

Research Article

Potential Role of Non-Ionizing Electromagnetic Fields in Cancer Development and Progression

Soheila Abdi*^{id}

Department of Physics, ShQ. C., Islamic Azad University, Shahr-e Qods, Iran

*Corresponding author: soheilaabdi@iau.ac.ir

Article History:

Received:
15 October 2025
Revised:
03 December 2025
Accepted:
20 January 2026
Published Online:
07 March 2026
Published in Issue:
30 June 2026

©2026 the Author(s). Published by the OICC Press under the terms of the [CC BY 4.0, Creative Commons Attribution License](https://creativecommons.org/licenses/by/4.0/), which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

Abstract

In recent decades, considerable scientific attention has been directed toward investigating the long-term effects of exposure to non-ionizing electromagnetic fields (EMFs) and their potential association with cancer risk. Most epidemiological studies have focused on vulnerable populations, particularly children, and their possible links to cancers such as leukaemia and brain tumors. In contrast, evidence in adults and other cancer types remains limited and sometimes inconsistent. Despite extensive research, no well-established biological mechanism has been identified to explain the potential carcinogenic effects of EMFs, as the energy carried by these fields is insufficient to directly damage DNA, distinguishing them fundamentally from ionizing radiation. Moreover, key factors such as the primary sources of EMFs, field intensity, exposure duration and frequency, and environmental conditions may play significant roles in potential biological effects. This review aims to provide a comprehensive overview of the characteristics, sources, and typical exposure conditions of EMFs, as well as to examine their possible influence on processes involved in cancer promotion and progression. Additionally, the review discusses current challenges, limitations of existing studies, and the need for future research to elucidate underlying mechanisms and establish safe exposure levels.

Keywords: Electromagnetic field, Non-ionizing radiation, Cancer epidemiology, Carcinogenesis mechanisms

Cite this article: Abdi, S., (2026). Potential Role of Non-Ionizing Electromagnetic Fields in Cancer Development and Progression. *J. Theor. Appl. Phys.*, 20(3), 273-287. <https://doi.org/10.57647/jtap.2026.17294.0303>

1. Introduction

Electromagnetic fields (EMFs) are among the most fundamental physical phenomena in the universe, encompassing both electric and magnetic components that propagate through space. Naturally occurring EMFs arise from sources such as the Earth's magnetic field, solar activity, and atmospheric phenomena [1, 2]. However with the advent of the industrial revolution and rapid technological advancements, human-made EMFs have become pervasive in the environment. These anthropogenic EMFs emanate from various sources, including electrical power lines, wireless communication

devices, medical imaging equipment like MRI machines, and industrial machinery [3]. Anthropogenic magnetic fields have not only increased in intensity and ubiquity, but have also been harnessed in biomedical applications for example in magnetic-nanoparticle mediated hyperthermia and related cancer therapies. Studies on the magnetic properties and engineering of magnetite/Fe-based nanoparticles show how particle composition and thermal/magnetic parameters determine heating efficiency under alternating fields [4]. Recent modeling work examines magnetic fluid hyperthermia specifically for tumor tissues and the relevant field/frequency ranges required for effective therapy [5]. Recent studies have also

demonstrated that magnetic fields could influence plant growth and seed germination suggesting that magnetic fields interact with biological systems across different kingdoms of life [6]. The electromagnetic spectrum include an extensive range of frequencies and energies, from extremely low frequency (ELF) static fields at 0 Hz, through intermediate and radiofrequency (RF) bands, to millimeter waves, infrared, visible light, ultraviolet (UV), X-rays, and γ -rays [7]. Ionizing waves such as ultraviolet (UV) radiation, X-rays, and γ -rays possess sufficient photon energy to directly disrupt chemical bonds, induce DNA strand breaks, and affect living organisms or cells [8].

In contrast, lower-energy waves, referred to as non-ionizing electromagnetic fields (EMFs) including static fields, extremely low frequency (ELF), intermediate frequencies (<100 kHz), radiofrequency (100 kHz–300 GHz), and millimeter waves (>300 GHz) lack the energy required to ionize atoms or molecules [9]. Consequently, the intensity and duration of exposure to EMFs have significantly increased, raising concerns about their potential biological effects on living organisms (Table 1). The interaction of electromagnetic fields (EMFs) with living organisms is a subject of intense scientific scrutiny,

as these fields whether natural or anthropogenic can induce effects at molecular, cellular, tissue, and whole-organism levels. EMFs can influence membrane potentials, ion channel gating, molecular conformations, and signaling pathways by virtue of their ability to exert forces on charged particles, polarize molecules, or deposit energy. Such interactions may be thermal (heating) or nonthermal (without significant temperature change), and their biological consequences depend critically on field parameters (frequency, amplitude, modulation, duration) and the susceptibility of the biological target (e.g. cell type, stage, environment).

At the cellular and subcellular level, rising evidence points to EMFs as modulators of ion fluxes, membrane permeability, and intracellular signaling cascades. For instance, magnetic and electric fields have been shown to affect membrane fluidity and the gating behavior of ion channels, thereby altering transmembrane potentials and downstream processes like calcium signaling [10]. Similarly, emerging paradigms conceptualize cells themselves as electromagnetic oscillators: oscillatory electromagnetic fields generated within and among biomolecules may regulate cell behavior, differentiation, and morphogenesis [11].

Table 1. The potential of electromagnetic fields (EMFs) to induce biological effects

EMF Category	Frequency	Energy	Ionizing Ability	Source	Potential Biological Effects
ELF	0-300 Hz	Low	Non-ionizing	Natural sources: Earth magnetic field	Potential alterations in cellular behavior, perturbation of ion channels
Intermediate Frequencies (IF)	<100 kHz	Low	Non-ionizing	Specific electronic devices	Possible disruptions in cellular signaling
Radiofrequency (RF)	100KHz-300GHz	Low	Non-ionizing	Mobile phones, Wi-Fi, Bluetooth, telecommunication devices	Thermal tissue effects, potential metabolic changes
Millimeter Waves	>300 GHz	Low	Non-ionizing	Radar, high-frequency communication devices	Surface effects on skin, potential cellular stimulation
Visible Light & Near-UV	$\sim 400\text{--}10^9$ Hz	Medium to high	Non-ionizing (UV: can be ionizing)	Sunlight	DNA damage (UV), vitamin D synthesis, skin damage
X-rays	$10^{16}\text{--}10^{19}$ Hz	High	Ionizing	Cosmic rays, Medical imaging, radiography	DNA strand breaks, cancer risk
Gamma Rays (γ -rays)	$>10^{19}$ Hz	Very high	Ionizing	Cosmic rays	Severe DNA damage, high cancer risk

These models propose that the electromagnetic “state” of the cell, synchronized with chromatin and cytoskeletal dynamics, constitutes an underappreciated regulatory axis in biology. One major advantage of non-ionizing EMFs in biomedical science is their ability to interact with biological tissues without causing direct DNA ionization or strand breaks [12].

This property allows EMFs to be used safely in a wide range of medical applications from diagnostic tools such as MRI, to therapeutic modalities including pulsed electromagnetic field therapy (PEMF), transcranial magnetic stimulation (TMS), tumor-treating fields (TTFields), and magnetic nanoparticle-mediated hyperthermia.

Additional advantages include their non-invasive nature, the ability to precisely adjust frequency and field intensity, deep tissue penetration at certain frequencies, and the opportunity to target specific tissues or cellular processes without chemical toxicity [13, 14].

Evidence indicates that exposure to radiofrequency electromagnetic fields (RF-EMFs; 100 kHz–300 GHz) does not significantly affect reproductive capacity (e.g., litter size), yet it is linked to a higher incidence of miscarriage and a decrease in average fetal weight under elevated specific absorption rate (SAR) conditions [15]. Another workshop report on biological effects of RF-EMFs above 100 MHz concluded that under realistic environmental levels, no conclusive scientific evidence exists for adverse impacts on animals or plants, and that thermal mechanisms remain the best-established pathway at high frequencies [16].

