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Effects of Exposure to Electromagnetic Fields (EMFs) on Biological Systems

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors contributed to the work and were involved in drafting and revising the manuscript. They both reviewed and the final version for submission was approved by REM. Both authors read and approved the final manuscript.

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Review Article

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ABSTRACT

Electromagnetic Field (EMF) is a natural phenomenon; however, anthropogenic activities have significantly shifted its equilibrium, leading to potential deleterious effects on biological systems. As technology becomes more integrated into daily life, the increased use of electronic devices has contributed to a rise in man-made EMF exposure. This exposure can affect biological systems on physiological and molecular levels, raising concerns about its potential effects on animal development, reproductive systems, and overall ecosystem health. The review explores the physiological effects of exposure to static, extremely low-frequency (ELF), and radiofrequency (RF) fields, analyzing how EMF impacts oxidative stress, reproductive physiology, cardiovascular function, brain and nervous system activity, and DNA/RNA integrity. It also acknowledges the emerging concern of EMF in aquatic environments, where underwater power supplies and extensive underwater cable networks are sources of EMF exposure that may affect marine and freshwater species. The potential effects on marine life include disruptions to migratory patterns, altered reproductive cycles, and changes in aquatic biodiversity. The review acknowledges that research on EMF has improved over time, but significant gaps and information remain. It emphasizes the need for immediate attention to address the challenges and opportunities in this field.

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1. INTRODUCTION

Electromagnetic fields (EMFs) pervade the whole of the earth's environment and have been present throughout the earth and life might have been influenced by EMF evolution. Life has evolved in the sea and it must have been under the influence of natural EMFs. Moreover, organisms have very peculiar electromagnetic properties. From the origin of life to now we are continuously exposed to electromagnetic radiation (EMR), the natural electric fields are one of the mainstays of life on earth [1], and are particularly noticeable based on physical limitations and biological effects [2]. Many marine fish use electric currents to search for food or to migrate [3]. However, their natural sensory system can be altered by the anthropogenic magnetic fields and electrical currents emitted by electrical conductors [4].

Since the 1950s an increased use of technology began where man-made EMFs were used. Increased use of devices like mobile, Wi-Fi, or Bluetooth-enabled devices has enhanced the level of exposure to radiofrequency electromagnetic radiation by about 10^{18} times. These levels are expected to increase again in the future due to the significant contribution of technologies like the Internet of Things and 5G [5]. EMFs usually produce a low-frequency field (usually 50 or 60 Hz) and have a quasi-stationary component consisting of two components – electric fields (E-fields) and magnetic fields (B-fields). The earth creates its geomagnetic field (GMF) with E-fields. E-fields are stationary but can be influenced by moving charges or changing magnetic fields. Their intensity and direction are governed by Coulomb's law, which describes the force between electric charges. In contrast, changing magnetic fields can induce electric fields, as described by Faraday's law of electromagnetic induction [6]. Electromagnetism involves the interaction between electric and magnetic fields, resulting in an electric current [7]. Ampère's law describes the relationship between electric currents and magnetic fields, while Faraday's law of electromagnetic induction explains how changing magnetic fields can induce electric fields. Maxwell's equations demonstrated the interconnectedness of electricity and magnetism, ultimately resulting in the prediction of electromagnetic waves [8]. EMFs are non-ionizing radiation, and they have a wave character on short frequencies and act as a magnetic field on long frequencies [9]. These fields are considered to have a potential negative impact on biodiversity.

Along the lengths, cables emit EMFs, in the marine environment and transmit high-voltage direct current (DC) or sinusoidal alternating current (AC). In DC cables, a static field is emitted, while in AC cables, a sinusoidal field [11]. AC fields generate thermal and DC fields, which are static and move in one direction, cause chemical effects.

