may experience various health effects. These include overheating of biological tissues, stimulation of the nervous system and visual disturbances. In addition, indirect effects can lead to injuries and increased hazardous working conditions [27].

Epidemiological studies have revealed an increased risk of leukemia in children living near high voltage lines. Based on this, very low frequency EMFs below 100 kHz are classified as carcinogenic to humans. Furthermore, people exposed to variable magnetic fields above a frequency of about 20 Hz and a magnetic field intensity of 2-3 mT may experience magnetophosphenes (the perception of luminous spots), also known as visual disturbances. For example, at a power grid frequency of 50 Hz, fields with magnetic induction of 4-6 mT can lead to such visual effects [28,29].

Although technological advances have improved the quality of life, the proliferation of EMFs has brought with it some health risks. In addition to natural sources (e.g. the earth's magnetic field, lightning strikes), technological devices also increase environmental exposure to EMFs [30].

This process, which started with the discovery of electricity, has increased exposure to EMFs with the introduction of devices such as televisions, computers and cell phones. According to TurkStat (Turkish Statistical Institute) data, the average age of cell phone use in Turkey has decreased to 10 years. The biological effects of EMFs are especially pronounced in children and adolescents in the developmental age group. While short-term exposure to EMFs may cause temporary complaints such as headache, fatigue, and burning eyes, long-term exposure may have negative effects on the immune system by disrupting cellular structures [31].

EMFs are a combination of electric and magnetic fields generated by the movement of charged particles and are common in modern life. There are different types, from ELF fields emitted by power lines to RF fields emitted by wireless devices. Although EMFs are used in important technologies in power generation, communications and medicine, their potential health impacts rAMFin a matter of concern. Research is examining possible links between exposure to EMFs and health problems such as cancer, reproductive health and neurological disorders. While the evidence is inconclusive, efforts to reduce exposure and regulatory measures [32,33].

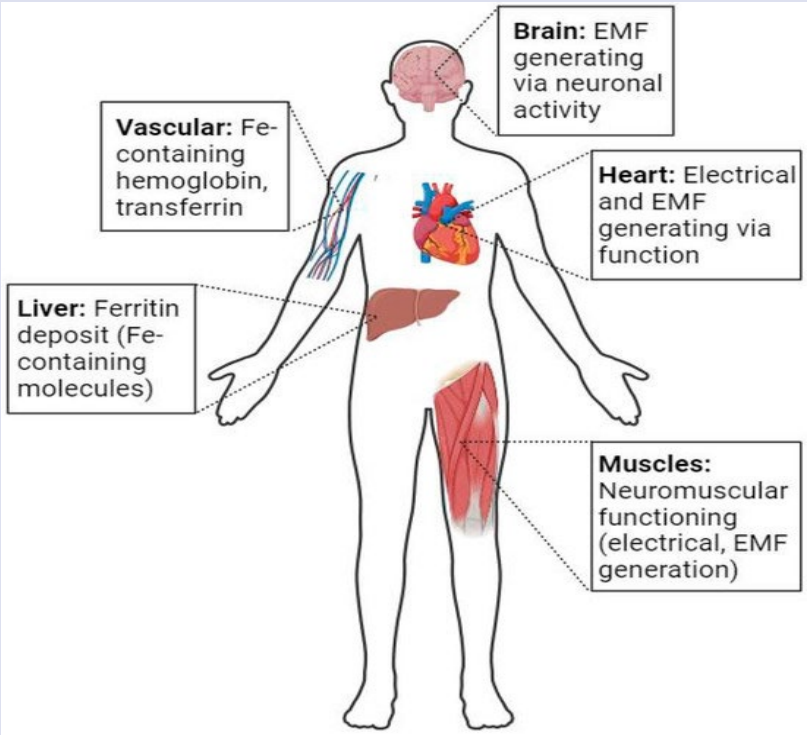

Figure 3. The Effect of Magnetic Fields on Complex Life Forms [34].

Interaction of Electromagnetic Fields with Biological Systems

The biological effects of EMFs are explained by thermal (heat-dependent) and athermal (heat-independent) mechanisms. Athermal EMFs emitted from mobile devices can cause mild temperature changes in superficial tissues and affect cellular functions by disrupting ion balance [35].

Epidemiologic and experimental studies show that EMFs can have various effects on the reproductive, cardiovascular and nervous systems. Although large-scale studies have not reached a clear conclusion on the association of cell phone use with tumor risk, they emphasize that long-term exposure should be carefully evaluated for potential health risks. In particular, the long-term effects of early-onset EMF exposure pose a particular risk for children. Occupational exposure studies have shown that fatigue, headaches, sleep disorders and decreased libido are more common in individuals working with high-voltage lines and electrical equipment [36,37].

Electromagnetic fields in the 0 Hz-1 THz range are a type of low-energy, non-ionizing radiation. Such waves carry insufficient energy to break chemical bonds or ionize biomolecules. They propagate in vacuum at the speed of light ($\approx 3 \times 10^8$ m/s).

Today, humans are increasingly exposed to man-made EMFs from telecommunications, medical devices and industry, as well as natural areas. Radiofrequencies in the 0.3-30 MHz range are widely used in medicine, while millimeter and THz waves have gained importance in security and biomedical applications. The biological effects of these frequencies vary according to the exposure conditions.

Increased exposure, especially in the ELF (3 Hz-3 kHz) and RF (300 MHz-6 GHz) ranges, has increased efforts to better understand the mechanisms of biological effects. These effects depend on the transfer, absorption or storage of energy in biological systems and should be correlated with exposure intensity [38].