However, the report also emphasizes the scarcity of well-designed field studies and calls for further research. Low-frequency magnetic fields, for example at 50 or 60 Hz (ELF-EMFs), have also been widely investigated for their biological effects. Some studies have reported that electromagnetic fields may modulate cardiovascular function, autonomic regulation, and nitric oxide synthesis [17]. Moreover, exposure to AC and DC magnetic fields has been shown to alter the physicochemical characteristics of human low-density lipoprotein (LDL), affecting their susceptibility to oxidation and aggregation [18, 19]. Several mechanisms such as Radical Pair Mechanism have been proposed to explain the biological effects of electromagnetic fields. In this mechanism, it is assumed that electromagnetic fields can alter the spin states of radical pairs that is, molecules containing unpaired electrons thereby modulating the pathways and yields of chemical reactions. This process may influence biological events involving reactive oxygen species (ROS) and electron transfer reactions within cells, providing a

plausible explanation for magnetic sensitivity observed in living organisms, such as in cryptochrome-based system [20].

The radical pair model has been explored not only in the context of magnetoreception, but also as a unifying hypothesis for weak magnetic field effects across organisms.

Additionally, studies report that weak fields may influence energy metabolism via subtle perturbations of mitochondrial proton flux and ATP synthase function [21]. In addition to biomedical applications, oscillating electric fields that generate non-ionizing electromagnetic exposures have also been shown to induce controlled biological effects in non-medical contexts. studies demonstrate that oxygen-assisted oscillating-field systems can effectively reduce microbial contamination in plant-derived materials [22].

Nonetheless, these mechanistic proposals are still subject to experimental validation, and no single model fully explains all observed phenomena. Despite decades of research, the field remains fraught with contradictions, methodological heterogeneity, and interpretational uncertainty.

Many studies suffer from insufficient dosimetry, inadequate temperature control, small sample sizes, or lack of proper controls.

Reviews repeatedly call for standardized exposure systems, rigorous blinding, multi-dose designs, and replication across independent laboratories to strengthen the evidence base [23].

Recent studies have investigated the impact of electromagnetic fields (EMFs) on cancer biology, revealing both therapeutic potentials and concerns regarding carcinogenicity.

Exposure to extremely low-frequency magnetic fields (ELF-MFs) has been shown to influence tumor cell behavior. A study by Sun et al. (2023) demonstrated that ELF-MF exposure can inhibit the proliferation of tumor cells and prolong their survival.

The mechanisms involved include enhancement of cellular oxidative stress responses and regulation of apoptotic signaling pathways, such as alterations in intracellular calcium concentrations leading to apoptosis [24] (Figure 1).

Dieper et al. (2024) suggests that RF-EMF exposure can induce significant anti-cancer effects, including mitotic arrest, growth inhibition, and cell death through autophagy and apoptosis.

These effects appear to be predominantly exclusive to cancer cells, indicating a potential therapeutic application of RF-EMFs in oncology [25].

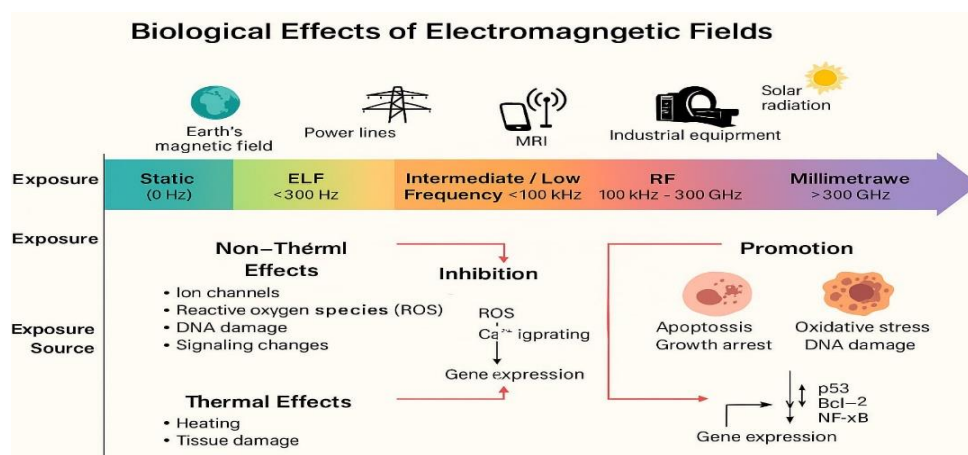


Figure 1. Schematic representation of ELF-MF-induced apoptosis in tumor cells

2. Biological and epidemiological perspectives on ELF-EMF and radiofrequency exposure in relation to cancer risk

To date, no definitive biological process has been identified that connects exposure to extremely low frequency electromagnetic fields (ELF-EMFs) or radiofrequency radiation with cancer initiation. Unlike ionizing radiation, which can directly cause damage to DNA and cellular components due to its high energy, non-ionizing EMFs lack sufficient energy to inflict such direct harm [26]. Some hypotheses suggest ELF-EMFs might influence cancer risk indirectly, for instance, by lowering melatonin levels, a hormone thought to inhibit tumor growth [27-29]. The National Institute of Environmental Health Sciences, a division of the NIH, is performing comprehensive studies on rodents exposed to radiofrequency energy similar to that from mobile phones. These experiments, conducted in precisely regulated laboratories, aim to clarify the biological impacts of such radiation, with preliminary findings released in 2016. Although no clear DNA-damaging mechanism has been found, even a slight increase in cancer risk merits consideration, given the ubiquity of EMF exposure. In 2002, the International Agency for Research on Cancer (IARC), affiliated with the World Health Organization, assembled a panel to evaluate all pertinent data on static and extremely low frequency electric and magnetic fields [29]. Reviewing limited human studies focused on childhood leukemia, the panel designated ELF-EMFs as “possibly carcinogenic to humans.” Conversely, other static electric and magnetic fields, along with extremely low frequency electric fields, were classified as “not classifiable” concerning carcinogenic potential in humans [29]. The primary focus has been on magnetic fields, a key constituent of non-ionizing EMFs, due to their potential biological effects. Epidemiological evidence can be interpreted in various ways: indicating a linear increase in

risk with higher exposure, suggesting a threshold effect near 0.3 to 0.4 μT below which risk does not rise, or showing no significant increase at all [30]. The European Commission's Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) review found that epidemiological data suggest a possible increased risk of childhood leukaemia with daily exposure to magnetic fields of approximately 0.3 to 0.4 microtesla (μT). However, the biological mechanism cannot justify this association, and experimental studies have not substantiated these findings. In addition, research on radiofrequency exposure has not linked it to increased brain tumor incidence or cancers in the head and neck area, though a potential connection to acoustic neuroma remains uncertain [30].

3. Non-ionizing EMF exposure and cancer risk: age-specific epidemiological evidence cancer risk in children extensive

epidemiological studies and systematic reviews have explored whether exposure to non-ionizing EMFs raises cancer risk in children [27, 31, 32]. Since magnetic fields compose Most investigations have targeted childhood leukemia and brain tumors, the most common cancers among children [33]. These studies have assessed factors like residential proximity to power lines, in-home magnetic field levels, and parental occupational exposure to high magnetic fields. Overall, no consistent link between these EMF sources and cancer has been established. An early study from 1979 indicated a possible link between living near high-voltage power lines and childhood leukemia [33], but subsequent research has yielded mixed results [34-41]. More recent studies generally found no association or reported elevated risk only for children residing in homes with very high magnetic field intensities, which are rare. A pooled analysis combining nine studies showed a twofold increase in leukemia risk among children

exposed to magnetic fields of 0.4 μT or higher, although fewer than 1% of children in these studies experienced such exposure [42]. Similarly, a meta-analysis of 15 studies reported a 1.7-fold increased risk for exposures at or above 0.3 μT , involving just over 3% of participants [43]. More recent pooled data from seven studies published after 2000 found a 1.4-fold increase in risk at exposures of 0.3 μT or higher, though less than 0.5% of children were exposed at this level [44]. The limited number of highly exposed children in these analyses restricts the precision of exposure-risk relationship estimates. Consequently, these findings might reflect a continuous dose-response, a threshold effect around 0.3 to 0.4 μT , or no meaningful risk elevation [43]. Children can also be exposed to magnetic fields from household electrical devices. Although magnetic field strength near many appliances can exceed that near power lines, their contribution to overall exposure is limited because appliances are typically used for brief periods, and moving a short distance away significantly reduces exposure. Studies have not found consistent evidence linking household electrical appliance use to childhood leukemia risk [35]. Given the extensive presence of Wi-Fi networks in schools, the UK Health Protection Agency undertook the largest and most detailed assessments to measure children's exposure to radiofrequency electromagnetic fields emitted by wireless computer systems [45-47]. Their findings indicated that exposure levels were significantly below the established safety limits, leading to the conclusion that "there is no justification to restrict Wi-Fi use in schools or similar environments" [45-47]. Research on cancer risk among children living near cellular base stations or broadcast transmitters, such as radio or television antennas, remains limited. Importantly, studies that have assessed individual exposure levels have not identified any increased incidence of tumors in children [34, 35, 48]. Cancer Risk in Adults Extensive research has also explored possible links between non-ionizing EMF exposure and cancer risk in adults. While the majority of studies report no association, a few have hinted at potential risks [49]. Most epidemiological investigations have not found a connection between women's breast cancer and exposure to extremely low frequency electromagnetic fields (ELF-EMFs) at home [50-53]. A small number of studies have suggested a possible link, but only one study reported statistically significant results [54]. Some research observed elevated cancer rates including leukemia, brain tumors, and male breast cancer among workers in electrical occupations with potential ELF exposure, such as power plant operators and telephone line technicians [33, 49, 55, 56]. More recent research, incorporating direct exposure assessments alongside occupational titles, generally does not support a heightened risk of leukemia, brain tumors, or

