



Effect of electromagnetic radiations from mobile towers on genetic damage and genetic polymorphism in humans: a review on India's perspective

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Accepted: 4 August 2025 / Published online: 26 August 2025

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Abstract

There have been concerns about possible health implications of radiofrequency electromagnetic radiation owing to increased cell phone use and proliferation of cell phone towers. The amount of RF-EMR energy absorbed in the human tissues relies on both the exposure characteristics of frequency, intensity, and exposure duration. This effect could be due to the exposure of genetic material by RF, resulting in an increased risk of cancer development and death in cells. Genetic polymorphisms involve variation in the DNA sequence in and among people, populations, or groups. These polymorphisms might contribute to susceptibility to RF effects. These genetic variations-which could be in the form of single nucleotide polymorphisms (SNPs) or copy number variations (CNVs)-may occur either by a sheer chance process or by external factors such as viruses or radiation. Knowing the influence of genetic polymorphisms on RF exposure would help level off related health risks of cell phone use and cell towers. This scientific review examines related scientific research data about the effects that cell terminal EMR has on human genetic damage and polymorphism. We critically appraise literature and peer review journals relevant to data in assessing our current knowledge in this area. Our study reveals the fact that some studies indicate exposure to EMR does bear a relation with genetic damage, but such results should be further researched as to which health impacts they bring forward.

Communicated by Jiyoung Ahn.

In the original article an article note shall be added: "The original online version of this article has been revised to reflect the following corrections: Kanu Priya was previously listed as the corresponding author and has been corrected to first author only. Kuldeep Sharma and his affiliation 2 have been removed from the author list, and all subsequent affiliations have been renumbered. The author name "Shiv Giri" was corrected to "Shiv Kumar Giri", and the author name "Sarvesh Rustogi" was corrected to "Sarvesh Rustagi". Additionally, affiliations 4 and 5 (formerly 5 and 6) have been updated. Affiliation 4 was revised from "Department of Mechanical Engineering, Chandigarh University, Gharuan, India" to "Institute of Engineering and e-Governance, Chandigarh University, Gharuan, India". Affiliation 5 was updated from "Department of Food Technology, School of Applied and Life Sciences, Uttaranchal University, Dehradun, Uttarakhand, India" to "Department of Food Technology, School of Agriculture and Technology, Maya Devi University, Uttarakhand, India". (ArticleNote/@OutputMedium="Online") The copyright line in A++ and OnlinePDF file must read © [CopyrightHolder] [year of online publication], corrected publication 2025

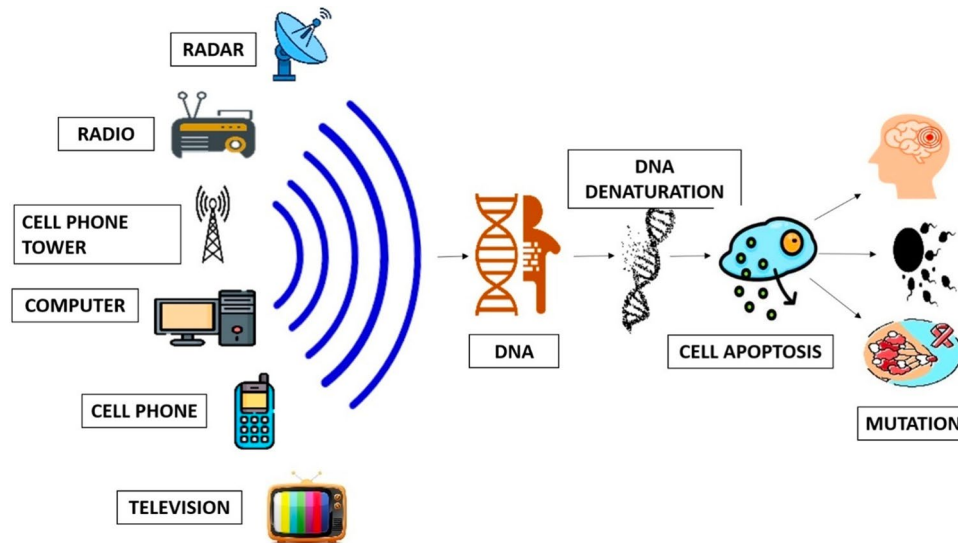
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Graphical abstract



Keywords Cell phones · Mobile towers · RF radiation · Single nucleotide polymorphisms · Copy number variations · Cancer

Introduction

With the expansion of mobile communication infrastructure in India, concerns have grown about the potential biological effects of radiofrequency electromagnetic radiation (RF-EMR) emitted by mobile towers, particularly its impact in genetic integrity and variation in humans. Most sources such as mobile phones and Wi-Fi routers emit non-ionizing radiation, which has become ubiquitous in daily life. In particular, the expansion of communication towers to support these technologies has raised questions about their possible role in inducing genetic changes including DNA damage and genetic polymorphism. Changes in DNA due to any external (radiations) and internal (metabolic by-products) factors are known as mutations. Mutations may lead to polymorphisms, which are alterations and can be inherited [1, 2].

The occurrence of two or more different alleles or variation in the DNA sequence is known as genetic polymorphism [3]. Single nucleotide polymorphisms, or SNPs, involves a change in a single base pair and can affect the function of one or more genes, potentially causing genetic disorder and are the most common type of polymorphism, and it is increasingly evident that polymorphisms are either directly linked to a variety of diseases or may affect an array of outcomes in terms of disease [4]. Other types of polymorphism include sequence repeats, insertions, deletions, and recombination events. Some polymorphism is harmless and simply account for normal traits such as hair texture (straight or curly) and eye color

(blue or brown). The human genome comprises 23 pairs of chromosomes, each having around 6 billion DNA nucleotides inherited from its respective parents. This humongous size increases the propensity for having polymorphic DNA. The human genome is polymorphic in all respects. The variations range from single nucleotide variations to base pair changes and repetitive sequences. Genetic polymorphism has been defined as the presence of a gene with more than one form of expression in at least 1% of the population [5]. Genetic polymorphisms can arise spontaneously or as a consequence of environmental stimuli like radiation or viruses. Mutations give rise to polymorphisms [6]. The mutation might result from a rearrangement of nucleotides, an insertion or deletion, or a change in nucleotide type. A polymorphism may be traced from parent to kid through inheritance since once generated, it can be passed like any other DNA sequence [7].

Polymorphisms can be found both inside and outside of genes, and non-coding DNA is more likely to contain them. Silent mutation or missense/nonsense mutation can occur from synonymous or non-synonymous SNPs found in the protein-coding region of the genome. Polymorphisms in protein-coding DNA sequences can have negative effects on humans, causing potential cell and tissue damage. The rapid growth of technology and increased use of smart devices has led to increased exposure to RF-EMR, emphasizing the importance of understanding its effects on genetic material and general health [8, 9].

Electromagnetic radiation: an overview

For many years, point-to-point and point-to-multipoint applications have utilized wireless communication lines as a means of achieving connectivity throughout the globe. Radio, radar, television broadcast stations, microwave systems, mobile and cellular phones, and AM/FM modulation are some of the most widely used wireless solutions. Light, any light, from radiofrequencies to gamma rays, is technically referred to as electromagnetic radiation. This includes visible light as well. As the name implies, combined electric and magnetic fields emit all types of light. The movement of photons through space is referred to as electromagnetic radiation based on the contemporary quantum theory. One hundred KHz (100 kHz) to three hundred GHz (300 GHz) represents the RF-EMF radiation range. The antennas of the cell tower use a frequency of 900 or 1800 MHz, pulsed at low frequencies, often referred to as microwaves (300 MHz to 300 GHz). Mobile phone technologies mostly use frequencies between 800 MHz 3 GHz, and 4 GHz [10, 11].