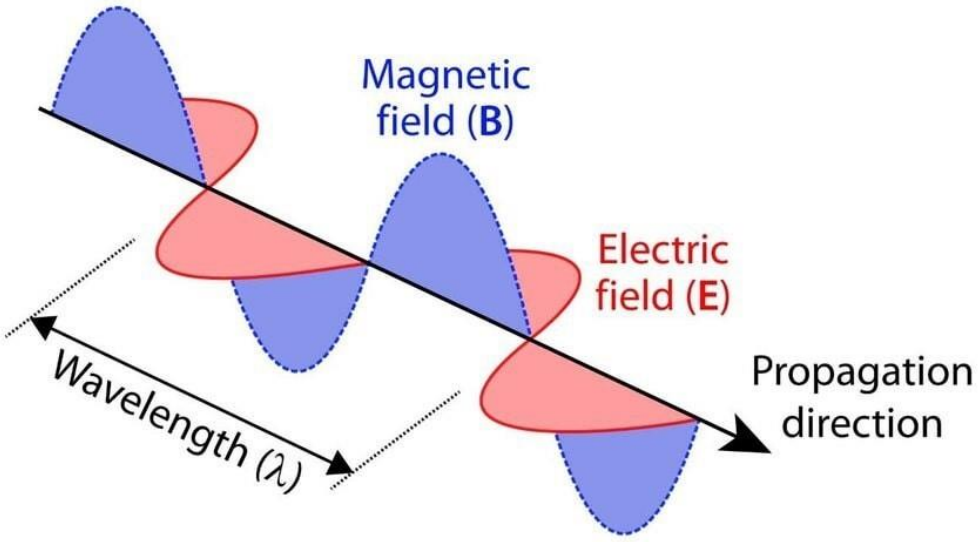

Fig. 1. Electromagnetic wave with electric and magnetic oscillating fields [10].

2. EFFECTS OF EMF

2.1 EMF: Oxidative Stress, Fenton Reaction and Reactive Oxygen Species

The use of electronic devices for communication and their public exposure, including LF-EMF and radio frequencies, are becoming significant environmental health concerns [12]. ELF-EMF is crucial in various life activities as organisms can swiftly detect and respond to lower environmental levels [12-13].

EMF exposure generally disturbs free radical production [15] and results in oxidative stress due to disturbances in free radicals on cellular or systemic oxidative stress [12,15]. The study found that acute exposure to 5G RF-EMF in guinea pigs caused oxidative stress, ultra-structural damage to the auditory cortex, and mitochondrial cell apoptosis [16]. These free-radical responses depend on the exposure period [13]. However, the impact of ELF-EMF on cellular free radical processes is not yet fully comprehended [13].

Free radicals are important for cellular functions [3]. Therefore, maintaining a critical physiological homeostatic level of free radicals is crucial to protect against potential biological harm [13]. Disrupting this balance can cause oxidative stress, leading to cellular damage [17], and the destruction of mitochondria, microfilaments, and proteins, ultimately impairing metabolic processes [12]. The oxidative stress is a result of disturbances in voltage-gated calcium channels (VGCCs), increasing calcium ions entering the cells. This influx then triggers the generation of reactive oxygen species (ROS), resulting in DNA damage and other forms of cellular injury [18-19], also a notable rise in the risk of cancer, infertility [20] and various health issues. These oxidative stress effects also include damage to sperm and testicular function [21], alterations in neuropsychiatric health, and disturbances to the endocrine system [17].

The Fenton reaction, a significant source of reactive oxygen (ROS), induces oxidative stress, with the EMF playing a crucial role in enhancing the conversion of hydrogen peroxide into a hydroxyl radical-driven metal-like transformer [13, 22,23].

Fenton's reaction to a 60-Hz magnetic field increased free radical formation in brain cells, leading to DNA strand fragmentation and cell death [22]. The free radicals in normal conditions are maintained by various antioxidant enzymes including superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GPx) [24,25]. Decreased endogenous Glutathione (GSH) inhibits glutathione peroxidase 4 (GPX4), leading to ferroptosis by increasing lipid peroxidation (LPO) levels, resulting in cell death [25].

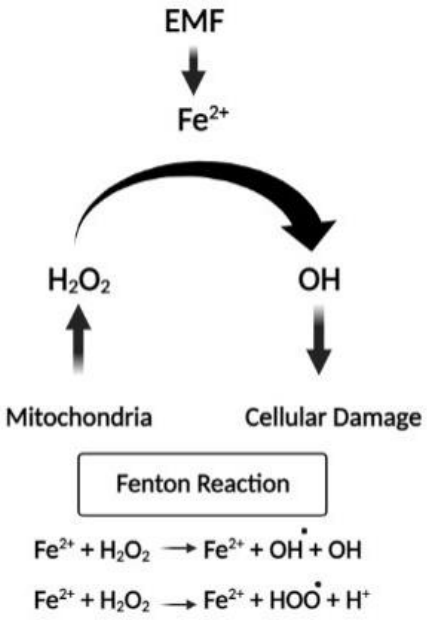

Fig. 2. Effect of EMF exposure on Fenton Reaction [13, 22-23]