female breast cancer linked to occupational magnetic field exposure [57-61]. One large investigation involving U.S. Navy personnel found no increased brain tumor rates among workers with high likelihood of radar exposure, including electronics and aviation technicians. However, a higher incidence of non-lymphocytic leukemia, particularly acute myeloid leukemia, was reported in aviation electronics technicians but not in other naval occupational groups [62]. A case-control study among U.S. Air Force personnel suggested a potential elevated brain cancer risk in individuals involved in maintenance or repair of radiofrequency or microwave equipment [63]. Similarly, another case-control study indicated an increased brain cancer mortality risk among men occupationally exposed to microwave or radiofrequency radiation, specifically in electrical and electronics jobs involving equipment design, manufacture, repair, or installation [55]. Conversely, there is no evidence that electrical utility workers exposed to pulsed electromagnetic fields from power lines have higher rates of brain tumors or leukemia than the general population [64, 65]. Additionally, employees of a major wireless communications equipment manufacturer did not exhibit increased mortality from brain tumors or cancers of the blood or lymphatic systems compared to population averages [66].

4. Optimizing non-ionizing EMF exposure parameters in oncology experiments

To date, the majority of laboratory animal experiments utilizing various cancer models exposed to non-ionizing electromagnetic fields (EMFs) have yielded largely negative results. However, two specific models, a skin tumor model [67, 68] and a breast tumor model [69-71] have recently demonstrated positive biological effects under carefully controlled and specific non-ionizing EMF exposure conditions.

These findings highlight the necessity for better defining and refining the concept of "dose" when evaluating exposure to non-ionizing EMFs [72, 73]. Three key avenues of laboratory research that may provide essential insights include [17]:

1. Detailed investigations into the subtle variations in exposure parameters required to induce biological effects [73].
2. Assessments of whether and how certain magnetic field exposures might enhance the activity of chemicals known to promote carcinogenesis [74, 75].
3. Studies focused on understanding how magnetic field exposures could alter the production, bioavailability, and function of important cancer-inhibiting hormones such as melatonin [74, 75].

It is important to note that exposure to non-ionizing EMFs should remain within established safety limits to prevent potential DNA damage, such as those recommended by ICNIRP and other regulatory bodies.

5. Refining exposure metrics: resonance and temporal dynamics in non-ionizing electromagnetic field interactions

Emerging research indicates that how non-ionizing EMFs interact with biological systems may depend significantly on resonance phenomena and the dynamics of exposure over time. For instance, Opti-ELF magnetic fields have been shown to affect mitochondrial complex II through both classical ion cyclotron resonance (ICR) patterns and radical pair mechanisms [76]. Likewise, meticulous experimental assessments have questioned the practical applicability of the ICR model, especially when exposure parameters deviate from resonance requirements [77]. Moreover, epidemiological reliance on the time-weighted average (TWA) as the standard exposure metric faces growing scrutiny. Studies comparing static and dynamic field exposures show that peak values may have stronger correlations with biological outcomes than long-term averages [78]. Innovatively, new modeling techniques similar to Environmental Exposure Models (EEM) are now being developed to refine TWA estimations and improve real-world exposure accuracy [32]. It is crucial that exposure to non-ionizing EMFs, including dynamic and peak-field conditions, remains within established safety limits recommended for DNA integrity and overall cellular health by organizations such as ICNIRP and IEEE.

6. The modulatory role of non-ionizing Electromagnetic fields in hormonal signaling and chemical promotion pathways in cancer

The biological effects of exposure to non-ionizing EMFs may be modulated by the presence of various chemicals within the organism [79]. This group includes external tumor-promoting agents and internal signaling compounds like hormones [80]. Tumor promoters generally impact biological systems only when their concentrations surpass a certain threshold. As suggested by Salvatore et al., magnetic fields may lower this threshold, potentially increasing biological responsiveness [81]. Hormones serve as key communicators between tissues, delivering timely signals that regulate specific cellular metabolic activities. Melatonin, which is secreted by the pineal gland, is essential for regulating the body's internal biological clock. It is also one of the most potent antioxidants in the body, capable of neutralizing free radicals and thereby potentially

preventing cancer initiation events [80]. Additionally, melatonin modulates gap junction intercellular communication [82]. This is vital for coordinating cellular functions and regulating the growth of pre-cancerous or “initiated” cells. Recent studies indicate that exposure to non-ionizing EMFs may influence circulating melatonin levels and its activity, potentially increasing biological vulnerability to disease [82] (Figure 2).

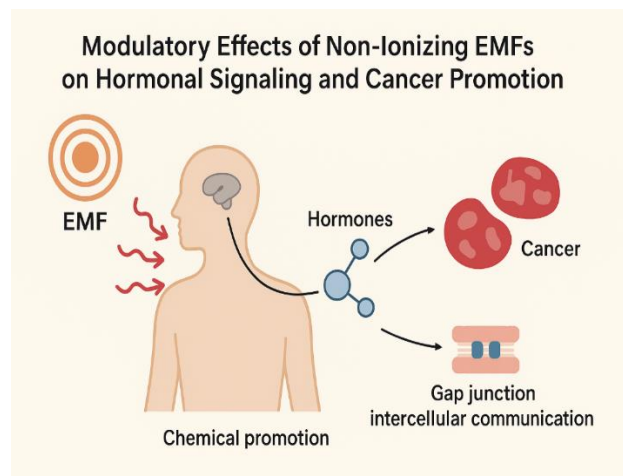


Figure 2. Modulatory effect of Non-Ionizing Electromagnetic Fields Hormonal Signalling and Cancer Promotion

7. Cellular and molecular-level interactions of magnetic fields

Electromagnetic fields (EMFs), particularly in the extremely low-frequency (ELF) range, are omnipresent in modern life. While non-ionizing by nature and thus incapable of breaking chemical bonds under certain conditions, these fields can subtly modulate cellular behavior. Research demonstrates that properly calibrated ELF-MF exposure can lead to measurable changes at the molecular level, sometimes yielding therapeutic effects in cancer models [83, 84] (Figure 3).

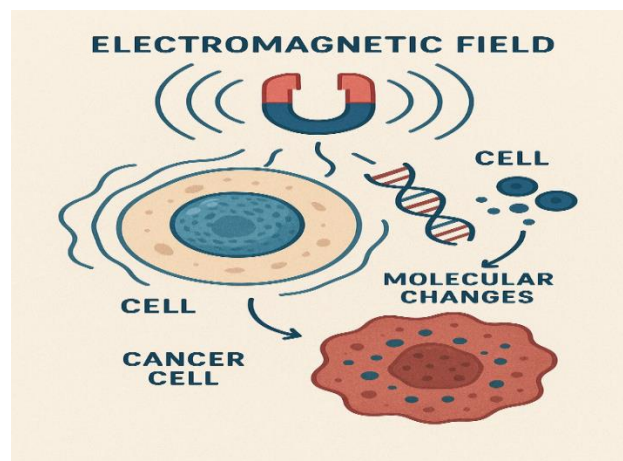


Figure 3. Cellular and Molecular-level Interactions of Magnetic Fields

8. Modulation of microRNAs and oncogenes

In human gastric adenocarcinoma (AGS) cells, exposure to intermittent 50 Hz ELF-MFs at flux densities of 0.2 and 2 mT resulted in marked increases in the expression of tumor-suppressive microRNAs miR-144 and miR-375, with a clear inverse relationship to cell viability [85]. These observations imply that ELF-MFs may exert growth-inhibitory effects via post-transcriptional gene regulation. Similarly, in the same cell line, ELF-MF exposure modulated the expression of BCL2 and its regulators (miR-15b and miR-16), suggesting a possible disruption of the apoptotic balance that favors tumor cell death [86]. Perhaps most strikingly, experiments probing the effects of ELF exposure on gene regulation highlighted changes in the expression of NOTCH1 and its associated circular RNA, hsa_circ_0005986. Interestingly, exposure reduced NOTCH1 expression in cancerous gastric cells while increasing it in normal fibroblasts, hinting at a possible dual effect that might suppress tumors while protecting healthy tissue [87]. These findings align with emerging evidence that miRNAs and exosomal miRNAs, act as crucial regulators of tumor progression and therapy response [88].