Physical Basis and Properties of Biological Tissues

Electromagnetic phenomena are described by the variations of electric and magnetic fields in time and space. These interactions are expressed by Maxwell's equations and are also valid in biological environments. Biological tissues show high dielectric constants at low frequencies. Cell membranes accumulate charge at these frequencies, while conductivity increases at high frequencies. In the 10 kHz-30 MHz range, the dielectric constant decreases, while at higher frequencies the movement of water molecules causes energy loss and determines the conductivity [39].

Effects of EMFs on the Reproductive System

The widespread use of technological devices continuously exposes people to non-ionizing EMFs, static magnetic fields, ELF, RF and microwaves. EMF exposure can affect various physiological systems, especially the reproductive system, through electromagnetic hypersensitivity, cytotoxicity and genotoxicity. With the increase in male infertility, the adverse effects of EMF on sperm function (motility, morphology, DNA integrity) have received attention. These effects are often associated with oxidative stress via reactive oxygen species (ROS). Although ROS play an important role in sperm physiology, their overproduction can cause infertility through lipid peroxidation and DNA damage. The body tries to balance these effects with antioxidant defense systems such as SOD, CAT and GSH-Px. Especially testicular tissue shows high sensitivity to EMFs. Animal experiments show that RF exposure increases oxidative stress and antioxidants can alleviate these effects [40].

Effects of EMFs on the Male Reproductive System

Infertility affects approximately 15% of couples worldwide, of which more than 30% are male, most of them idiopathic. EMF, especially RF waves, can have adverse effects on sperm parameters. Studies on cell phone use have shown a decrease in sperm count, motility and morphology with increasing daily use. In addition, the use of laptops connected to wireless networks close to the testes also causes a significant decrease in sperm motility. These findings point to the potential harmful effects of EMFs on male fertility [41-43].

Effects of EMFs on Pregnancy

In daily life, many devices such as televisions, cell phones and computers emit EMFs and people are constantly exposed to these areas. The biological effects of EMF vary depending on the duration, intensity and frequency of exposure. Institutions such as the World Health Organization are investigating the effects of EMF on fetal development, especially during pregnancy. The widespread use of technological devices exposes pregnant women to EMFs continuously, posing potential risks to maternal and fetal health. While some studies suggest that exposure to low-frequency EMF, particularly in early pregnancy, may increase the risk of miscarriage, the evidence is conflicting. More research is needed to clarify the possible effects of EMF. A systAMFtic review and meta-analysis published in 2023 evaluated the results of six studies involving a total of 3,187 participants. The findings suggest that high levels of EMF exposure may significantly increase the risk of miscarriage. This result suggests that exposure to EMF during pregnancy should be treated with caution [44-50].

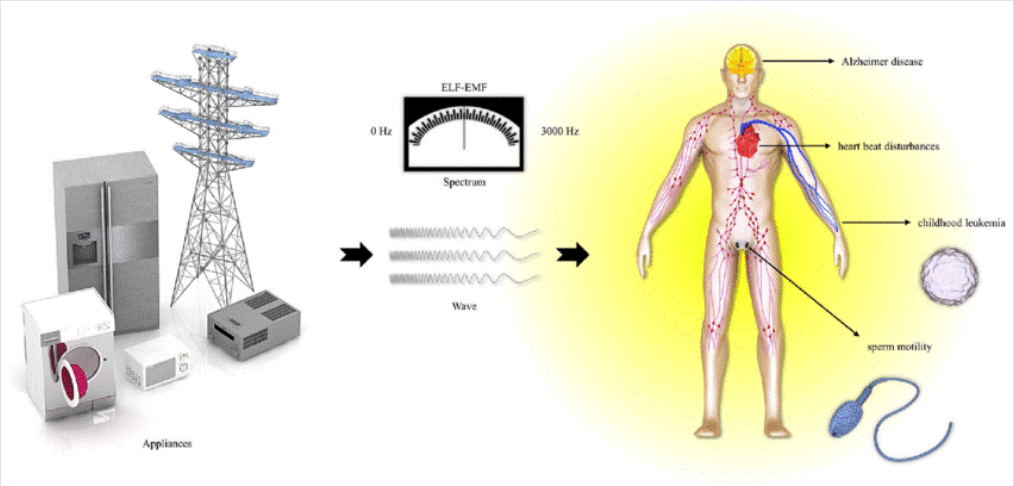

Figure 4. Biological Implications of Extremely Low-Frequency Magnetic Field Exposure on Human Health [50].

Relationship of EMFs with Psychological Symptoms

Studies on the effects of EMFs on psychological symptoms have increased in recent years. However, the findings are contradictory and there are not yet clear data that definitively demonstrate this relationship. In a field study conducted in Şanlıurfa province center, the possible relationship between exposure to EMF and symptoms of anxiety and depression was evaluated in TEİAŞ employees and individuals living close to high voltage lines and transformers. According to a review published in 2024, low-frequency EMF in the range of 3-3000 Hz can trigger anxiety-like behaviors. Possible biological mechanisms for these effects include impaired neurotransmission between the hippocampus and prefrontal cortex, increased oxidative stress levels and reduced neuroplasticity. The findings draw attention to the possible neuropsychiatric effects of low-frequency EMF on the central nervous system [51,52].

Effects of AMFs on Oxidative Stress

ROS are involved in fundamental processes such as elimination of cellular damage, initiation of inflammation and activation of the immune system. However, prolonged suppression or sustained activation of ROS can cause imbalances in the organism. In this context, the effects of EMFs, especially radiofrequency EMF (RF-AMF), on the immune system and oxidative stress is an important area of research [53].