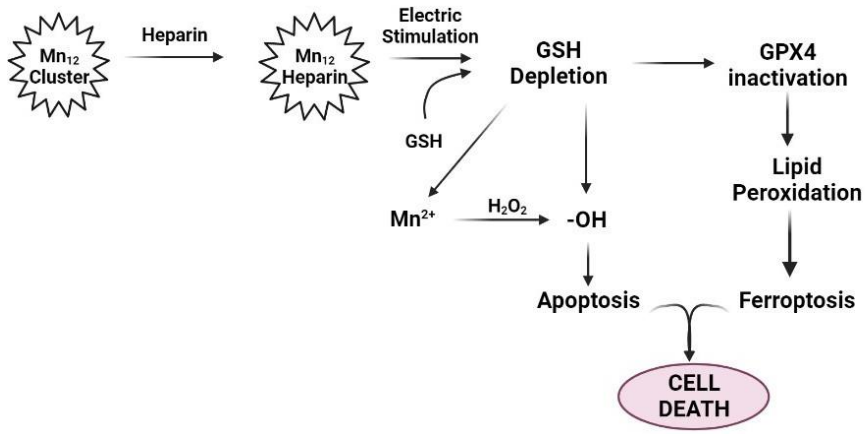

Fig. 3. EMF exposure and Cell death [25]

EMF exposure alters free radical activities, including cellular reactive oxygen (ROS)/nitrogen (RNS) species [26-28]. and endogenous antioxidant enzymes to maintain physiological free radical concentrations in cells. These changes affect many biochemical [29], and physiological functions [12,13,30], and also cause structural and quantitative chemical changes in brain and liver tissue [29]. Chronic exposure changes the biological material, as well as genetic and epigenetic information, resulting in health-related malfunctions [12]. The cell alterations induced by ELF-EMF are not irreversible [30].

2.2 Effect of EMF on Reproductive Physiology

The infant developmental stages are more vulnerable to EMR because it inhibits the formation and dissociation of neural stem cells during development [31-33] in Zebrafish reported that LF-EMF affected embryonic growth, lowered heart rate, and apoptosis. Studies have confirmed EMF's effect on animals' reproductive physiology [34,35,1,9]. Reported an increase in the estrous cycle. [30] reported uterine contraction, bleeding, dead embryos, and re-sucking in the exposed groups during the 2nd and 3rd trimesters of pregnancy. The EMF affects the testicular tissues [36], and a decrease in testosterone levels was attributed to a decrease in testicular size [34,37,38] reported that EMF affects spermatogenesis and apoptosis in the testicular tissue.

The ELF-EMF influences sperm mobility in rabbits and the breeding rate [39]. A reduction in active sperm with an increase in lipid peroxidation and a lower GSH content in the testicles and epididymis [40] and reduced sperm count in rats [41] and in humans [42]. Histo-morphometric analysis showed delayed testicular development [38] and histopathological changes in the kidneys and testicles due to prolonged exposure [38, 43,44].

2.3 Effect of EMF on the Cardiovascular System

The impact of electromagnetic field (EMF) exposure on biological systems has raised concerns about various health risks. It has been associated with histopathological changes in the heart and blood vessels, which could lead to conditions such as myocardial infarction [45]. EMF exposure can also increase certain enzymes like serum creatinine phosphokinase, lactate dehydrogenase, and aspartate aminotransferase while reducing plasma calcium levels and total antioxidant capacity [46]. A study on prolonged RF-EMF exposure in Swiss Albino Mice revealed changes in blood count parameters [47] which aligned with the findings of along with increased aggressiveness and hyperactivity [48-51].

EMF in rats increased blood pressure [46], reduced the heart rate, altered the histopathology of the heart, irregular myocardial cells, ruptured sarcomeres, loss of mitochondria cristae, and blebs of mitochondria [52]. Prolonged exposure to microwave radiation increased red blood cell (RBC) count [53-55] while a decrease in white blood cell (WBCs) and lymphocytes was observed by [54]. However, EMF decreased RBCs and their indices [56,57]. EMFs also cause an increase in the viscosity of blood, and cell adhesion [58]. The alteration in RBC shape was similar to the effect with free radicals [59]. The

free radicals cause the leaking of hemoglobin out of cells [53].