9. Free radical dynamics and redox signaling

One plausible biological pathway through which ELF-MFs exert influence is the radical pair mechanism, wherein magnetic fields affect the spin states and reactivity of transient free radicals. The downstream effect may shift the balance between oxidative damage and protective antioxidant responses. Studies have shown that ELF-MFs exposures can alter levels of reactive oxygen species (ROS) and affect the activity of antioxidant enzymes, which may in turn influence redox-sensitive transcription factors [89-91] (Figure 4).

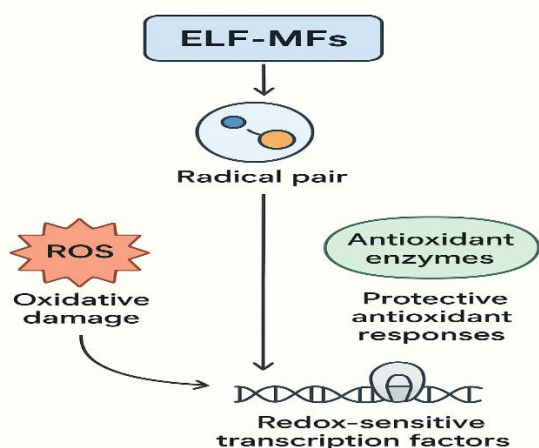


Figure 4. Free Radical Dynamics and Redox Signaling

10. Membrane electrodynamics and calcium flux

Magnetic fields can induce weak electric currents in conductive tissues. In cells, this may translate to altered membrane potential and perturbed function of voltage-gated ion channels most notably, L-type calcium channels. Disturbances in calcium homeostasis can activate a cascade involving CaMK, calcineurin, NF- κ B, and other pathways crucial for cell survival, proliferation, and apoptosis [92, 93] (Figure 5).

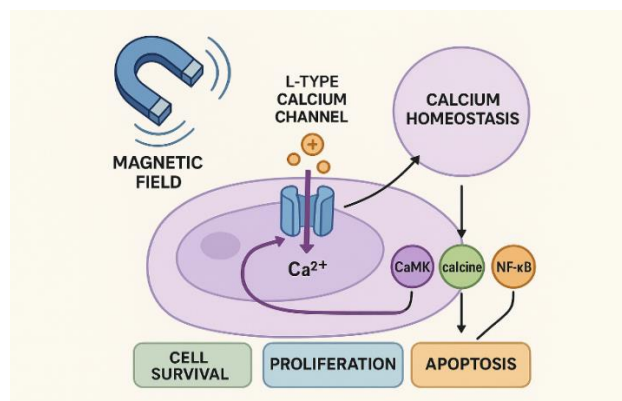


Figure 5. Membrane Electrodynamics and Calcium Flux

11. Electromagnetic field effects on DNA charge transport: a mechanistic perspective

DNA has been recognized as a conductor of electrons. Studies on ATPase, cytochrome oxidase, and the Belousov-Zhabotinsky (BZ) reaction has been demonstrated that electromagnetic (EM) fields can accelerate electron transfer rates. It has been proposed that EM fields activate DNA by generating repulsive forces when accelerating electrons along the double helix [94-96]. The velocity of charge movement estimated from Na,K-ATPase measurements is on the order of 10^3 m/s, which is comparable to ultrafast electron transfer rates in DNA (~ 400 m/s) reported by Wan et al. (1999). At such velocities, even low-intensity EM fields can induce forces sufficient to alter enzymatic reactions and potentially initiate conformational changes in DNA. Because EM fields penetrate living cells, they may directly interact with nuclear DNA (and mitochondrial DNA). The nCTCTn sequences, identified as electromagnetic response elements (EMREs) in the promoters of c-myc and HSP70, could function as sensors or molecular antennae. This hypothesis aligns with experimental observations where EM fields initiate transcriptional activity [95].

The proposed mechanism involves EM-field-driven electron motion within DNA, generating repulsive forces that may separate DNA strands at specific promoter regions (Figure 6).

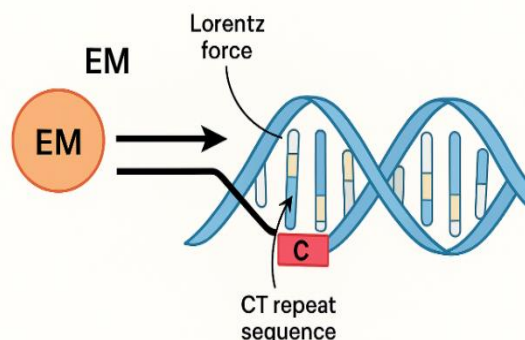


Figure 6. Direct Physical Interactions with DNA

Ensuring that exposure to non-ionizing EMFs, even at low intensities affecting DNA electron dynamics, remains within established safety limits recommended for genomic integrity by ICNIRP and other regulatory agencies is essential.

11.1. Lorentz force on electrons within DNA

The motion of electrons within the π -stacked base pairs of DNA renders them susceptible to Lorentz forces generated by applied EM fields. The governing relationship is:

$$\vec{F} = q(\vec{v} \times \vec{B})$$

Where q , \vec{v} , and B are the elementary charge (1.6×10^{-19} C), the elementary charge (1.6×10^{-19} C), and applied magnetic flux density, respectively. For a typical exposure of applied magnetic flux density about 80 mG = 8×10^{-6} T, the magnetic force is $(1.6 \times 10^{-19})(10^3)(8 \times 10^{-6}) \approx 1.3 \times 10^{-21}$ N.

Although the absolute force per electron is extremely small, its cumulative effect across extended base-pair stacks may result in measurable perturbations of DNA stability.

11.2. Competition between repulsive and stabilizing forces

The stability of the DNA double helix arises from hydrogen bonding between complementary bases A- and C-C-G pairs ($10 \text{ kcal/mol} \approx 7 \times 10^{-20} \text{ J}$ and $15 \text{ kcal/mol} \approx 1 \times 10^{-19} \text{ J}$) respectively.

If EM-field-induced electron motion generates repulsive forces between DNA strands, the net balance of forces ($F_{\text{repulsion}} - F_{\text{H-bond}}$) will determine whether local strand separation occurs. Importantly, CT-rich sequences possess lower electron density (electron affinity values: A=0.97, G=1.51, T=0.81, C=0.57), which implies higher electron velocities and thus stronger Lorentz forces. These characteristics make CT-rich EMRE sequences

particularly susceptible to EM-induced destabilization [94-96].

12. Synthesis: convergence of pathways

The gene expression changes observed, whether via microRNA modulation (miR-144, miR-375), reshaping signal transduction through NOTCH1, or altering apoptotic balance via BCL2 likely arise from overlapping mechanisms. ELF-MFs may influence cell fate by triggering redox changes, membrane excitability shifts, and DNA structural modifications, each converging on key regulatory nodes within tumor cells.

The observed upregulation of tumor-suppressive miRs and modulation of signaling genes suggests that controlled magnetic exposure could have application in therapeutic strategies, though precise dosing and comprehensive mechanistic understanding are essential prerequisites [85-87].

13. Interactions of magnetic fields with cellular organelles

13.1 Mitochondria: ROS, energy metabolism, and apoptosis

The mitochondrion, central to a cell's energy metabolism, is an increasingly recognized target for non-ionizing EMFs [97]. Several studies have reported that ELF-MF exposure disrupts mitochondrial function [97] raising reactive oxygen species (ROS) [98, 99], altering membrane potential [100], and influencing apoptotic pathways [83, 101].