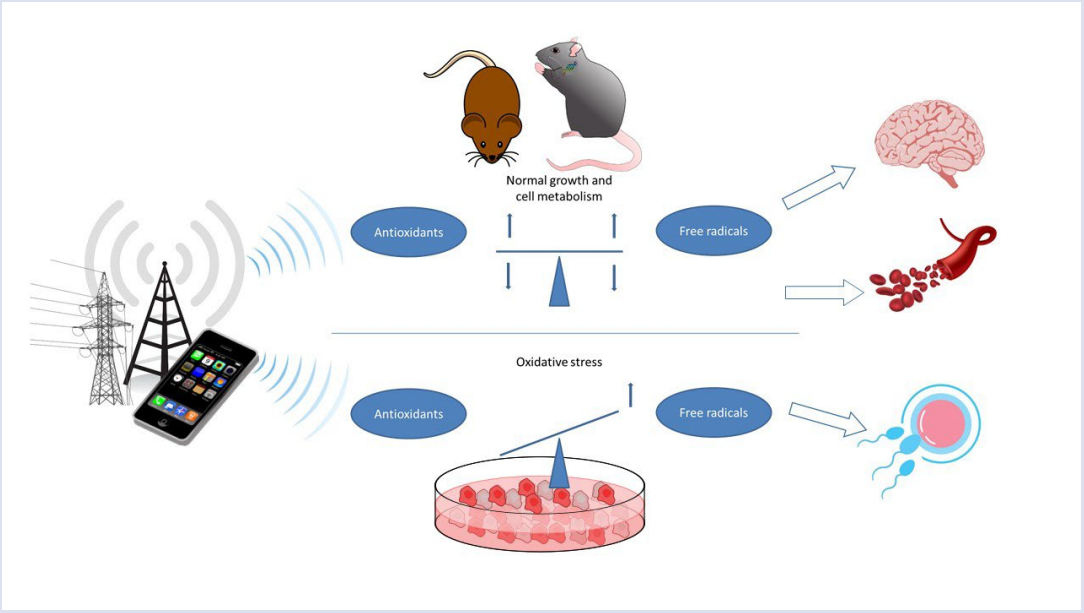

Figure 5. Artificial Electromagnetic Fields and Oxidative Stress: Biological Effects and Health Consequences [57].

Biological responses to EMF may differ depending on variables such as age, exposure duration and environmental factors. Young organisms have a more limited capacity to cope with oxidative stress, while antioxidant defense mechanisms may be more effective in older individuals. In cell culture studies, short-term exposure to EMF has been shown to cause a transient increase in oxidative stress in immune cells. While experimental data on the effects of RF-AMF and ELF-MF on oxidative stress are strong, there is no consensus on

the long-term health risks in human studies. EMF-induced ROS generation continues to be investigated as an important environmental health risk. Current data do not fully clarify the effects of EMF on the immune system. Therefore, more controlled and comprehensive studies that take into account age and environmental factors are needed [54-56].

In their interaction with biological systems, excessive ELF-AMFs can trigger oxidative stress, particularly through the radical pair mechanism. Magnetic fields can prolong the lifetime of free radicals and increase their intracellular concentrations by altering the balance of double radical reactions. However, the effects of ELF-AMFs on brain oxidative stress and related neurological diseases are still not fully elucidated [58].

Effects of EMF on the Nervous System

Neurons are susceptible to oxidative stress due to their long lifespan and limited regenerative capacity. Scientific studies on the biological mechanisms of action are also needed. It has been found that RF-EMF can cause changes in central nervous system nerve cells, including neuronal cell apoptosis and changes in the functions of nerve myelin and ion channels; furthermore, RF-EMF acts as a stressor in living organisms. The possible biological effects of RF-EMF exposure have not yet been proven. Oxidative stress triggered by chronic inflammation has been linked to the development of neurodegenerative diseases and aging processes by causing cellular damage. It has been suggested that EMF exposure may be involved in these processes through oxidative stress. However, experimental findings vary depending on frequency range and disease type, and results in this field are still inconsistent. However, ROS are not only harmful; certain levels of ROS production are essential for processes such as neuronal development, plasticity and signal transduction. Therefore, the adverse effects of changes in ROS levels usually occur when physiological tolerance limits are exceeded. AMF exposure can disrupt this delicate oxidative balance in the nervous system. However, in some cases, AMF-induced ROS increase may also play a regulatory role in neural adaptation and plasticity mechanisms. In this context, the effects of EMF on neurological functions need to be examined in more detail through comprehensive and equilibrium-based studies [59-61].

In recent years, epidemiologic data on the relationship between AMFs and neurodegenerative diseases have been increasing. The current literature does not provide conclusive and universal findings on the effect of AMFs on oxidative stress. Therefore, comprehensive studies with appropriate biological models and controlled experimental conditions are needed [62,63].

Effects of EMFs on Diabetes

Diabetes is a chronic disease caused by disturbances in glucose metabolism and is characterized by a deficiency in insulin production or activity. Current research suggests that exposure to EMFs may affect insulin secretion and blood glucose levels. In this context, in vivo, in vitro and epidemiologic studies provide rAMFrkable findings on the potential effects of EMFs on metabolic processes. However, the cellular and molecular mechanisms underlying the effects of EMFs on glucose metabolism have not yet been established [64].

It is of great importance to increase studies to understand the role of EMF exposure in both the development and management of diabetes. In this context, more in-depth research on the biological effects of EMFs may guide the development of health policies and individual prevention strategies for metabolic diseases such as diabetes [65].