2.4 Effect of EMF on the Brain and Nervous System

Several studies have investigated the effects of radio frequency (RF) waves and electromagnetic fields (EMF) on brain health. [60]. studied RF on adolescent mice and concluded that RF exposure leads to severe histopathological alterations in the brains, causing brain necrosis. This study also concluded that the effect of RF is more pronounced in adolescent mice compared to adults, suggesting younger individuals might be more susceptible to RF-induced brain damage [61-62]. These results indicate the need for additional research to understand the underlying mechanisms and the broader implications for human health, especially among children and adolescents. Studies by [63-66] have shown that cell phone radiofrequency radiation can cause structural damage to the hippocampus, affecting cell proliferation, neurogenesis, memory, hippocampus-dependent cognition, and learning processes. This can lead to broader detrimental brain changes. Exposure to RF-EMF can cause autonomic dysfunctions, weakness, irritability, rapid fatigue, sleep disturbance, disturbed higher nervous activity, weakening of memory, and increased stress reactions [67]. RF-EMF at low frequencies affects brain physiology, causing periodic alterations in neuronal electric parameters [68]. Further studies indicated that mobile phone radiation can damage brain cells and alter the activities of neurons [69,70]. EMF radiation can cause changes in the central nervous system (CNS) [71-74] and affects the brain cells of Drosophila and alterations in organ morphology [70]. CNS is sensitive to EMF stimuli [75]. An alarming study suggested that daily use of mobile phones for an hour increases the risk of developing a brain tumor over a decade or more of exposure [76].

These findings from various studies indicate a range of negative effects from RF and EMF exposure, emphasizing the importance of understanding these risks and their potential long-term consequences. Further research is needed to fully comprehend the impacts and guide regulatory decisions regarding RF and EMF exposure, particularly among younger and more vulnerable populations. EMF is reported to cause Neurodegeneration cancer and mental disorders, are shown in Fig 4.

Gut microbes are crucial in maintaining brain physiological function, neuropsychiatric behavior, brain development, aging, and neurodegenerative processes [77] and EMF being a physical environmental factor, can impact gut microbes and cause central nervous system disorders. Gut microbes are also linked to depression [78].

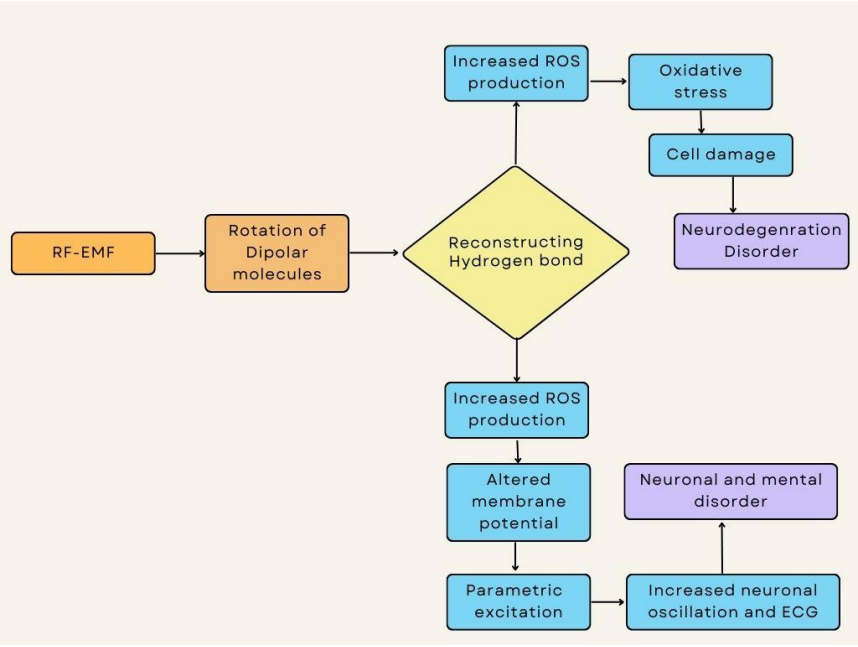

Fig. 4. Effects of RF-EMF on Neurodegeneration Cancer and Mental Disorders [28]