Ionizing and non-ionizing radiation are the components of the electromagnetic spectrum. The three types of radiation that are considered ionizing are ultraviolet (UV), X-rays, and gamma (γ) waves. Mostly, high-frequency radio waves or microwaves make up electromagnetic radiation (EMR) emitted by cellular towers. The electromagnetic spectrum comprises low-frequency radio waves, which are found in computers and power lines; medium-frequency radio waves, which are found in televisions and

radios; and high-frequency radio waves, which are found in microwaves and mobile devices [12–14] (Fig. 1).

Ionizing and non-ionizing radiation

Ionizing radiation represents energy released by atoms in the form of electromagnetic waves or particles that have enough energy to remove tightly bound electrons from atoms, producing ions. This process can lead to alteration of chemical reactions within one's body and potentially damage the surrounding tissues. Ionizing radiation primarily includes gamma rays and X-rays, both of which can cause significant biological damage. To minimize exposure, nuclear power plants are equipped with extensive shielding and protective lead aprons are used during medical imaging procedures such as X-rays. Despite these precautions, humans are constantly expose to low levels of ionizing radiation from natural sources in the environment. Natural background radiation mainly comes from three sources: cosmic rays that reach Earth from space, radioactive elements in the Earth's crust (such as uranium in granite and coal), and internal radiation from naturally occurring radioactive substances within the human body, like potassium-40. Radon gas, which seeps from soil and rocks, is also a significant contributor to terrestrial radiation [15, 16].

Electromagnetic radiation (EMR) at lower frequencies is regarded as non-ionizing since its energy levels are lower than those necessary to produce atomic-level effects. UV and other non-ionizing radiation may not have the energy to ionize atoms, yet they can nevertheless cause harm to

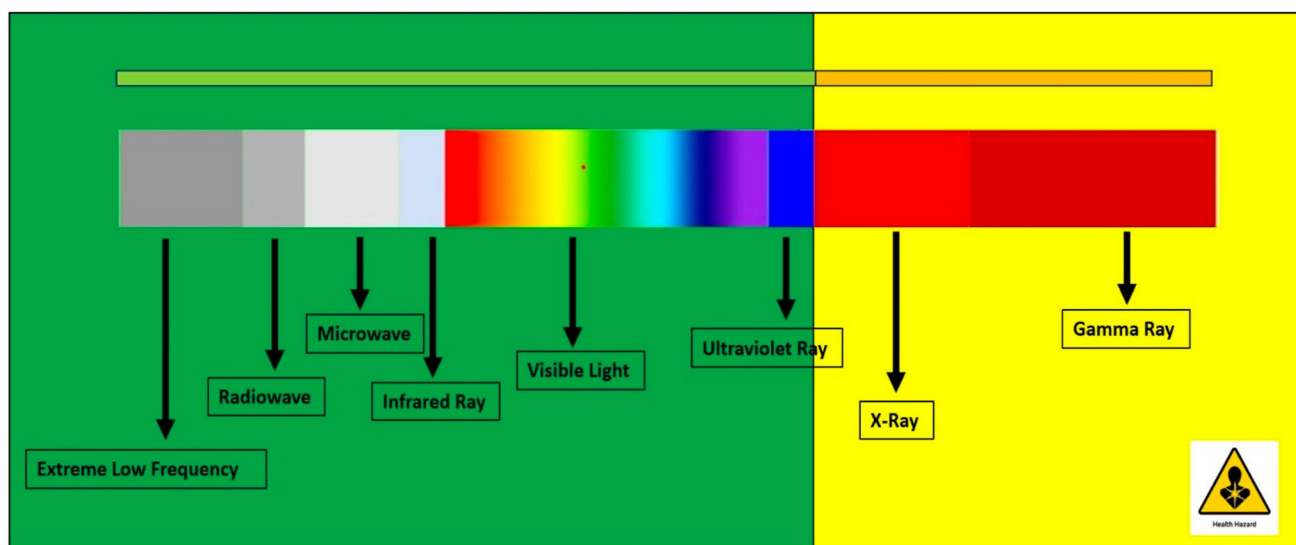


Fig. 1 Classification of ionizing and non-ionizing radiation. Compared to non-ionizing radiation like extreme low frequency (100,000–100 km), radiowave (100 km to 1 m), microwaves (1 m to 1 mm),

infrared (1 mm to 700 nm), radiofrequency (100 km to 1 mm), and others. Ionizing radiations includes particles such as gamma rays (<0.01 nm), UV rays (10 to 400 nm), X-rays (0.01 to 10 nm) etc.

living tissue. It is critical to reduce our exposure to both forms of radiation to safeguard our health and prevent any risks. Lower frequency non-ionizing radiation is safe at ordinary exposure levels, according to the majority of experts. Nonetheless, there is proof that some frequencies might be dangerous. Some research indicates that long-term exposure to high-strength non-ionizing radiation can lead to health issues like cancer, tumors, headaches, exhaustion, and Parkinson's and Alzheimer's illnesses [17, 18].

Radiofrequency radiation

The electromagnetic (EM) spectrum has properties of particles as well as propagated waves (pond ripple oscillations are an example of a propagated wave). Even while Wi-Fi greatly enhances human life, its widespread usage has resulted in a rise in radiofrequency electromagnetic radiation (RF-EMR) in public settings. A common type of non-ionizing radiation released by a variety of electronic gadgets is called radiofrequency electromagnetic radiation, or RF-EMR. It is also produced spontaneously by lightning and by the sun, stars, and other celestial bodies releasing their energy [19, 20]. These days, there are many man-made RF sources, including wireless internet routers, mobile phones, cordless (DECT) phones, radios, televisions, and home monitors. The amount

of RF exposure varies based on the technology, how it is utilized, and how far away from the sources. There are RF-based devices in use in public areas, companies, schools, households, and public transit. These technologies are used in our everyday lives in an unprecedented amount, which has sparked worries about possible health repercussions. Cell phone towers, smartphone, laptops, Wi-Fi, microwave ovens, and other electronic gadgets all emit it at different frequencies (Fig. 2). The frequency range of RFR is 300 GHz to 10 kHz. Microwave ovens and Wi-Fi applications use 2450 MHz on average. While cell phone towers usually run

Table 1 Different sources of radiation and their frequencies

Designation	Frequencies
Television	1 kHz to 300 GHz
Mobile phone	0.7–2.7 GHz
Computer	400–800 THz
Satellite	30–60 GHz
Radio	3 kHz to 300 GHz
Radar	300 MHz to 15 GHz
Wi-Fi	2.4 GHz or 5 GHz
Base tower	824–894 MHz

Fig. 2 Essential operational frequency bands are displayed together with common radiation sources from residences and commercial buildings



at 1900 MHz, cellular technology employs transmission frequencies between 800 MHz and 3 GHz [21, 22] (Table 1).