Effect of EMFs on Circadian Rhythm

Recent studies have shown that circadian rhythms can be synchronized not only with light cycles but also with these natural EMFs. Circadian rhythms play a central role in regulating many physiological processes such as sleep-wake cycles, hormone secretion, immune functions and metabolism. Cyclic solar activities, especially sunspots and seasonal weakening of the geomagnetic field, can disrupt circadian rhythms and have negative effects on human health. Circadian disruptions can cause fatigue, fever and flu-like symptoms, as well as trigger inflammatory processes in the elderly and individuals with chronic diseases, worsening existing health conditions. This can lead to increases in the incidence of infectious and chronic diseases during certain periods [66].

Possible biophysical mechanisms related to the perception of Earth's natural electromagnetic fields by organisms include; These include the steering of electrons by EMFs, the formation of light-induced radical pairs in retinal cryptochrome proteins, and the sensitivity of paramagnetic magnetite nanoparticles found in some living tissues to magnetic fields. However, today, artificial EMF pollution caused by human-induced EMFs (e.g. wireless communication devices, base stations, low-orbit internet satellites) can make it difficult for organisms to perceive these natural electromagnetic signals. In addition, factors such as non-conductive shoe soles, building materials used in buildings, and local geomagnetic anomalies can contribute to circadian rhythm disorders by modifying the Earth's natural magnetic environment. Such disruptions can trigger health problems such as imbalances in immune system functions and increases in chronic diseases [67,68].

EMFs and Cancer Relationship

In 2011, WHO and the International Agency for Research on Cancer (IARC) classified EMFs as “probably carcinogenic” (Group 2B) based on the increased risk of glioma associated with wireless phone use (WHO/IARC Press Release No. 208, May 31, 2011) [69].

Several studies have shown that EMFs may play a role in the development of different types of cancer, including leukemia, lymphoma, glioma, testicular cancer, breast cancer, uveal melanoma, and eye tumors [70].

A study by Kapri-Pardes et al. provided some evidence for the potential for cellular proliferation and oncogenic transformation of ELF-EMF. Similarly, Teepen et al. presented epidemiological data indicating an increased risk of childhood leukemia in children exposed to ELF-AMF levels above 0.3 µT. The Interphone study published in 2010 reported that the risk of brain glioma more than doubled if cell phone use continued for 10 years or more. The meta-analysis by Bortkiewicz et al. supported an increase in the risk of intracranial tumors with long-term cell phone use. However, some studies have not found a clear and consistent relationship between cell phone use and cancer development. For example, some studies based on the location distance to GSM or cell towers have not found a significant association between glioma, acoustic neuroma, and parotid gland cancers and location distance [71].

Epidemiological data suggest that chronic exposure to high-frequency EMFs may increase the risk of developing lymphatic and hAMFtopoietic cancers. A study conducted in the vicinity of a radio station in Rome found that childhood leukemia cases were higher than in the general population. Similarly, in Australia, Hocking and colleagues reported a higher incidence of leukemia in those living near television broadcasting stations. However, since these studies did not measure leukemia cases and radiofrequency exposure, a definitive relationship could not be established. Morgan and colleagues' study of workers in the production of wireless devices concluded that the mortality rates associated with brain cancer, leukemia, and lymphoma were no different from the normal population [72].

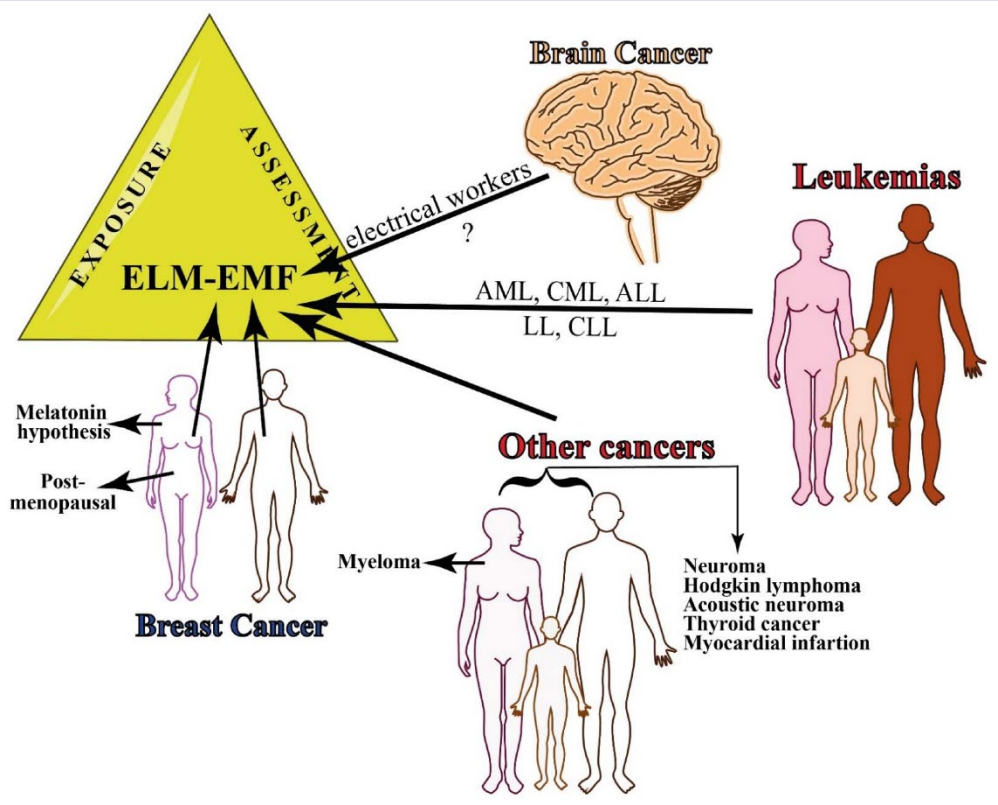

Figure 6. Magnetic Fields in Cancer: Epidemiological Evidence, Cellular Mechanisms, and Theranostic Applications [73].