For instance, rotating non-invasive magnetic fields were shown to arrest electron transport in mitochondria, disrupting energy production and triggering death in glioblastoma cells while sparing normal astrocytes (though in high-precision exposure settings) [102]. Other investigations report that exposure to 50 Hz ELF-MFs (e.g., 0.25 mT, 2 hours/day over 3 consecutive days) increases mitochondrial respiratory activity yet decreases cancer cell proliferation, suggesting a mitochondrial compensatory response to increased energy demand [103]. These findings align with the mitohormesis concept, where mild mitochondrial stress (e.g., ROS generation) can promote cell adaptation, while higher levels cross thresholds leading to cell death [104].

Within this context, another study on gastric cancer cells revealed that ELF-MF exposure modulates expression of mitochondrial apoptosis regulators like BCL2 and its controlling microRNAs (miR-15b, miR-16), pointing to mitochondrial-mediated apoptosis as a key effect of magnetic exposure [86] (Figure 7).

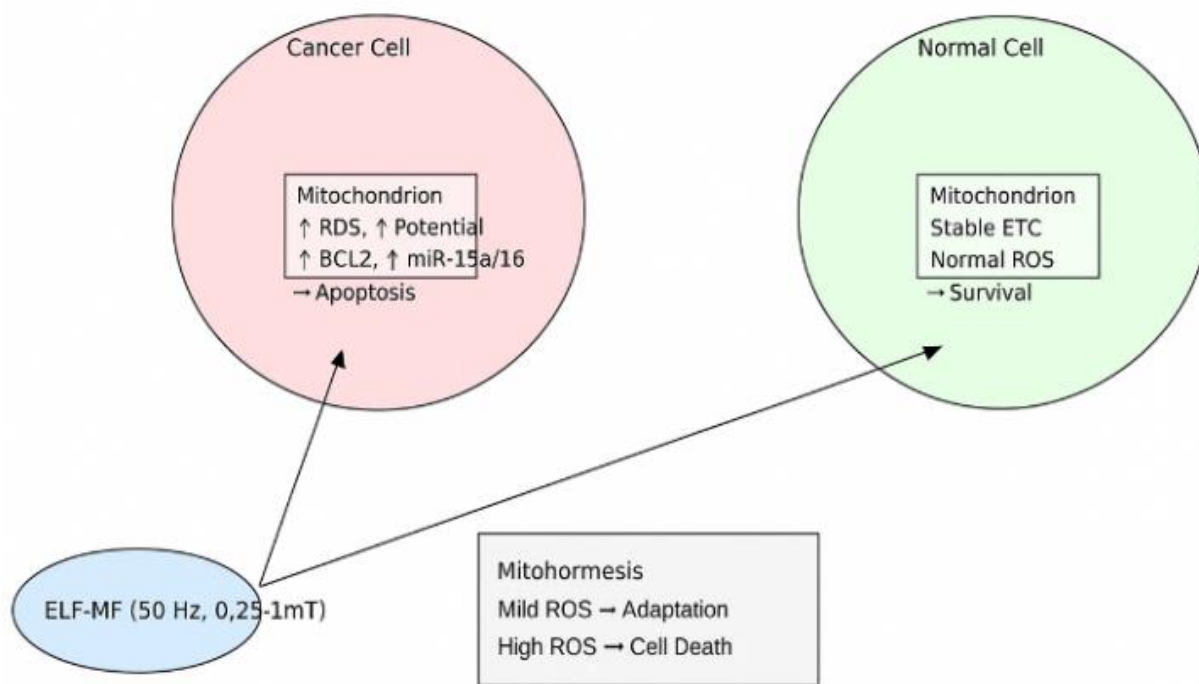


Figure 7. Effects of ELF-MF on mitochondria and cancer cells

13.2. Cytoskeletal structure and intracellular dynamics

The cytoskeleton underlies essential cell functions, and its components actin filaments, microtubules are sensitive to physical force. Exposure to ELF-MFs (50 Hz, 2 mT, 96 hours) induced subtle morphological changes in F-actin and mitochondria in A549 lung carcinoma cells, along with chromatin condensation, suggesting an effect on structural integrity and possibly signaling routes tied to apoptosis [105]. The reorganization of the cytoskeleton influences cell motility and division because cytoskeletal filaments not only provide structural support but also regulate force generation and signaling pathways, thereby initiating mechanotransductive processes [105].

14. Molecular mechanisms: from physics to biology

14.1. Radical pair mechanism and amplification

One of the most intriguing explanations for ELF-MF biological effects is the radical pair mechanism [89], where magnetic fields affect the spin states of paired radicals, ultimately altering reaction kinetics [106]. Recent modeling demonstrates that weak ELF-MFs could amplify the normal ROS oscillations in mitochondria especially near resonance frequencies, enhancing their biological effects [107]. This could partly explain why even low-intensity exposure can lead to significant outcomes in cells poised at a mitochondrial regulatory threshold [108].

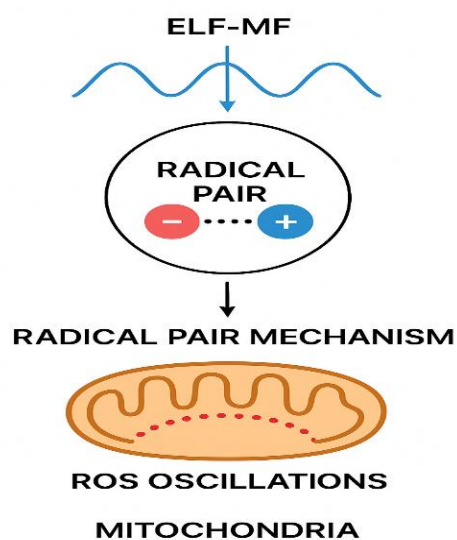


Figure 8. Effects of ELF-MF on radical pair mechanism

14.2. Membrane disruption and calcium channel modulation

Magnetic fields can induce currents in conductive membranes, potentially disrupting ion channel dynamics. Panagopoulos and colleagues proposed the Ion Forced Oscillation (IFO) model, suggesting that EMF exposure leads to irregular gating of Voltage-Gated Ion Channels (VGICs), especially calcium channels, which drives downstream ROS production and stress signaling [109]. In tumor cells, calcium dysregulation can lead to altered transcription and proliferative control.

In agreement, my experiments showed that ELF-MF exposure modifies expression of NOTCH1 and its circRNA regulator, potentially mediated by calcium-dependent signaling [87].

14.3. DNA and chromatin: structural and epigenetic effects

Though incapable of ionizing DNA, ELF-MFs may exert mechanical forces on the charged DNA backbone, altering chromatin architecture and gene accessibility. Some studies observed DNA strand breaks in Vero cells after 45 minutes exposure to 100 Hz, 5.6 mT EMF-MFs, effects plausibly linked to ROS-mediated damage [110]. The combination of these structural influences and microRNA-mediated transcriptional shifts suggests that magnetic fields may subtly reprogram the cancer epigenome, affecting critical genes like BCL2, miR-144/375, and miR-15/16 in our work [85, 86].

15. Therapeutic implications

Emerging findings indicate that non-ionizing electromagnetic fields (EMFs) can be employed

selectively to target cancer cells. For example, “Oncomagnetic” devices generating spinning oscillating magnetic fields have been shown to induce ROS-mediated apoptosis in glioma cells, while leaving surrounding healthy cells unaffected [102]. Studies have also demonstrated that exposure to ELF fields can modulate the expression of tumor suppressors such as miR-144 and miR-375, as well as oncogenes like NOTCH1 and BCL2, providing the potential for combinatory strategies with chemotherapy or radiotherapy to enhance therapeutic outcomes [85-87].

These findings suggest that EMFs can serve as targeted and adjunctive therapeutic modalities in cancer, where careful selection of field parameters, exposure duration, and frequency is critical for achieving optimal effects. Given that EMFs can penetrate living cells and interact directly with nuclear and mitochondrial DNA, adherence to safety limits and field intensity standards is essential to prevent potential genotoxic effects and ensure patient safety. For instance, for ELF fields, the general public exposure limit recommended by ICNIRP is below $\sim 200 \mu\text{T}$, which should be considered in designing therapeutic interventions to maximize anti-cancer efficacy while minimizing adverse effects.