Specific absorption rate (SAR)

The term "specific absorption rate" refers to the quantity of power that a radiofrequency field deposits into a particular mass of tissue. For this reason, watts per kilogram (W/kg) are used to represent SAR units. The primary factor governing how mobile phones affect human tissues is the Specific Absorption Rate (SAR), whose management is crucial for limiting the release of electromagnetic radiation. The organ's shapes, sizes and also by the electrical properties of the tissue, such as conductivity and permittivity have an impact on the SAR findings. The RF electrical currents in the antenna and the portable container of the mobile device will undoubtedly cause RF electrical fields to reach the tissue. As a result, a portion of this radiation energy may be absorbed by human tissue, increasing the tissue's temperature. The power loss due to dielectric polarization is the cause of such absorption occurrences. The primary causes of the dielectric polarization of biological material at radiofrequencies are the vibrations of free ions, bound charges linked to macromolecules, and water molecules. A few distinct criteria must be employed to estimate the degree of heating because it is not feasible to directly monitor the temperature changes brought on by RF radiation. One such criterion is power density (W/m^2), which indicates the level of radiation exposure that may be safely tolerated, especially in the outdoor environment [23–26].

Radiation from cell phone towers

As of June 2025, there will be 8,28,643 telecom towers in India as per DOT (Department of Telecommunication). Indian operators use macro cells, micro cells, and nano-cells as base stations. Macro cellular base stations are the backbone of a mobile telephone network. The place for the installation of antennas is at an optimum height to guarantee enough geographical coverage. A lone macrocellular base station transmitter can have an output of up to 20 watts. The effective radiated power is a number that incorporates both the power of the transmitter and the directivity of the antenna. So, an ERP of 100 W would equate to a real power radiated of some 5–10 W again dependent on the type of antenna. Mobile towers in India usually radiate hundreds of watts of power with an antenna gain of 50, so ERP occasionally exceeds 5000 W. A cellular tower enables the user to establish a wireless connection to the network. It contains many radio transmitters mounted and wired onto the base station antenna. So, the sum of radiated power will add up to each one of its outputs. During peak times when all the channels are in usage, the sector which has most calls will be

highly exposed to EM radiation. Most antennas are 15–50 m tall. On a base station, there are many "omni-directional" antennas each pointing in a different direction. From these antennas, a rather narrow beam of signal is focused on the vertical plane to cover the target location. When assessing exposure to electromagnetic radiation, antenna gain, and transmission power levels are important considerations. Omni-directional antennas provide more strength on gain but with a higher exposure possibility compared to sector antennas, which offer much efficiency and coverage. The primary lobes contain the highest horizontal radiation. The strength of secondary lobe radiations ranges from medium to low. The radiation level drops as we move to the side lobes from the antenna's line of sight. The electromagnetic radiation from mobile towers is affected by the frequency, duration of exposure, and distance [27–30].

Radiation from mobile phones

Cell phones, due to their known thermal effects are designed to operate at power levels below threshold level; however, radiofrequency radiation may have additional consequences that are referred to as biological impacts. Every mobile phone comes with SAR ratings, despite attempts by certain manufacturers to hide them. Due to interference from neighboring structures like trees and buildings, a mobile phone's transmission strength may vary even within the same close area. The number of nearby base stations, distance between base station and phone and the volume of network activity are the main factors that influence how much radiofrequency radiation a mobile phone produces [31, 32].

Significant progress has been made in the technology of mobile phones throughout time, with each subsequent version offering faster data speeds, improved connectivity, and enhanced features. However, this evolutionary process has also led to changes in the levels of electromagnetic radiation (EMR) signals emitted by mobile phones. This paper presents a comprehensive analysis of many mobile phone technologies, including their electromagnetic radiation (EMR) emissions and the impact they have on human health.

2G (second generation)

1. Frequency range: 800 MHz to 1.9 GHz
2. EMR emissions: Lower power density, typically around 0.1–1.0 W/m²
3. Health impact: Lower risk of adverse health effects due to lower EMR emissions

Adopted in the 1990s, 2G technology employs analog signals for the transmission of voice and text messages. The electromagnetic radiation (EMR) emissions from 2G phones

are quite little, and the technology is regarded to be less detrimental in comparison with more recent generations [33].

3G (third generation)

1. Frequency range: 1.9 GHz to 2.6 GHz
2. EMR emissions: Moderate power density, typically around 1.0–10 W/m²
3. Health impact: Moderate risk of adverse health effects due to increased EMR emissions

With the advent of 3G technologies in the early 2000s, speech, text, and data are sent via digital signals. While 3G phones produce more electromagnetic radiation (EMR) than 2G phones, they remain very low when compared to subsequent models [34].

4G (fourth generation)

1. Frequency range: 2.6 GHz to 3.5 GHz
2. EMR emissions: Higher power density, typically around 10–100 W/m²
3. Health impact: Higher risk of adverse health effects due to increased EMR emissions

Introduced in the late 2000s, 4G technology employs digital signals for the transmission of high-speed data, phone, and video. The electromagnetic radiation (EMR) emissions from 4G phones surpass those from 2 and 3G phones, giving rise to worrying implications for possible health effects [35].

5G (fifth generation)

1. Frequency range: 24 GHz to 90 GHz (millimeter wave)
2. EMR emissions: Higher power density, typically around 100–1000 W/m²
3. Health impact: Higher risk of adverse health effects due to increased EMR emissions and new frequency range

5G technology, launched in 2019, utilizes millimeter wave frequencies for the transmission of high-speed data, audio, and video. The electromagnetic radiation (EMR) emissions emitted by 5G phones surpass those of 4G phones by a considerable margin. The introduction of the new frequency range gives rise to apprehensions over possible health consequences, such as heightened susceptibility to skin and eye complications [36].

Variations in health impacts

While the scientific community is still debating the potential health impacts of EMR emissions from mobile phones, some studies suggest that:

1. Higher frequency ranges (e.g., 5G) may be more harmful than lower frequency ranges (e.g., 2G)
2. Prolonged exposure to EMR emissions may increase the risk of adverse health effects
3. Children and adolescents may be more vulnerable to EMR emissions due to their developing brains and bodies
4. EMR emissions may interact with other environmental factors, for instance air pollution, to increase the risk of adverse health effects

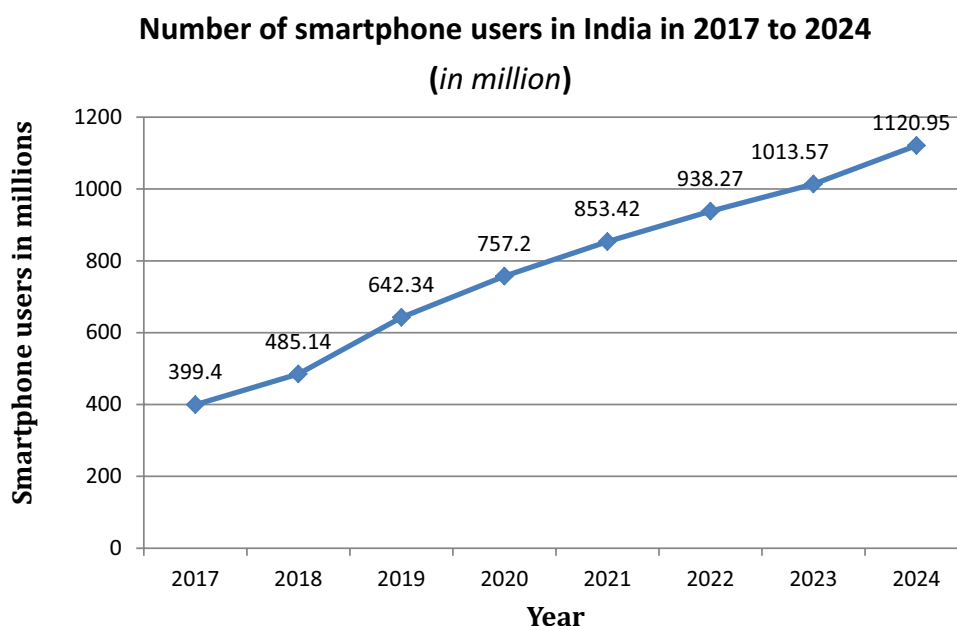
Importantly, the International Commission on Non-Ionizing Radiation Protection (ICNIRP) has developed standards to restrict the amount of exposure to electromagnetic radiation (EMR) emissions from mobile phones [37]. Nevertheless, other experts contend that these recommendations may not be enough in safeguarding public health, and further investigation is necessary to comprehensively explore the possible health consequences of EMR emissions from mobile phones [38].