Table 1. Summarize the effects of EMF

Effects of EMF	References
Changes in biological, genetic, and epigenetic material	[12]
DNA strand fragmentation, mutation	[15]
In guinea pigs, induced oxidative stress damages ACx, and cell apoptosis.	[16]
In Mice, DNA damage of single and double-strand in brain cells, cell death	[22]
Increased level of ROS, cell death via Ferroptosis	[25]
Alters free radicals; neuronal parameters; RNS; changes in brain physiology	[28]
Reduced superoxide dismutase and increased glutathione; increased ROS	[30]
Structural and quantitative chemical changes in the brain and liver	[30]
Toxic effects; damaged proteins, lipids, and DNA of the cell	[31]
During fetal development, neural stem cell formation inhibited	[32]
In zebrafish, reduced heart rate, growth, and hatching	[33]
Affects spermatogenesis, and induces apoptosis in testicular tissue	[37]
Delayed testicular development	[38]
In rabbits, motility, breeding rate, and fertility affected	[39]
More pronounced histopathological changes in kidneys and testicles	[43]
Histopathological changes in heart and blood vessel structure	[45]
Increases CPK, LDH, AST; decreases plasma calcium, antioxidant capacity	[46]
Decreased White Blood cell (WBC) and lymphocyte count	[46]
In rats, increased blood pressure; altered myocardial cells	[52]
Increased Red Blood cell (RBC) count	[55]
In mice, increased blood viscosity and cell size variation, pale color of RBCs	[58]
Alteration in RBC shape	[59]
In Swiss albino male mice, changed structural integrity of the hippocampus	[65]
Affects neurogenesis, hippocampus-dependent cognition, brain physiology	[66]
Disruption in nerve impulses, autonomic dysfunctions	[67]
Damages brain cells, neurons, and Purkinje cells, alters hypothalamic region	[70]
Affects gut microbes	[74]
Central nervous system dysfunction	[74]
Disturbed mRNA expression of Bax/Bcl2 in the hippocampus of mice	[80]
Decreases diameter of seminiferous tubes and reduced germinal epithelium	[82]
DNA breakage and damage to brain cells	[83]
Tissue separation in non-differentiating cells	[84]
In rats, increased heart rate, hypocalcemia	[85]
Affects the nucleus of the cell; damages DNA, and mRNA; shortens cell life	[86]
Alters metabolism of heart, liver, kidneys, and brain tissues	[87]
Altered heart palpitations, pain in the chest area	[88]
In Cyprinus carpio, damage to muscles and necrosis	[89]
Alters biomolecules; DNA, RNA, and protein	[90]

2.5. Effect of EMF on DNA and RNA

RF-EMR (1800 MHz) with a low specific absorption rate (SAR) creates a toxic effect and damages cell components like proteins, lipids, and DNA [31]. At higher levels of EMF, DNA strand fragmentation and mutations occur [15]. Increased free radicals and (Ca^{2+}) at the cellular level can mediate the effect of EMFs, causing cell growth inhibition, impaired protein synthesis, and DNA breakdown [9]. The RF-EMF exposure causes cellular mutations and induces single-strand DNA and double-stranded fibers in human diploid fibroblasts and mice granulosa cells [79]. A recent study reported that Radio frequencies emitted by mobile phones disturb the mRNA expression of Bax/Bcl2 in the hippocampus of mice [80]. In contrast, it significantly increased the expression of c-fos mRNA in pregnant mice [81].

The effects of exposure to EMF mentioned above are summarized above in Table 1.

2.6. Other Effects of EMF

The EMF causes tissue separation in non-differentiating cells [84] EMF exposure has both adverse and beneficial effects, including Malaria treatment involves a low-frequency magnetic

field inducing hemozoin vibration in malaria parasites, potentially causing free radical damage and mechanical damage, ultimately leading to parasite death [23]. EMF exposure can selectively kill cancer cells through the Fenton Reaction [13]. RF-EMF long-term exposure has been found to enhance the cognitive abilities of transgenic Alzheimer's mice [70]. Also, aiding in the treatment of bone fractures and promoting bone and wound healing [92], including regeneration of embryos and, tissues [93].

3. CONCLUSION

Electromagnetic radiation (EMF) is a natural phenomenon that contributes to health hazards through anthropogenic activities. It causes oxidative stress, and DNA damage, alters mRNA expression, and affects gut microbes. However, the mechanism of EMF altering biological systems is controversial and unfocused. Further research is needed to develop preventive potential measures. For this, the study of the aquatic ecosystem can be helpful, as EMFs are directly present inside water yet this system is mostly untouched.

COMPETING INTERESTS

The authors have declared that no competing interests exist.

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