DNA and Chromatin: Structural and Epigenetic Effects



Figure 9. Effects of ELF-MF on BCL2, miR-144/375, and miR-15/16

Table 2. Safety Guidelines and Recommended EMF Parameters for Clinical and Experimental Applications

Notes / Remarks	Recommended Limit	Organization / Reference	Field Type / Frequency / Therapeutic Application
For public exposure; safety benchmark	$\leq 200 \mu\text{T}$	ICNIRP	ELF-MF (50/60 Hz) – General Public
For controlled work environments	Higher than general public	ICNIRP	ELF-MF (50/60 Hz) – Occupational / Controlled
Short-term or peak exposure	$\leq 400 \text{ mT}$ (spatial peak)	ICNIRP	Static Magnetic Field
Requires careful monitoring and dosimetry	Typically 1–100 mT depending on device & frequency	Clinical Protocols	PEMF (Therapeutic Devices)
Based on clinical protocol and pulse duration	1–2 T (peak) – short pulses	FDA / IEC Guidelines	TMS (Transcranial Magnetic Stimulation)

16. Conclusion

In conclusion, non-ionizing electromagnetic fields (EMFs) exhibit a complex range of biological effects that may influence cancer development and progression through both direct and indirect mechanisms. Evidence suggests that EMFs can modulate oxidative stress, alter gene expression, affect cell signaling pathways, and influence cellular proliferation and apoptosis. While some studies indicate potential pro-tumorigenic effects, others report neutral or even protective impacts depending on field frequency, intensity, exposure duration, and cellular context. Overall, the current body of literature underscores the need for well-designed *in vitro*, *in vivo*, and epidemiological studies to clarify the molecular mechanisms underlying EMF exposure and its potential implications for cancer risk. A deeper understanding of these interactions could ultimately inform evidence-based guidelines for safe EMF exposure and open avenues for novel therapeutic strategies leveraging electromagnetic modulation in oncology.

Authors Contribution

All the authors have participated sufficiently in the intellectual content, conception and design of this work or the analysis and interpretation of the data (when applicable), as well as the writing of the manuscript.

Availability of data and materials

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Conflict of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

- [1] Presman, A., *Electromagnetic fields and life*. 2013: Springer Science & Business Media.
- [2] Lutz, K., et al. *Electromagnetic fields to sustain life on earth, in space, and planets*. in *Proceedings of the 72nd International Astronautical Congress (IAC), Dubai, United Arab Emirates*. 2021.
- [3] Panagopoulos, D.J., et al., *Human-made electromagnetic fields: Ion forced-oscillation and voltage-gated ion channel dysfunction, oxidative stress and DNA damage*. *International Journal of Oncology*, 2021. 59(5): p. 1-16.
- [4] Ramazanov, M., et al., *Theoretical and experimental investigation of the magnetic properties of polyvinylidene fluoride and magnetite nanoparticles-based nanocomposites*. *Journal of Theoretical and Applied Physics*, 2018. 12(1): p. 7-13.
- [5] Azad, M., M. Ranjbaran, and S. Souidi, *Modeling magnetic fluid hyperthermia for tumors: A comprehensive study on skin tissue*. *Journal of Theoretical and Applied Physics*, 2025. 19(3).
- [6] Bahar, M., A. Majd, and S. Abdi, *Effects of (ELF) extremely low frequency (50 Hz) AC and DC magnetic fields on lentil germination and seedlings growth*. 2009.
- [7] Protection, I.C.o.N.-I.R., *ICNIRP statement on the "Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz)"*. *Health physics*, 2009. 97(3): p. 257-258.
- [8] Balasubramanian, D., et al., *Multiple radiations and its effect on biological system—a review on in vitro and in vivo mechanisms*. *Annals of Medicine*, 2025. 57(1): p. 2486595.
- [9] Shahbazi-Gahrouei, D., et al., *Biological effects of non-ionizing electromagnetic fields on human body and biological system: A systematic literature review*. *Journal of Medicine Science*, 2018: p. 149-156.
- [10] Guzmán-Armenteros, T.M., J. Ruales, and L. Ramos-Guerrero, *A Review of Electromagnetic Fields in Cellular Interactions and Cacao Bean Fermentation*. *Foods*, 2024. 13(19): p. 3058.
- [11] Sun, G., et al., *Electromagnetic interactions in regulations of cell behaviors and morphogenesis*. *Frontiers in Cell and Developmental Biology*, 2022. 10: p. 1014030.
- [12] Saliev, T., et al., *Bio-effects of non-ionizing electromagnetic fields in context of cancer therapy*. *Front Biosci (Elite Ed)*, 2014. 6(1): p. 175-84.
- [13] Alipour, M., et al., *Advances in magnetic field approaches for non-invasive targeting neuromodulation*. *Frontiers in Human Neuroscience*, 2025. 19: p. 1489940.
- [14] Yang, Y., et al., *A review of combined imaging and therapeutic applications based on MNMs*. *Frontiers in Chemistry*, 2025. 13: p. 1595376.
- [15] Cordelli, E., et al., *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*, 2023. 180: p. 108178.
- [16] Pophof, B., et al., *Biological effects of radiofrequency electromagnetic fields above 100 MHz on fauna and flora: workshop report*. *Health Physics*, 2023. 124(1): p. 31-38.
- [17] Tian, H., et al., *System-level biological effects of extremely low-frequency electromagnetic fields: an in*

- vivo experimental review. *Frontiers in Neuroscience*, 2023. 17: p. 1247021.
- [18] Abdi, S., et al., *Changes in physicochemical characteristics of human low density lipoprotein nanoparticles by electromagnetic field exposure*. *Stud U Babes-Bol Che*, 2016. 61(1): p. 185-197.
- [19] Abdi, S., et al., *Evaluation of the effects of weak and moderate static magnetic fields on the characteristics of human low density lipoprotein in vitro*. *Bioelectromagnetics*, 2013. 34(5): p. 397-404.
- [20] Zadeh-Haghighi, H. and C. Simon, *Magnetic field effects in biology from the perspective of the radical pair mechanism*. *Journal of the Royal Society Interface*, 2022. 19(193): p. 20220325.
- [21] Gerhards, L., et al., *Weak radiofrequency field effects on biological systems mediated through the radical pair mechanism*. *Chemical Reviews*, 2025.
- [22] Abdi, S., D. Dorranean, and K. Mohammadi, *Effect of oxygen on decontamination of cumin seeds by atmospheric pressure dielectric barrier discharge plasma*. *Plasma Medicine*, 2016. 6(3-4).
- [23] Liu, L., et al., *Interactions between electromagnetic radiation and biological systems*. *Iscience*, 2024. 27(3).
- [24] Sun, J., et al., *Effects of extremely low frequency electromagnetic fields on the tumor cell inhibition and the possible mechanism*. *Scientific Reports*, 2023. 13(1): p. 6989.
- [25] Dieper, A., et al., *Literature review: potential non-thermal molecular effects of external radiofrequency electromagnetic fields on cancer*. *International Journal of Hyperthermia*, 2024. 41(1): p. 2379992.
- [26] Lagroye, I., et al., *ELF magnetic fields: animal studies, mechanisms of action*. *Progress in biophysics and molecular biology*, 2011. 107(3): p. 369-373.
- [27] McCormick, D.L., et al., *Chronic toxicity/oncogenicity evaluation of 60 Hz (power frequency) magnetic fields in B6C3F1 mice*. *Toxicologic pathology*, 1999. 27(3): p. 279-285.
- [28] Boorman, G.A., et al., *Chronic toxicity/oncogenicity evaluation of 60 Hz (power frequency) magnetic fields in F344/N rats*. *Toxicologic pathology*, 1999. 27(3): p. 267-278.
- [29] Organization, W.H., *International agency for research in cancer*. IARC Monographs on the Evaluation of the Carcinogenic Risk of Chemicals to Man, 1994.
- [30] Bor, D., *Cep telefonlari sagligimiza zararli mi?/Are mobile phones dangerous to our health*. *Turkish Journal of Radiology*, 2016. 35(3): p. 85-88.
- [31] Kleinerman, R.A., et al., *Are children living near high-voltage power lines at increased risk of acute lymphoblastic leukemia?* *American Journal of Epidemiology*, 2000. 151(5): p. 512-515.
- [32] Loizeau, N., et al., *Extremely low frequency magnetic fields (ELF-MF) in Switzerland: From exposure monitoring to daily exposure scenarios*. *Environment International*, 2024. 194: p. 109181.
- [33] Me, K., *Childhood cancer and magnetic fields from high-voltage power lines in England and Wales: a case-control study*. *Br J Cancer*, 2010. 103: p. 1122-1127.
- [34] Sermage-Faure, C., et al., *Childhood leukaemia close to high-voltage power lines—the Geocap study, 2002–2007*. *British journal of cancer*, 2013. 108(9): p. 1899-1906.
- [35] Kabuto, M., et al., *Childhood leukemia and magnetic fields in Japan: A case-control study of childhood leukemia and residential power-frequency magnetic fields in Japan*. *International Journal of Cancer*, 2006. 119(3): p. 643-650.
- [36] Wünsch-Filho, V., et al., *Exposure to magnetic fields and childhood acute lymphocytic leukemia in São Paulo, Brazil*. *Cancer Epidemiology*, 2011. 35(6): p. 534-539.
- [37] Kheifets, L., et al., *A pooled analysis of extremely low-frequency magnetic fields and childhood brain tumors*. *American journal of epidemiology*, 2010. 172(7): p. 752-761.
- [38] Ahlbom, A., et al., *A pooled analysis of magnetic fields and childhood leukaemia*. *British journal of cancer*, 2000. 83(5): p. 692-698.
- [39] Greenland, S., et al., *Pooled Analysis of Magnetic Fields, Wire Codes, and Childhood Leukemia*. *Epidemiology*, 2001. 12(4): p. 473-474.
- [40] Linet, M.S., et al., *Residential exposure to magnetic fields and acute lymphoblastic leukemia in children*. *New England journal of medicine*, 1997. 337(1): p. 1-8.
- [41] Mezei, G., M. Gadallah, and L. Kheifets, *Residential magnetic field exposure and childhood brain cancer: a meta-analysis*. *Epidemiology*, 2008. 19(3): p. 424-430.
- [42] Kheifets, L., et al., *Pooled analysis of recent studies on magnetic fields and childhood leukaemia*. *British journal of cancer*, 2010. 103(7): p. 1128-1135.
- [43] Does, M., et al., *Exposure to electrical contact currents and the risk of childhood leukemia*. *Radiation research*,