India's mobile market sector

The Indian and worldwide telecom environments have seen a radical transformation because of the mobile industry. Mobile phones for their benefit and ease have become incredibly popular during the last 10 years. The telecom industry in India is currently one of the biggest and fastest-growing in the world [31]. By total phone users, India represents the second-largest telecom network in the world. According to GSMA and DataReportal, 1.12 billion individuals have their mobile phones in early 2025. The nation's fast-developing economy has benefited greatly from the telecom industry's extraordinary development in phone density and significant drop in different package pricing in India (Fig. 3).

In addition to making up around 6% of India's GDP, telecom and information technology (IT) have been vital in fostering the expansion of the social and economic sectors. The Indian mobile device market is predicted to grow from its anticipated US\$52.6 billion in 2025 to US\$89 billion in 2032. There are more than 150 manufacturers of devices in India, making the mobile industry there extremely competitive. India makes up over 12% of worldwide sales, making it a significant market for gadget makers [39].

Fig. 3 Graphical representation of Smartphone users in India from 2017 to 2024



India represents the second-largest internet user base with more than 1,000 million users, globally in 2023. Given how commonplace mobile phones, are the question of whether using them affects human health has inevitably come up. Scientists claim that radiation is detrimental in all forms, but that microwave frequencies, which are utilized in base station and mobile phone transmission, are more hazardous [40, 41].

Interaction of RF-EM radiation with the biological systems

The permeability of magnetic fields in tissues is the same as in air; therefore, fields identical to the external environment are generated in tissues. Humans and animals interact with magnetic fields according to Faraday's law, and electric fields are also caused by movement in a static field. Energy accumulation in tissues is affected by the wavelength and intensity of radiation, and objects absorb waves if their size corresponds to the wavelength. Infrared waves are absorbed by the skin, causing thermal stimulation [42].

Communication within and between cells is essential for biological processes. If low-frequency ion currents and optical wavelengths are used for signaling in biological systems, the possibilities of radiofrequency electromagnetic fields for communication are also explored [43]. The effects of radiation on biological systems are key areas of research, and studies show both positive and negative effects [37]. The absorption of RF-EMR energy in the human body, especially in the head and neck region, has received increasing attention, and several studies have investigated the interaction

between radio waves and biological systems at different levels [43].

RF-EMF waves interact with biological bodies by absorption, transmission, reflection, and propagation, resulting in the induction of electric and magnetic fields that can disturb the normal physiological balance. Factors affecting the magnitude of the interaction include frequencies, waveforms, exposure duration, and differential absorption rate. These physical variables affect biological tissues based on their properties, resulting in changes at the cellular and molecular levels. Exposure to strong RF radiation can cause energy to be absorbed and accumulated in biological molecules, which can cause changes in their chemical nature and affect normal physiological functions. RF-induced dipoles in water and other polar molecules can accumulate and cause polarity reversals in other biological molecules. These changes can have significant health effects, so more research is needed to understand and confirm the scientific evidence [44, 45].

Exploring the impact of electromagnetic fields on oxidative stress and tissue function

Free radicals are produced during oxygen-based reactions and can cause oxidative stress in tissues, leading to cellular damage and disease. Exposure to electromagnetic fields (EMF) may contribute to this process by generating reactive oxygen species (ROS) through the Fenton reaction and other mechanisms [46]. ROS can damage biomolecules, including DNA, and alter gene expression, leading to various diseases [47]. Some studies have linked EMF exposure to oxidative damage in proteins and lipids, as well as neurological

disorders like Alzheimer's disease, epilepsy and multiple sclerosis [48]. The disruption of the blood–brain barrier and increased accumulation of heavy metals in the brain may also contribute to these effects. Further insight is needed to fully understand the impact of EMF on human health and to identify potential risks and benefits of exposure.

Free radicals are highly reactive molecules that are generated as a by-product of the metabolic process when our bodies convert food into energy using oxygen. This oxidation reaction, which occurs on an oxygen basis, leads to the formation of free radicals. Given the critical role of oxygen in sustaining life, it is inevitable that free radicals will form. It is worth noting that various factors, such as ionizing and non-ionizing radiation, have the ability to impact the expression of certain genes, including JUN, HSP 70, and MYC. This is achieved through the activation of the epidermal growth factor receptor-Ras pathway, which ultimately leads to the production of reactive oxygen species (ROS) and an excessive accumulation of ROS in tissues. This process, known as the Fenton reaction, is a catalytic mechanism that transforms hydrogen peroxide, a by-product of mitochondrial oxidative respiration, into a potent and harmful hydroxyl free radical. Several studies have indicated that EMF may function as a catalyst for the Fenton

reaction, thereby potentially enhancing the generation of free radicals within cells. Some researchers have observed that while ROS can have positive effects, excess ROS production can result in cellular damage and contribute to various diseases. These radicals interact with a range of biomolecules, including DNA specifically, free radicals lack sufficient energy, causing them to act as thieves, stealing energy from other cells and depleting a person's resources to satisfy their own needs. Multiple studies have indicated that EMF has the potential to induce the generation of reactive oxygen species in cells, both in laboratory settings and in living organisms as reviewed by Kivrak et al. [47]. At the onset, the generation of ROS in the presence of RF is regulated by the NADPH oxidase enzyme situated in the plasma membrane. As a result, the activation of matrix metalloproteases by ROS triggers intracellular signaling cascades, which serve as a signal to the nucleus about the presence of external stimulation (Fig. 4). Observations of changes in transcription and protein expression have been made following RF exposure. Kazemi et al. [49] examined the impact of 900-MHz exposure in human mononuclear cells leading to oxidative stress and intracellular ROS levels. Excessive elevation in ROS levels can lead to significant oxidative damage in lipids, proteins, and nucleic acids. These changes in