Effects of EMFs on the Cardiovascular and Circulatory System

Fang and colleagues investigated the effects of short-term exposure to extremely high ELF-AMF on the electrocardiogram (ECG). In these studies, significant changes were observed, especially in the RR interval, while no significant differences were found in other ECG parameters. However, more comprehensive studies are needed to fully evaluate the clinical and physiological significance of these findings. In addition, evidence has been obtained for genotoxic effects of ELF-AMF on peripheral lymphocytes in groups of workers exposed to long-term and low-level non-ionizing radiation. Although the potential effects of EMF exposure on lymphomonocyte morphology have also been reported in some studies, more experimental and epidemiological studies are needed on the effects of parameters such as the type, intensity, and frequency of EMF [77,75].

Epidemiological Findings and Clinical Observations

Epidemiological studies and individual observations show that symptoms such as headache, dizziness, tinnitus, distraction, fatigue, anxiety, insomnia, and even increased suicide rates are more common in individuals living near cell phone towers and antennas. An increase in neurodegenerative diseases and some types of cancer has also been reported [76].

The fact that young and healthy individuals often do not exhibit significant symptoms in the short term may lead to these risks not being taken seriously enough in society. However, older individuals and those with chronic diseases may be more sensitive to the possible harmful effects of EMFs. This sensitivity is often associated with factors such as disruption of circadian rhythm, an immune profile prone to inflammation, and reduced stress tolerance [77].

Conclusion and Future Perspective

Many biological mechanisms have been proposed for the effects of man-made EMFs on health, and thousands of studies have been published showing the non-thermal effects of low-intensity microwaves. However, these findings are mostly ignored. Considering the potential effects on human and environmental health, the development of more biocompatible technologies and environmental regulations is becoming increasingly important [80].

In recent years, animal and cell studies have shown that EMFs can cause harmful effects, especially in the nervous and reproductive systems, by creating oxidative stress. Neurons and reproductive cells appear to be more sensitive to these effects. RF-EMF and ELF-EMF exposure increases oxidative stress levels, especially in the brain and testes. Similar effects have also been observed in other organs such as the liver, kidney and ovary [79].

It is thought that these effects vary depending on the duration, frequency and intensity of exposure; they are especially more pronounced in the young, the elderly and individuals with chronic diseases. However, the methodological deficiencies of some studies make it difficult to generalize the findings.

However, the general trend is that even low-level EMF exposure can disrupt cellular balance. It is thought that some individuals are more sensitive to EMF and that this situation is due to weak defense mechanisms against oxidative stress [80].

Electromagnetic field exposure and health problems among college students.

Therefore, it is important to develop ways to protect against EMF exposure. This protection can be supported by healthy nutrition, sufficient sunlight, antioxidant intake, stress management, appropriate exercise and electromagnetic hygiene practices. It is necessary to increase awareness in society on this issue, to inform individuals, especially children, and to reduce exposure with legal measures, especially in work environments. In addition, it is important to inform users about the safe use of commonly used devices such as mobile phones.

Neurodegenerative disorders, cardiovascular disease, reproductive health problems, and some types of cancer are prominent among the potential illnesses associated with electromagnetic field exposure. Therefore, understanding not only the biological effects but also the development of preventive strategies is critical. Limiting exposure, disseminating safe use protocols, strengthening regulatory standards, and increasing public awareness offer effective approaches to reducing the health risks posed by electromagnetic fields. These results point to the need for a more holistic assessment, encompassing both clinical and public health aspects.

In conclusion, although the effects of EMFs on health have not yet been fully elucidated, current data indicate that caution should be exercised against potential risks. More comprehensive and standardized scientific studies are needed in this area.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this review.

References

[1] 1.AMF T., Ghvedashvili G., Sources of the Electromagnetic Pollution, Effects, Safety Measures, *Junior Researchers*, 2 (2024) 67-77.

[2] Torkaman FMT., Momeni, F., Positive and negative effects of electricity on human health. *Journal of Biological Studies*, 6 (2023) 193-203.

[3] Sookman C., Health Risks of Electromagnetic Fields (EMF) and Radiofrequency Radiation (RFR), (2025).

[4] Cordelli E., Ardoino L., Benassi B., Consales C., Eleuteri P., Marino C., Pacchierotti F., Effects of Radiofrequency Electromagnetic Field (RF-EMF) exposure on pregnancy and birth outcomes: A systematic review of experimental studies on non-human mammals, *Environment International*, 180 (2023) 108178.

[5] Van Bladel J.G., *Electromagnetic fields*, John Wiley & Sons, (2007)

[6] Adorno TC., Gitman, D.M., Shabad, A.E., Electric charge is a magnetic dipole when placed in a background magnetic field, *Physical Review D,* 89 (2014) 047504.

[7] Shoji E., New Insights into Radio Wave Energy Harvesting across Wide Geographical Ranges Harnessing Medium-Wave Radio Broadcasting Infrastructure, *Energy Technology*, 12 (2024) 2300604.

[8] Verhoeven G., The reflection of two fields–Electromagnetic radiation and its role in (aerial) imaging, *AARG news*, 55 (2017) 10-18.