2011. 175(3): p. 390-396.
- [44] Hatch, E.E., et al., *Association between childhood acute lymphoblastic leukemia and use of electrical appliances during pregnancy and childhood*. *Epidemiology*, 1998: p. 234-245.
- [45] Peyman, A., et al., *Assessment of exposure to electromagnetic fields from wireless computer networks (wi-fi) in schools; results of laboratory measurements*. *Health physics*, 2011. 100(6): p. 594-612.
- [46] Morgan, R.W., et al., *Radiofrequency exposure and mortality from cancer of the brain and lymphatic/hematopoietic systems*. *Epidemiology*, 2000. 11(2): p. 118-127.
- [47] Foster, K.R. and J.E. Moulder, *Wi-Fi and health: review of current status of research*. *Health physics*, 2013. 105(6): p. 561-575.
- [48] Merzenich, H., et al., *Childhood leukemia in relation to radio frequency electromagnetic fields in the vicinity of TV and radio broadcast transmitters*. *American journal of epidemiology*, 2008. 168(10): p. 1169-1178.
- [49] Gupta, S., R.S. Sharma, and R. Singh, *Non-ionizing radiation as possible carcinogen*. *International journal of environmental health research*, 2022. 32(4): p. 916-940.
- [50] Kabat, G.C., et al., *Electric blanket use and breast cancer on Long Island*. *Epidemiology*, 2003. 14(5): p. 514-520.
- [51] Schoenfeld, E., et al., *Electromagnetic fields and breast cancer on Long Island: a case-control study*. *American journal of epidemiology*, 2003. 158(1): p. 47-58.
- [52] London, S.J., et al., *Residential magnetic field exposure and breast cancer risk: a nested case-control study from a multiethnic cohort in Los Angeles County, California*. *American journal of epidemiology*, 2003. 158(10): p. 969-980.
- [53] Davis, S., D.K. Mirick, and R.G. Stevens, *Residential magnetic fields and the risk of breast cancer*. *American journal of epidemiology*, 2002. 155(5): p. 446-454.
- [54] Kocaman, A., et al., *Genotoxic and carcinogenic effects of non-ionizing electromagnetic fields*. *Environmental research*, 2018. 163: p. 71-79.
- [55] Thomas, T.L., et al., *Brain tumor mortality risk among men with electrical and electronics jobs: a case-control study*. *Journal of the National Cancer Institute*, 1987. 79(2): p. 233-238.
- [56] Salvatore, J., et al., *Non-ionizing electromagnetic radiation: a study of carcinogenic and cancer treatment potential*. *Reviews on Environmental Health*, 1994. 10(3-4): p. 197-208.
- [57] Willett, E., et al., *Occupational exposure to electromagnetic fields and acute leukaemia: analysis of a case-control study*. *Occupational and environmental medicine*, 2003. 60(8): p. 577-583.
- [58] Li, W., et al., *Occupational exposure to magnetic fields and breast cancer among women textile workers in Shanghai, China*. *American journal of epidemiology*, 2013. 178(7): p. 1038-1045.
- [59] Coble, J.B., et al., *Occupational exposure to magnetic fields and the risk of brain tumors*. *Neuro-Oncology*, 2009. 11(3): p. 242-249.
- [60] Labreche, F., et al., *Occupational exposures to extremely low frequency magnetic fields and postmenopausal breast cancer*. *American journal of industrial medicine*, 2003. 44(6): p. 643-652.
- [61] Kliukiene, J., T. Tynes, and A. Andersen, *Residential and occupational exposures to 50-Hz magnetic fields and breast cancer in women: a population-based study*. *American journal of epidemiology*, 2004. 159(9): p. 852-861.
- [62] Groves, F.D., et al., *Cancer in Korean war navy technicians: mortality survey after 40 years*. *American journal of epidemiology*, 2002. 155(9): p. 810-818.
- [63] Grayson, J.K., *Radiation exposure, socioeconomic status, and brain tumor risk in the US Air Force: a nested case-control study*. *American Journal of Epidemiology*, 1996. 143(5): p. 480-486.
- [64] Savitz, D.A. and D.P. Loomis, *Magnetic field exposure in relation to leukemia and brain cancer mortality among electric utility workers*. *American Journal of Epidemiology*, 1995. 141(2): p. 123-134.
- [65] Milham Jr, S., *Mortality in workers exposed to electromagnetic fields*. *Environmental Health Perspectives*, 1985. 62: p. 297-300.
- [66] Armstrong, B., et al., *Association between exposure to pulsed electromagnetic fields and cancer in electric utility workers in Quebec, Canada, and France*. *American Journal of Epidemiology*, 1994. 140(9): p. 805-820.
- [67] Rannug, A., et al., *ACCELERATED PAPER: Intermittent 50 Hz magnetic field and skin tumour promotion in SENCAR mice*. *Carcinogenesis*, 1994. 15(2): p. 153-157.
- [68] Stuchly, M., et al., *Modification of tumor promotion in the mouse skin by exposure to an alternating magnetic*