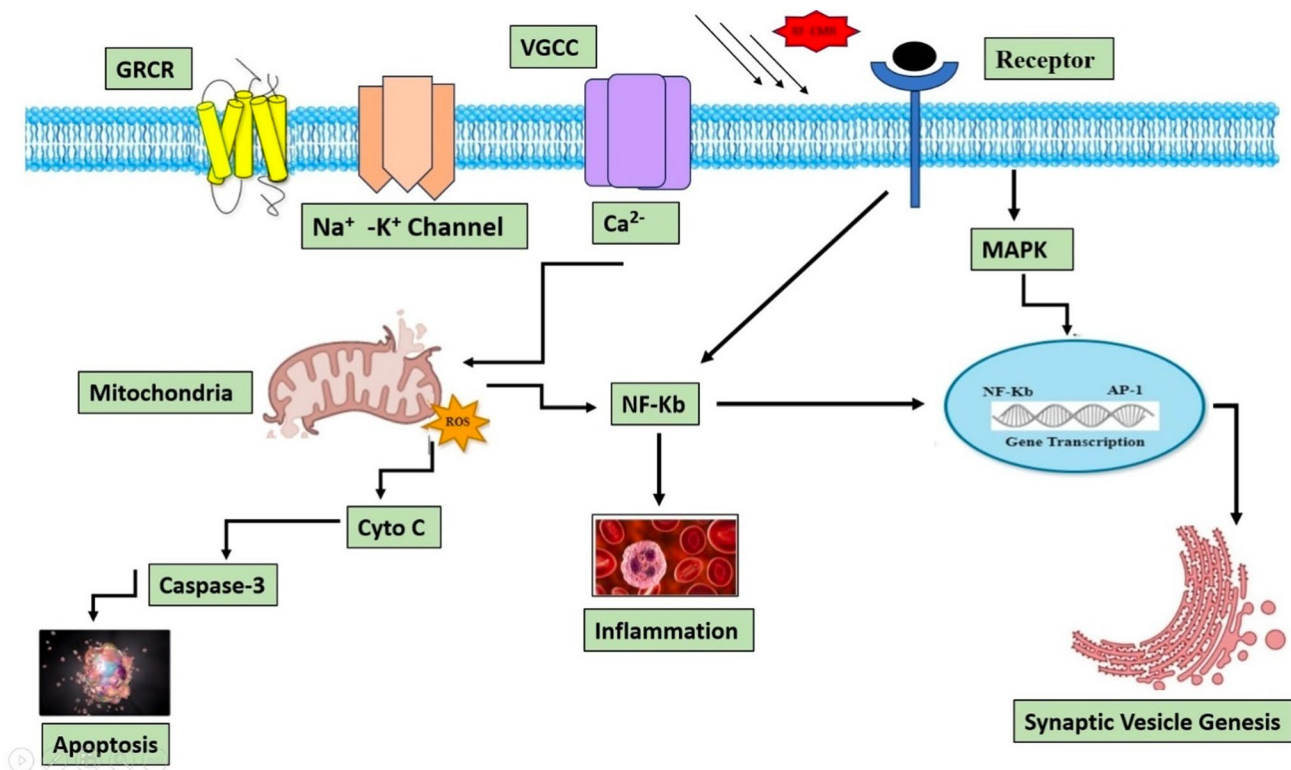


Fig. 4 RF-EMR interacts with biological systems affecting the levels of molecular ions, electrons, ROS, protein, and DNA/RNA. It causes cytotoxic effects in cells such as degeneration, apoptosis, and necrosis

and affects the central nervous system, reproductive, cardiovascular, and hematological systems

enzyme activity and gene expression can have far-reaching consequences, resulting in sleep disorder, atherosclerosis, dizziness, diabetes, and nausea, loss of appetite, rheumatoid arthritis, cardiovascular disease, and stroke. Furthermore, an unregulated rise in ROS can lead to lipid peroxidation, causing a disruption in the pro-oxidant-antioxidant balance. The rapid destruction of cell membranes occurs when components of phospholipids containing unsaturated fatty acids undergo oxidation, a process known as lipid peroxidation. This reaction leads to the accumulation of lipid peroxides ($-CO, H$) in the membrane, resulting in the formation of biologically active compounds from polyunsaturated fatty acids. As a result, lipid peroxidation causes extensive harm to the cells, including disruptions in membrane transport, structural alterations, and changes in cell membrane fluidity, impairment of protein receptors in membrane, and modifications in the activity of cell membrane enzymes. It was found that exposure to EMF resulted in a notable increase in lipid peroxidation in both mouse SH-SY5Y cells and L929 fibroblast cells [50]. Research has indicated that the oxidation of lipids in the walls of blood vessels could play a crucial role in the progression of atherosclerosis [51].

Research typically centers on the brain due to the proximity of cell phone usage to the head. Extensive research suggests that EMF has the potential to impact neural functions within the human brain. The connection between EMF and neurological disorders can be understood by examining the heat shock response. The heat shock protein (HSP) response is typically associated with heat shock, exposure to heavy metals, and environmental factors like EMF. In general, HSP serves as a marker in cells that are experiencing stress [47]. Living organisms produce stress proteins as a means of surviving environmental stressors. The heat shock response is considered a broad response to various stresses, including oxidative stress. This paper explores the effects of various environmental stimuli on humans and other mammals. Specifically, it investigates how ultraviolet radiation, ionizing radiation, and laser radiation can induce cellular stresses and lead to changes in Hsp 70 and Hsp90 levels. Non-ionizing radiations can lead to changes in HSP levels in different tissues, such as the brain, myocardium, testis, and skin. Research has discussed these findings as a process where cellular stress proteins adapt and readjust themselves in preparation for a significant environmental change [52]. This paper highlights the significant impact that small, temporary adjustments to circuits can have on overall stress tolerance [47].

There have been reports of low frequency (0–300 Hz) and RF (10 MHz to 300 GHz) EMF affecting the permeability across the blood–brain barrier. Additionally, the alterations in the blood–brain barrier can result in an excessive buildup of heavy metals, particularly iron, within the brain. This effect has the potential to contribute to the development of

various neuronal disorders. Several studies have found a correlation between DNA damage and blood–brain barrier disruption, as well as a link between EMF exposure and autism spectrum conditions [53]. There could be a potential link between infertility and reproduction caused by EMF/RFR and the rising prevalence of autism spectrum conditions.

Oxidative stress is a crucial factor in various biological processes, including DNA damage, gene expression, and cell apoptosis. The brain's high metabolic rate makes it more susceptible to damage from reactive oxygen species (ROS) and oxidative damage, in contrast to other organs. This paper discusses the harmful effects of excessive amounts of ROS in tissues, which can result in necrosis, neuronal damage, and various neurological disorders including multiple sclerosis, Alzheimer's disease, epilepsy and spinal cord injury. Multiple studies have documented the detrimental effects of EMF exposure on various areas of the brain, such as the cortex, basal ganglia, hippocampus, and cerebellum [47]. A study found a link between amyotrophic lateral sclerosis and exposure to high-intensity EMF, but did not find any connection with other neurodegenerative diseases [54]. It was observed that the intensity of headache pain showed a temporary increase during exposure, but promptly decreased once the exposure ended. There may be a potential connection between exposure to extremely low frequency (ELF)-EMF and amyotrophic lateral sclerosis, a devastating neurodegenerative disease [50]. Maskey et al. [55] examined the impact of 835-MHz exposure on the brain for varying durations. They found a noteworthy decrease in pyramidal cells within the CA1 region of the hippocampus [55]. The research done by Villeneuve et al. [56] revealed that those who were exposed to electromagnetic fields (EMF) had a 5.3-fold higher likelihood of getting glioblastoma, a form of brain cancer. However, there was no apparent increase in risk for other forms of brain malignancies.

Genetic polymorphism

Genetic expressions are derived from the Greek word "*genetikos*" meaning "genitive" which is derived from the word "*genesis*" meaning "descent." Genetic polymorphisms can result from random processes or external factors such as viruses or radiation. When multiple forms of a gene are expressed in at least 1 percent of a population, it is called genetic polymorphism, which varies between species and genomes and affects evolution and species survival [57]. By changing a single nucleotide base in a gene's coding sequence, genetic variants can alter the structure and function of proteins. Additionally, they may have an impact on transcription factor binding in the 5' promoter region of a gene or the stability of mRNA in the 3' untranslated region of a gene, which may boost or reduce gene expression.