[9] Heald M.A., Marion J.B., *Classical electromagnetic radiation*, Courier Corporation, (2012).

[10] İkinci A., 900 megahertz elektromanyetik alanın adolesan erkek sıçanların hipokampus morfolojisi ve öğrenme davranışı üzerine etkisi, Karadeniz Teknik Üniversitesi, Sağlık Bilimleri Enstitüsü, Doktora tezi, (2015).

[11] Hirata A., Diao Y., Onishi T., Sasaki K., Ahn S., Colombi D., Chen J., Assessment of human exposure to electromagnetic fields: Review and future directions, *IEEE Transactions on Electromagnetic Compatibility,* 63 (2021) 1619-1630.

[12] Ghazanfarpour M., Kashani Z.A., Pakzad R., Abdi F., RahnAMFei F.A., Akbari P.A., Roozbeh N., Effect of electromagnetic field on abortion: A systAMFtic review and meta-analysis, *Open Medicine,* 16 (2021)1628-1641.

[13] Gonoskov A., Blackburn T.G., Marklund M., Bulanov, S.S., Charged particle motion and radiation in strong electromagnetic fields, *Reviews of Modern Physics*, 94 (2022) 045001.

[14] Secades C., O'Connor B., Brown C., Walpole M., Skidmore A.K., Wang T., Niamir A., Review of the use of remotely-sensed data for monitoring biodiversity change and tracking progress towards the Aichi, *Biodiversity Targets*, (2013).

[15] Martel J., Chang S.H., Chevalier G., Ojcius D.M., Young, J.D., Influence of electromagnetic fields on the circadian rhythm: Implications for human health and disease, *Biomedical Journal,* 46 (2023) 48-59.

[16] Habash R.W. *Electromagnetic fields and radiation: human bioeffects and safety*, *CRC Press,* (2018).

[17] Kaszuba-Zwoińska J., Gremba J., Gałdzińska-Calik B., Wójcik-Piotrowicz K., Thor P., Electromagnetic field induced biological effects in humans, Przegl Lek, 72 (2015) 636-41.

[18] Narayanan S.N., Jetti R., Kesari K.K., Kumar R.S., Nayak S.B., Bhat P.G., Radiofrequency electromagnetic radiation-induced behavioral changes and their possible basis, *Environmental Science and Pollution Research*, 26 (2019) 30693-30710.

[19] Jayaraju N., Kumar M.P., Sreenivasulu G., Prasad T.L., Lakshmanna B., Nagalaksmi K., Madakka M., Mobile phone and base stations radiation and its effects on human health and environment: A review, *Sustainable Technology and Entrepreneurship*, 2 (2023) 100031.

[20] Adair R.K., Static and low-frequency magnetic field effects: health risks and therapies, *Reports on progress in Physics*, 63 (2000) 415.

[21] Hardell L., Sage, C., Biological effects from electromagnetic field exposure and public exposure standards, *Biomedicine & pharmacotherapy*, 62 (2008) 104-109.

[22] Wertheimer N., Leeper E.D. Electrical wiring configurations and childhood cancer, American journal of epidemiology, 109 (1979) 273-284.

[23] Martel J., Rouleau N., Murugan N.J., Chin W.C., Ojcius D.M., Young, J.D., Effects of light, electromagnetic fields and water on biological rhythms, *Biomedical Journal,* (2024) 100824.

[24] Yilmaz D.A., Çağiran İ.H., Dege G., Yildirim M.S., Effects of Electromagnetic Pollution on Health, *MAUN Sag Bil. Derg*, 2 (2022), 67-79.

[25] Guizani M., Electromagnetic Radiation Due to Cellular, Wi-Fi and Bluetooth Technologies: How Safe Are We?, *IEEE*, 8 (2020) 42980-43000.

[26] Tokpınar A., Altuntaş E., Değermenci M., Yılmaz H., Bas, O., The impact of electromagnetic fields on human health: A review, *Middle Black Sea Journal of Health Science*, 10 (2024) 229-238.

[27] Lambrozo J., Electric and magnetic fields with a frequency of 50–60 hz: Assessment of 20 years of research, *Indoor and Built Environment*, 10 (2001) 299-305.

[28] Faye S., Camino R., Rziga G., Sarvari P.A., Al-Naffakh N., Estrada-Jiménez J.C., Khadraoui D., A survey on EMF-aware mobile network planning, *IEEE Access*, 11 (2023) 85927-85950.

[29] Juutilainen J., Lagroye I., Miyakoshi J., van Rongen E., Saunders R., de Seze R., Xu, Z., Exposure to high frequency electromagnetic fields, biological effects and health consequences (100 kHz 300 GHz), In *Review of experimental studies of RF biological effects (100 kHz 300 GHz),* (2009) 94-319.

[30] Black D.R., Heynick L.N., Radiofrequency (RF) effects on blood cells, cardiac, endocrine, and immunological functions, *Bioelectromagnetics*, 24 (2003) S187-S195.

[31] Nzao A.B.S., Analysis, Sources and Study of the Biological Consequences of Electromagnetic Pollution, *Open Journal of Applied Sciences*, 12 (2022) 2096-2123.

[32] Torregrossa M.V., Biological and health effects on electric and magnetic fields at extremely low frequencies Annali di Igiene: *Medicina Preventiva e di Comunita*, 17 (2005) 441-453.

[33] Bortkiewicz A., Health effects of radiofrequency electromagnetic fields (RF EMF), *Industrial health*, 57 (2019) 403-405.