- field*. Cancer letters, 1992. 65(1): p. 1-7.
- [69] Baum, A., et al., *A histopathological study on alterations in DMBA-induced mammary carcinogenesis in rats with 50 Hz, 100 μ T magnetic field exposure*. Carcinogenesis, 1995. 16(1): p. 119-125.
- [70] Mevissen, M., M. Kietzmann, and W. Löscher, *In vivo exposure of rats to a weak alternating magnetic field increases ornithine decarboxylase activity in the mammary gland by a similar extent as the carcinogen DMBA*. Cancer Letters, 1995. 90(2): p. 207-214.
- [71] Löscher, W., et al., *Tumor promotion in a breast cancer model by exposure to a weak alternating magnetic field*. Cancer letters, 1993. 71(1-3): p. 75-81.
- [72] Sarimov, R.M., D.A. Serov, and S.V. Gudkov, *Biological effects of magnetic storms and ELF magnetic fields*. Biology, 2023. 12(12): p. 1506.
- [73] Binhi, V. and A. Savin, *Molecular gyroscopes and biological effects of weak extremely low-frequency magnetic fields*. Physical Review E, 2002. 65(5): p. 051912.
- [74] Rosen, A.D., *Mechanism of action of moderate-intensity static magnetic fields on biological systems*. Cell biochemistry and biophysics, 2003. 39(2): p. 163-173.
- [75] Lednev, V., *Possible mechanism for the influence of weak magnetic fields on biological systems*. Bioelectromagnetics, 1991. 12(2): p. 71-75.
- [76] Toda, T., et al., *Extremely low-frequency pulses of faint magnetic field induce mitophagy to rejuvenate mitochondria*. Communications Biology, 2022. 5(1): p. 453.
- [77] Radil, R., et al., *Exploring non-thermal mechanisms of biological reactions to extremely low-frequency magnetic field exposure*. Applied Sciences, 2024. 14(20): p. 9409.
- [78] Schaap, K., et al., *Exposure to static and time-varying magnetic fields from working in the static magnetic stray fields of MRI scanners: a comprehensive survey in the Netherlands*. Annals of occupational hygiene, 2014. 58(9): p. 1094-1110.
- [79] Turner, M.C., et al., *Interactions between occupational exposure to extremely low frequency magnetic fields and chemicals for brain tumour risk in the INTEROCC study*. Occupational and Environmental Medicine, 2017. 74(11): p. 802-809.
- [80] Halgamuge, M.N., *Pineal melatonin level disruption in humans due to electromagnetic fields and ICNIRP limits*. Radiation protection dosimetry, 2013. 154(4): p. 405-416.
- [81] Salvatore, J.R., J. Harrington, and T. Kummet, *Phase I clinical study of a static magnetic field combined with anti-neoplastic chemotherapy in the treatment of human malignancy: Initial safety and toxicity data*. Bioelectromagnetics: Journal of the Bioelectromagnetics Society, The Society for Physical Regulation in Biology and Medicine, The European Bioelectromagnetics Association, 2003. 24(7): p. 524-527.
- [82] Warille, A.A., et al., *Skeptical approaches concerning the effect of exposure to electromagnetic fields on brain hormones and enzyme activities*. Journal of microscopy and ultrastructure, 2017. 5(4): p. 177-184.
- [83] Barati, M., et al., *Cellular stress response to extremely low-frequency electromagnetic fields (ELF-EMF): An explanation for controversial effects of ELF-EMF on apoptosis*. Cell Proliferation, 2021. 54(12): p. e13154.
- [84] Nezamtaheri, M.S., et al., *Differential biological responses of adherent and non-adherent (cancer and non-cancerous) cells to variable extremely low frequency magnetic fields*. Scientific Reports, 2022. 12(1): p. 14225.
- [85] Aalami Zavareh, F., S. Abdi, and M. Entezari, *Up-regulation of miR-144 and miR-375 in the human gastric cancer cell line following the exposure to extremely low-frequency electromagnetic fields*. International Journal of Radiation Biology, 2021. 97(9): p. 1324-1332.
- [86] Heidari, S., S. Abdi, and S.Z. Karizi, *Evaluation of BCL2 and its regulatory miRs, miR-15-b and miR-16 expression changes under the exposure of extremely low-frequency electromagnetic fields on human gastric cancer cell line*. Radiation protection dosimetry, 2021. 197(2): p. 93-100.
- [87] Mansoury, F., et al., *Changes in NOTCH1 gene and its regulatory circRNA, hsa_circ_0005986 expression pattern in human gastric adenocarcinoma and human normal fibroblast cell line following the exposure to extremely low frequency magnetic field*. Electromagnetic Biology and Medicine, 2021. 40(3): p. 375-383.
- [88] Hashemi, M., et al., *miRNAs and exosomal miRNAs in lung cancer: New emerging players in tumor progression and therapy response*. Pathology-Research and Practice, 2023. 251: p. 154906.
- [89] Barnes, F.S. and B. Greenebaum, *The effects of weak magnetic fields on radical pairs*. Bioelectromagnetics, 2015. 36(1): p. 45-54.
- [90] Lai, H., *Exposure to static and extremely-low frequency electromagnetic fields and cellular free radicals*. Electromagnetic biology and medicine, 2019. 38(4): p.

- 231-248.
- [91] Brocklehurst, B. and K.A. McLauchlan, *Free radical mechanism for the effects of environmental electromagnetic fields on biological systems*. International journal of radiation biology, 1996. 69(1): p. 3-24.
- [92] Pall, M.L., *Electromagnetic fields act via activation of voltage-gated calcium channels to produce beneficial or adverse effects*. Journal of cellular and molecular medicine, 2013. 17(8): p. 958-965.
- [93] Barbado, M., et al., *Gene regulation by voltage-dependent calcium channels*. Biochimica et Biophysica Acta (BBA)-Molecular Cell Research, 2009. 1793(6): p. 1096-1104.
- [94] Blank, M. and R. Goodman, *Do electromagnetic fields interact directly with DNA?* Bioelectromagnetics: Journal of the Bioelectromagnetics Society, The Society for Physical Regulation in Biology and Medicine, The European Bioelectromagnetics Association, 1997. 18(2): p. 111-115.
- [95] Blank, M. and R. Goodman, *Electromagnetic fields may act directly on DNA*. Journal of Cellular Biochemistry, 1999. 75(3): p. 369-374.
- [96] Blank, M. and R. Goodman, *Electromagnetic initiation of transcription at specific DNA sites*. Journal of Cellular Biochemistry, 2001. 81(4): p. 689-692.
- [97] Santini, S.J., et al., *Role of mitochondria in the oxidative stress induced by electromagnetic fields: focus on reproductive systems*. Oxidative Medicine and Cellular Longevity, 2018. 2018(1): p. 5076271.
- [98] Poniedzialek, B., et al., *The effect of electromagnetic field on reactive oxygen species production in human neutrophils in vitro*. Electromagnetic biology and medicine, 2013. 32(3): p. 333-341.
- [99] Wang, H. and X. Zhang, *Magnetic fields and reactive oxygen species*. International journal of molecular sciences, 2017. 18(10): p. 2175.
- [100] Krutáková, M., et al. *Analysis of electromagnetic field effect on cell plasma membrane potential*. in 2016 ELEKTRO. 2016. IEEE.
- [101] Kaszuba-Zwoinska, J., et al., *Pulsed electromagnetic field affects intrinsic and endoplasmic reticulum apoptosis induction pathways in MonoMac6 cell line culture*. J Physiol Pharmacol, 2012. 63(5): p. 537-545.
- [102] Sharpe, M.A., et al., *Rotating magnetic fields inhibit mitochondrial respiration, promote oxidative stress and produce loss of mitochondrial integrity in cancer cells*. Frontiers in Oncology, 2021. 11: p. 768758.
- [103] Destefanis, M., et al., *Extremely low frequency electromagnetic fields affect proliferation and mitochondrial activity of human cancer cell lines*. International Journal of Radiation Biology, 2015. 91(12): p. 964-972.
- [104] Franco-Obregón, A., *Harmonizing magnetic mitohormetic regenerative strategies: developmental implications of a calcium-mitochondrial Axis invoked by magnetic field exposure*. Bioengineering, 2023. 10(10): p. 1176.
- [105] Kroupová, J., et al., *Low-frequency magnetic field effect on cytoskeleton and chromatin*. Bioelectrochemistry, 2007. 70(1): p. 96-100.
- [106] Weller, A., H. Staerk, and R. Treichel, *Magnetic-field effects on geminate radical-pair recombination*. Faraday discussions of the Chemical Society, 1984. 78: p. 271-278.
- [107] Zandieh, A., et al., *An amplification mechanism for weak ELF magnetic fields quantum-bio effects in cancer cells*. Scientific Reports, 2025. 15(1): p. 2964.
- [108] Aitken, R.J., et al., *Sperm motility is lost in vitro as a consequence of mitochondrial free radical production and the generation of electrophilic aldehydes but can be significantly rescued by the presence of nucleophilic thiols*. Biology of reproduction, 2012. 87(5): p. 110, 1-11.
- [109] Panagopoulos, D.J., et al., *A comprehensive mechanism of biological and health effects of anthropogenic extremely low frequency and wireless communication electromagnetic fields*. Frontiers in Public Health, 2025. 13: p. 1585441.
- [110] Miha, C.T., et al., *Extremely low-frequency electromagnetic fields cause DNA strand breaks in normal Vero cells*. arXiv preprint arXiv:1301.5418, 2013.