However, a polymorphism may exist in regions of the DNA unrelated to the transcription or translation of genes and have no discernible effect on the production of proteins. Based on polymorphisms discovered at these sites as alterations in repeat sequences throughout the genome, genetic linkage analysis has been conducted [58, 59].

Genetic diversity, influenced by differences in actual population size, is crucial in influencing disease prognosis in human and animal behavior. Disease clinical phenotypes often have genetic components, and certain genetic variants are associated with human genetic diseases. Screening for these alleles can identify genetic predispositions to disease, while some polymorphisms affect the risk of certain traits. Polymorphisms within the gene can affect traits such as height and hair color and can affect disease susceptibility and response to treatment [4, 58].

Single nucleotide polymorphisms (SNPs)

Gene variations known as single nucleotide polymorphisms (SNPs) occur in the DNA, with each nucleotide denoting an allele of the SNP like when there is variation in a single nucleotide: adenine (A), thymine (T), cytosine (C), or guanine (G) in the genome sequences is changed. These variations can be non-synonymous (changing the sequence of an

amino acid) or synonymous (keeping the protein sequence unchanged) [60].

One of the most prevalent heritable variations, single nucleotide polymorphisms (SNPs) results from a change in a single nucleotide at a particular location within the genome. Transition, transversion, insertion, and deletion are examples of these base modifications [61] (Fig. 5). SNPs are single base pair locations in genomic DNA where in some population(s) there are different sequence alternatives present in normal individuals; the least frequent allele has an abundance of at least 1% or more. SNPs do not include single base insertion/deletion variants, or indels. The characteristics linked to SNPs, however, also apply to insertion and deletion [62] (Fig. 6).

Epidemiology

The foundation for this study and secondary data acquired from journals, research papers, textbooks, and articles are the survey and theory utilized to gather resolutions from the north Indian states of India. Different data were collected from various sources. Different states were chosen in all, taking into account variables such as the degree of exposure, public utility and accessibility, and separation from the mobile phone and towers. The duration of exposure to

Fig. 5 Impact of electromagnetic fields on oxidative stress and tissue function

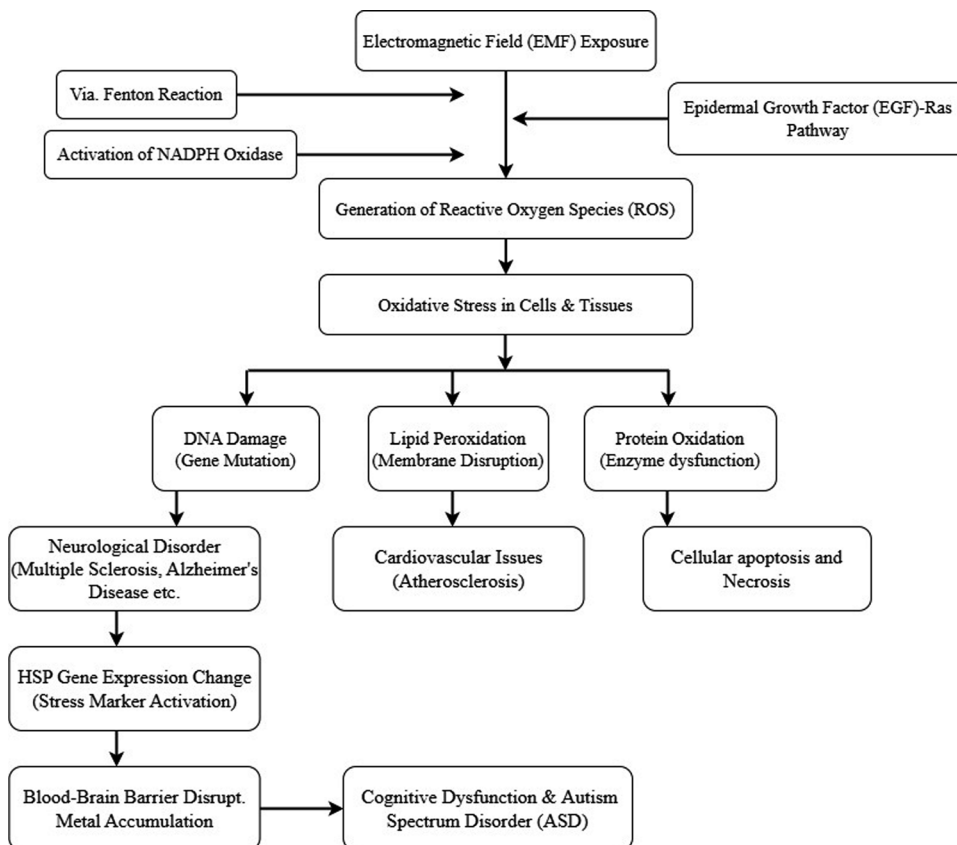
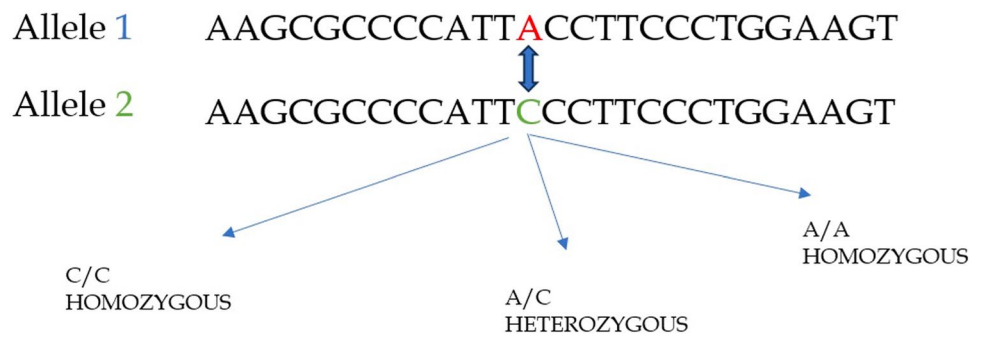


Fig. 6 Two alleles with a single nucleotide polymorphism

the public and sensitive locations scattered across the states, such as hospitals, offices, schools, and homes, have been taken into consideration while selecting the sites. Providing strong enough signals for mobile phones is the main purpose of cell towers [63]. Some of the carcinogenic diseases include leukemia, brain tumor and cardiovascular disease such as coronary heart disease, stroke, peripheral arterial disease, aortic disease, neurological diseases such as acute spinal cord injury, Parkinson, Alzheimer's disease, amyotrophic lateral sclerosis (ALS), cerebral aneurysm, epilepsy and seizures, and psychological disease like dissociative disorders, post-traumatic stress disorder, anxiety disorders, bipolar disorder, dissociative disorders, attention deficit hyperactivity disorder (ADHD), schizophrenia, obsessive–compulsive disorder (OCD), etc. [64–66].

Based on information gathered from various sources, including the ICMR, 14.6 lakh instances of cancer have been reported in India as of 2024, while 3 crore cases of neurological disorders, including Alzheimer's and Parkinson's, have been reported [67]. The World Health Organization (WHO) estimates that between 6 and 7 crore Indians suffer from both common and serious mental illnesses in 2024. The fact that India has more than 2.6 lakh suicide cases annually makes it the suicide capital of the globe, which is concerning [68].

Impact on human health

Exposure to low-level radiofrequency (RF) energy can cause a variety of health problems, including cancer, immunological disorders, neurological abnormalities, sleep disorders, and difficulty concentrating [69, 70]. The causal chain of RF exposure to death involves multiple steps, including the transduction mechanism, tissue heating, and molecular damage. Human health risks arise from the biological effects of RFR exposure on living organisms, including tissues, molecules, blood–brain barrier, DNA, nervous system, and psychological components [69–72].