[34] Şahin C.U., Exposure to electromagnetic field, cell phone use behaviors, SAR values, and changes in health following exposure in adolescent university students, *Arquivos de Neuro-Psiquiatria*, 79 (2021) 139-148.

[35] Kashani Z.A., Pakzad R., Fakari F.R., Haghparast M.S., Abdi F., Kiani Z., Haghgoo S.M., Electromagnetic fields exposure on fetal and childhood abnormalities: SystAMFtic review and meta-analysis, *Open Medicine*, 18 (2023).

[36] Kıvrak E.G., Yurt K.K., Kaplan A.A., Alkan I., Altun G., Effects of electromagnetic fields exposure on the antioxidant defense system, *Journal of microscopy and ultrastructure*, 5 (2017) 167-176.

[37] Hart D.A., The Influence of Magnetic Fields, Including the Planetary Magnetic Field, on Complex Life Forms: How Do Biological Systems Function in This Field and in Electromagnetic Fields?, *Biophysica*, 4 (2024) 1-21.

[38] Saunders T., Health hazards and electromagnetic fields, *Complementary Therapies in Nursing and Midwifery*, 9 (2003) 191-197.

[39] Asghari A., Khaki A.A., Rajabzadeh A., Khaki A.A., review on Electromagnetic fields (AMFs) and the reproductive system, *Electronic physician*, 8 (2016) 2655.

[40] Macri M.A., di Luzio Sr., Di Luzio S., Biological effects of electromagnetic fields, *International journal of immunopathology and pharmacology*, 15 (2002) 95-105.

[41] Bortkiewicz A., Health effects of radiofrequency electromagnetic fields (RF EMF), *Industrial health*, 57 (2019) 403-405.

[42] Ebrahim S., Azab, A. E., Albasha, M. O., Albishti, N., The biological effects of electromagnetic fields on human and experimental animals, *Inter Res J Natur Appl Sci*, 3 (2016) 106-121.

[43] Panagopoulos D.J., Electromagnetic Fields of Wireless Communications: Biological and Health Effects, *CRC Press*, (2022).

[44] Açıkgöz Ş., Effects of experimental low dose electromagnetic field on rat testis and semen tissues and investigation of antioxidant role of caffeic acid phenethyl ester, (2019). Uzmanlık Tezi.

[45] Karbalay-Doust S., Darabyan M., Sisakht M., Haddadi G., Sotoudeh N., Haghani M., Mortazavi S.M.J., Extremely low frequency-electromagnetic fields (ELF-AMF) can decrease spermatocyte count and motility and change testicular tissue, *Journal of Biomedical Physics & Engineering*, 13 (2023) 135.

[46] Nisbet H.O., Nisbet C., Akar A., Cevik M., Karayigit M.O., Effects of exposure to electromagnetic field (1.8/0.9 GHz) on testicular function and structure in growing rats, *Research in veterinary science*, 93 (2012) 1001-1005.

[47] Sahu M., Behera S. Chattopadhyay B., The influence of electromagnetic field pollution on human health: A systAMFtic review, *Siriraj Medical Journal,* 73 (2021) 485-492.

[48] Kaya F., Nacar M.C., Tutar Çölgeçen E.F., The Effect of Electromagnetic Field Exposure on Fetal Development Elektromanyetik Alan Maruziyetinin Fetal Gelişime Etkisi, Journal of General Medicine, (2024) 34.

[49] Lin J.C., Electromagnetic fields in biological systems, CRC Press, Taylor & Francis (2012) 458.

[50] Romanenko S., Begley R., Harvey A.R., Hool L., Wallace V.P., The interaction between electromagnetic fields at megahertz, gigahertz and terahertz frequencies with cells, tissues and organisms: risks and potential, *Journal of The Royal Society Interface*, 14 (2017) 20170585.

[51] Pophof B., Henschenmacher B., Kattnig D. R., Kuhne J., Vian A., Ziegelberger G., Biological effects of electric,

magnetic, and electromagnetic fields from 0 to 100 MHz on fauna and flora: Workshop report, *Health Physics*, 124 (2023) 39-52.

[52] Irani M., Aradmehr M., Ghorbani M., Baghani R., Electromagnetic field exposure and abortion in pregnant women: A systematic review and meta-analysis, *The Malaysian Journal of Medical Sciences: MJMS*, 30 (2023) 70-80.

[53] Johnson E.E., Kenny R.P., Adesanya A. M., Richmond C., Beyer F., Calderon C., Pearson F., The effects of radiofrequency exposure on adverse female reproductive outcomes: a systematic review of human observational studies with dose–response meta-analysis, *Environment International*, 190 (2024). 108816.

[54] Zhou F., Ma C., Li Y. J., Zhang M., Liu W., Effect of extremely low-frequency electromagnetic radiation on pregnancy outcome: A meta-analysis, *African Journal of Reproductive Health*, 27 (2023) 95-104.

[55] Karimi A., Ghadiri Moghaddam F., Valipour M., Insights in the biology of extremely low-frequency magnetic fields exposure on human health, *Molecular biology reports*, 47 (2020) 5621-5633.

[56] Sert C., Başak N., Koruk İ., Electric and magnetic field pollution in near substations and investigation of anxiety and depressive effects on adult individuals living in this area, *Electromagnetic, Biology and Medicine*, 43 (2024) 145-155.

[57] Hosseini E., Ubiquitous extremely low frequency electromagnetic fields induces anxiety-like behavior: mechanistic perspectives, *Electromagnetic Biology and Medicine,* 43 (2024) 220-235.