On average, a person is exposed to RF-EMF radiation through cell phones and wireless networks depending on the usage of mobile phones and the proximity of mobile

towers. Children, elders, sick, and pregnant women are at greater risk. RF-EMF radiation can cause DNA single-strand breaks, and short-term exposure can cause DNA fragmentation. In addition, spontaneous abortion is a common complication of human pregnancy, with results that vary depending on the period of exposure. Recent epidemiological studies show that holding cell phones near the testicles negatively affects sperm concentration and the percentage of motile sperm [73–76].

Psychological and neurological effects

Globally, mental illnesses are common, impairing both mental and physical well-being and ultimately resulting in disability [77]. Anxiety, acute stress disorder, PTSD, depression, sleeplessness, and psychosis were the most common mental illnesses. Manic, hypomanic, or mixed periods, along with severe mood swings, are the hallmarks of bipolar disorder (BD) [78]. Addiction to the internet can impact both adults and children, especially with the advent of new games and touch screen gadgets. The negative outcomes of autism can include agitation, aggression, and social isolation. Electro-magnetic fields (EMR) can alter the structure and function of the nervous system because it is sensitive to them. Calcium ions have an impact on neurotransmitters, which are essential for synaptic transmission. This can interfere with regular neuronal communication, which may result in impaired synaptic transmission and general brain dysfunction [79–81].

Carcinogenic effect

Genetic differences in the human genome called single nucleotide polymorphisms (SNPs) have been connected to an increased risk of cancer. These SNPs are located in genes that control immunity, metabolism, cell cycle regulation, and DNA mismatch repair. These SNPs' locations have an impact on gene expression and cancer susceptibility. For example, children who live close to transformers or power lines are 60% times more likely to develop childhood leukemia. Men who carry their phones in standby mode in their pockets are more likely to develop testicular

cancer, while women who have kept them in their bras for ten years or longer are more likely to develop multifocal breast cancer. The *CYP3A4* polymorphism is linked to an increased risk of breast cancer and separates the general population into poor, normal, and rapid metabolizers [30, 82–84].

Effect on male fertility

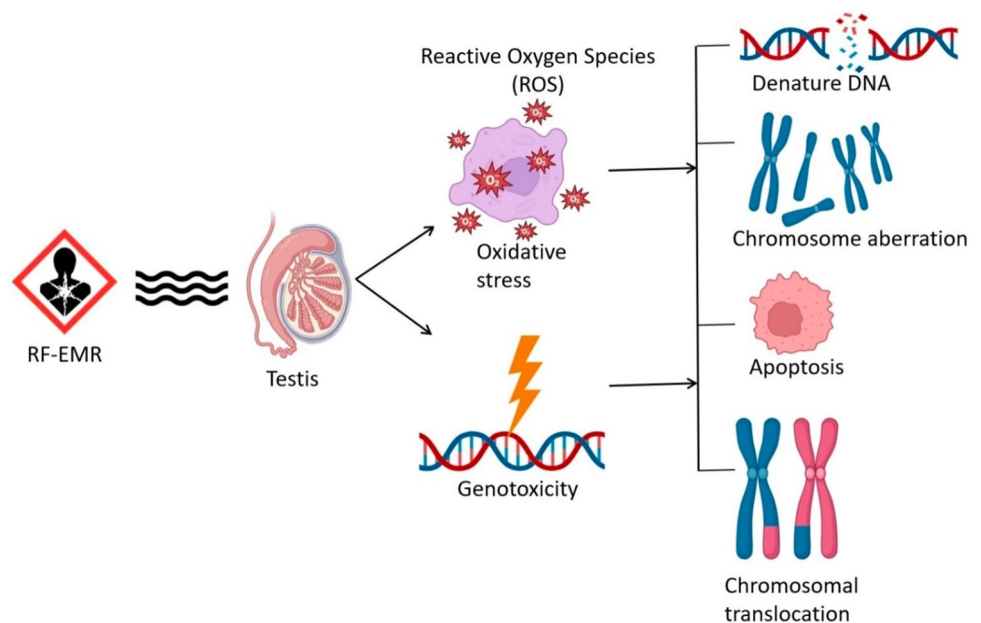
Genetic factors play a role in approximately 15% of male infertility cases, with chromosomal abnormalities and single gene mutations contributing to spermatogenic failure and sperm dysfunction. It is now known that estrogens, previously considered "female hormones," are produced in the male reproductive system and can affect testosterone production and sperm development. The Y chromosome contains an infertility-related spermatogenesis locus called azoospermia factor (AZF). Some researches indicate that the effects of estrogen on male reproduction may be related to oxidative DNA damage. There are concerns about the potential health risks of 5G wireless radiation, especially in already exposed environments [85, 86]. Further research is needed to understand the interaction between 5G technology and radiofrequency electromagnetic fields (RF-EMF) from other sources. Telecom companies should support comprehensive epidemiological studies to accurately measure exposure and reduce potential risks to human health. At the same time, the effects of RF-EMF exposure on male fertility hormones are also being studied to better understand the effects of electromagnetic radiation on reproductive health [71, 87] (Fig. 7).

Effects on children

Children are more susceptible to long-term exposure to radiofrequency radiation (RFR) from cell phones and wireless technology devices (WTDs) due to their rapid growth and developing nervous systems. Studies have shown that children absorb higher doses of radiation than adults when they hold cell phones to their heads, leading to concerns about potential cancer risks later in life. Studies have also linked prenatal cell phone exposure to behavioral problems and hyperactivity in children, while excessive screen time and lack of sleep are linked to cognitive impairment in children. In addition, studies have suggested a possible negative effect of RFR on cognitive function in young people. In addition, some researchers have shown that epigenetic factors and DNA damage have adverse effects of wireless devices on children's development. As children increasingly use cell phones and WTD devices, there is growing concern about the potential health risks and behavioral effects associated with long-term exposure to RFR radiation [19, 88].

An abnormal development of brain cells, whether malignant or not, is called a brain tumor. Malignant tumors are cancerous and lack defined limits, whereas benign tumors are less aggressive and have defined boundaries. When diagnosing brain tumors with medical imaging techniques like MR and CT scans, multiple segmentation approaches are also needed. Brain picture pre-processing, feature extraction, and classification are all part of the procedure. Skull masking, up scaling, and denoising are examples of pre-processing. While brain tumors may now be classified as benign or malignant, low grade or high grade, and normal or abnormal with great accuracy, it is still difficult to categorize tumors into different categories [89].

Fig. 7 Representation of how Rf Radiation affects the fertility of male



The metabolism of several substances, including solvents, is regulated by the glutathione S-transferase (*GST*) and Cytochrome P450(*CYP2E1*) genes, which may be relevant in the development of brain cancer. Adult brain tumors are poorly understood to have unclear etiology. Although some uncommon genetic abnormalities and high doses of ionizing radiation have been repeatedly linked to an elevated occurrence, these known risk factors only account for a small percentage of these diverse cancers. Enzymes that facilitate the stimulation and purification of a wide range of substances are encoded by the *GST* and *CYP* genes. Enzymes derived from *GST* genes, including theta (T), pi (P), and mu (M) *GSTs*, catalyze reactions involving molecules that have an electrophilic core and reduced glutathione. A functional gene product is absent due to polymorphisms in *GSTM1* and *GSTT1*. *CYP2E1*, a gene that metabolizes and activates solvents including benzene, styrene, carbon tetrachloride, ethylene glycol, and ethanol that also serve to promote its production, is another gene that has been linked to human brain cancers. Individuals who possess variable alleles for the *GST* and *CYP2E1* genes may exhibit variations in their capacity to metabolize carcinogenic substances, perhaps leading to a modified cancer risk [72, 90].