[58] Piszczek P., Wójcik-Piotrowicz K., Gil K., Kaszuba-Zwoińska J., Immunity and electromagnetic fields, *Environmental Research*, 200 (2021) 111505.

[59] Schuermann D., Mevissen, M., Manmade electromagnetic fields and oxidative stress—biological effects and consequences for health, *International Journal Of Molecular Sciences,* 22 (2021) 3772.

[60] Ongel K., Gumral N., Ozguner F., The potential effects of electromagnetic oxidative stress—biological effects and consequences for health. *International Journal Of Molecular Sciences*, 22 (2021) 772.

[61] Consales C., Merla C., Marino C., Benassi B., Electromagnetic fields, oxidative stress, and neurodegeneration, *International journal of cell biology*, 2012 (2012) 683897.

[62] Kim J.H., Lee J.K., Kim H.G., Kim K.B., Kim, H.R., Possible effects of radiofrequency electromagnetic field exposure on central nerve system, *Biomolecules & therapeutics*, 27 (2018) 265.

[63] Wilson C., Muñoz-Palma E., González-Billault C., From birth to death: A role for reactive oxygen species in neuronal development, *In Seminars in cell & developmental biology*, 80 (2018) 43-49.

[64] Carpenter D.O., Possible effects of electromagnetic fields on the nervous system and development, *Mental retardation and developmental disabilities research reviews,* 3 (1997) 270-274.

[65] Emerit J., Edeas M., Bricaire F., Neurodegenerative diseases and oxidative stress, *Biomedicine & pharmacotherapy,* 58 (2004) 39-46.

[66] Fouladi Dehaghi B., Vahabi Shekarloo M., Golbaghi A., Ibrahimi Ghavamabadi L., The Impact of Electromagnetic Field Exposure on Diabetes: A Narrative Review, *Journal of Environmental Health and Sustainable Development*, 9 (2024) 2390-2404.

[67] Xinyi S., Treating diabetes with electromagnetic fields, Science Translational Medicine, 12 (2020) eabe9220.

[68] Martel J., Rouleau N., Murugan N.J., Chin W.C., Ojcius, D.M., Young, J.D., Effects of light, electromagnetic fields and water on biological rhythms, *Biomedical Journal*, 48 (2025) 100824.

[69] Contalbrigo L., Stelletta C., Falcioni L., Casella S., Piccione G., Soffritti M., Morgante M., Effects of different electromagnetic fields on circadian rhythms of some haAMFtochemical parameters in rats, *Biomedical and environmental sciences*, 22 (2009) 348-353.

[70] Lewczuk B., Redlarski G., Żak A., Ziółkowska N., Przybylska-Gornowicz B., Krawczuk, M., Influence of electric, magnetic, and electromagnetic fields on the circadian system: current stage of knowledge, *BioMed research international,* 2014 (2014) 169459.

[71] Sengier G., Barr A., Raimbault C.A., Electromagnetic Fields, In Emerging Risks, Routledge, (2016).

[72] Maffei M.E., Magnetic fields and cancer: epidemiology, cellular biology, and theranostics, *International Journal of Molecular Sciences*, 23 (2022) 1339.

[73] Kapri-Pardes E., Hanoch T., Maik-Rachline G., Murbach M., Bounds P.L., Kuster N., Seger R., Activation of signaling cascades by weak extremely low frequency electromagnetic fields, *Cellular Physiology and Biochemistry*, 43 (2017) 533-1546.

[74] Khurana V.G., Hardell L., Everaert J., Bortkiewicz A., Carlberg M., Ahonen M., Epidemiological evidence for a health risk from mobile phone base stations, *International journal of occupational and environmental health*, 16 (2010) 263-267.

[75] Miller A.B., Morgan L.L., Udasin I., Davis D.L., Cancer epidemiology update, following the 2011 IARC evaluation of radiofrequency electromagnetic fields (Monograph 102), *Environmental research*, 167 (2018) 673-683.

[76] Yılmaz D.A., Çağıran İ.H., Dege G., Yıldız M., Yıldırım M.S. Elektromanyetik Kirliliğin Sağlığa Etkileri, Muş Alparslan Üniversitesi Sağlık Bilimleri Dergisi, 2 (2022) 67-79.

[77] Sun J., Tong Y., Jia Y., Jia X., Wang H., Chen Y., Yang G., Effects of extremely low frequency electromagnetic fields on the tumor cell inhibition and the possible mechanism, *Scientific Reports*, 13 (2023) 6989.

[78] Parizek D., Visnovcova N., Sladicekova K.H., Misek J., Jakus J., Jakusova J., Tonhajzerova I., Electromagnetic fields-do they pose a cardiovascular risk? *Physiological research*, 72 (2023) 199.

[79] Subhan F., Khan A., Ahmed S., Malik M.N., Bakshah S.T., Tahir S., Mobile antenna's and its impact on human health, *Journal of Medical Imaging and Health Informatics*, 8 (2018) 1266-1273.

[80] Balmori A., Evidence for a health risk by RF on humans living around mobile phone base stations: From radiofrequency sickness to cancer, *Environmental Research*, 214 (2022) 113851.

[81] Yousif M.E., The electromagnetic radiation mechanism, *International Journal of Fundamental Physical Sciences*, 4 (2014) 72-79.

[82] Gherardini L., Ciuti G., Tognarelli S., Cinti C., Searching for the perfect wave: the effect of radiofrequency electromagnetic fields on cells, *International journal of molecular sciences*, 15 (2014) 5366-5387.

[83] Duhaini, I., The effects of electromagnetic fields on human health. *Physica Medica*, 32 (2016) 213.