Radiation exposure, obesity, prior malignancies, family history, and chemical exposure are a few of the potential causes of brain tumors. Headaches, seizures, blurred vision, vomiting, behavioral abnormalities, memory loss, drooping eyelids, dizziness, loss of control over the bowels or bladder, changes in smell or hearing, and loss of consciousness are some of the symptoms of the condition. It is estimated that between 40,000 and 50,000 Indians receive a brain tumor diagnosis each year. Approximately twenty percent of these are kids [91] (Fig. 8).

Percentage of brain tumor and cancer according to Age

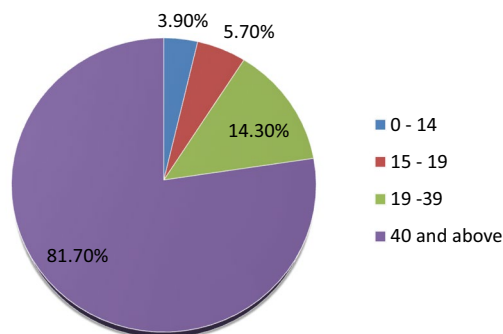


Fig. 8 Percentage of brain tumor and cancer according to age in India, 2023–2024

Wet lab-based methodologist for detection of polymorphisms

Our body's cells carry out several everyday tasks, such as producing energy and blood, which keeps us alive. Our first focus should be tending, but other approaches are needed when evaluating pharmaceuticals to prevent illnesses like cancer, dementia, aortic disease, Alzheimer's, Parkinson's, bipolar disorder, etc., in our cells and body. Among the noteworthy techniques are:

Biopsy

The standard of excellence for determining a cancer's grade and diagnosing it is a biopsy. The size, shape, and color of the tumor sample's cell nuclei are all examined during a biopsy. This increases the challenge of manually analyzing tiny biopsy images. Since the pathologist's knowledge and expertise determine the accuracy, computer-assisted technologies can aid in the interpretation of Digital Pathological Images (DPIs) and may yield greater outcomes than manual methods. For the study of a biopsy sample, hematoxylin and eosin (H&E) staining is the most often used technique. To understand the chemistry, structure, and function of cells, one uses cytopathology. To evaluate tissue proteins, immunofluorescence imaging is used [92, 93].

Restriction fragment length polymorphism

SNPs, such as SNPs that can eliminate a restriction site, can be detected by means of a restriction enzyme. In this case, in a particular position, certain molecules will carry a T–A nucleotide pair while others will carry a C–G pair at the same site within the restriction site for a restriction enzyme called EcoRI: 50-GAATTC-30. DNA molecules that possess T–A in the SNP are cleaved at both flanking sites and the middle site, thereby liberating two EcoRI restriction fragments. However, DNA molecules with C–G in the SNP have two flanking sites cleavage but not the middle site, thus leading to one larger restriction fragment. These can be detected via the Southern blotting procedure by looking for the restriction fragment length polymorphisms. In this experiment, the probe DNA is labeled and hybridizes adjacent to a restriction site, thus locating the position of the restriction fragment in an electrophoresis gel. The duplex 'allele A' contains the middle restriction site, whereas the duplex 'allele a' does not and yields a larger band. In such a cross, there are three genotypes produced- AA, Aa or aa. All of these genotypes harbor one copy of each allele in the heterozygous genotype Aa [1, 94–96].

DNA microarray chip

This hybridization genotyping technique allows several polymorphisms to be analyzed simultaneously. DNA microarray chip: It facilitates the production of high-density microarrays by attaching hundreds of thousands of oligonucleotides onto a silicon surface, arranged in an ordered array. The amplified DNA sample contains fluorescently labeled nucleotides and hybridizes to the chip array. Each oligonucleotide-an oligonucleotide is one short nucleic acid polymer in the high-density array is an allele-specific probe, making the fluorescent signals brighter over mismatched probe target combinations. Signals of hybridizations are quantitated by high-resolution fluorescent scanning and analyzed through computer software. This technology can identify DNA alterations, including heterozygous base-pair polymorphisms or mutations, insertions, and deletions. This view is realized in SNP, and the popularity accrues as a result of frequent DNA sequence variations found within the human genome. High-density SNP maps can expand genomic capabilities for the identification of critical disease genes and drug response genes in non-familial studies [97–99].

Heteroduplex analysis (HA)

Because of slight variations in electrophoretic mobility, heteroduplex DNA fragments with single nucleotide abnormalities may be distinguished from their homoduplex counterparts on non-denaturing "Hydrolink" gels. This approach is straight forward; however, it has an 80% detection rate and needs a unique gel matrix. Recent developments in capillary electrophoresis suggest that HA will become a more potent technique for SNP scanning [100–102].

Denaturing high-performance liquid chromatography (DHPLC)

The denaturation of high-performance liquid chromatography (DHPLC) is a heteroduplex analysis technique that analyzes DNA fragments without the need for electrophoresis by using modified resin and HPLC. With this technique, partial melting at high temperatures produces varying retention periods for mismatched heteroduplex DNA. Because of its reliable technology and auto-sampling, DHPLC is easy to use. With recent software advancements, it also boasts good sensitivity and repeatability. However, processing each sample individually is the reason for the system's low throughput [103–105].

Quantitative polymerase chain reaction (Q-PCR)

A valuable real-time technique for determining the amount of PCR products is quantitative polymerase chain reaction

(Q-PCR), which may be applied to the study of gene expression. Because of its versatility and lack of need for downstream analysis like electrophoresis or densitometry, it may be used to evaluate many PCR targets at once. Relative fluorescence units, which are graphical depictions of the PCR product accumulation over time, are used to display the results. The genotype of an individual may be determined using these units. The person is homozygous to the wild type if the initial probe's fluorophore wavelength is the only one observed. Should the wavelength of the second probe be the only one identified, the person is homozygous for the mutant allele. Both cellular beacons must be blending with their counterparts if both wavelengths are found, suggesting that the person [106, 107].

Comet assay

Another popular technique for identifying DNA damage and repair in cells and tissues is alkaline single-cell gel electrophoresis or comet test. Rather than extracting DNA, whole cells are examined using a form of electrophoresis. It can ascertain how much eukaryotic cells' DNA has fragmented [108, 109]. The assay's fundamental idea is that when an electric field is applied, cleaved and denatured DNA fragments can move out of the nucleoid, but intact DNA migrates more slowly and stays inside the nucleoid. Assessing DNA damage is possible by analyzing the shape and migratory pattern of the DNA "comet" tail. As part of the standard Comet test methodology, cells are first immobilized in a bed of low melting point agarose, and then they are gently lysed and treated with neutral or alkali solutions to denature and unwind DNA as well as hydrolyze damaged sites. After that, fluorescent DNA intercalating dye is used to stain the DNA and it is electrophoresed [110, 111].

Experimental procedures and statistical method EMR affect studies

Electromagnetic radiation (EMR) is a type of electromagnetic energy that is released by cell phone terminals during transmission. Cell phones commonly generate electromagnetic radiation (EMR) within the frequency range of 800 MHz to 2.6 GHz, which falls under the radiofrequency (RF) component of the electromagnetic spectrum. Radiofrequency (RF) energy is a type of non-ionizing radiation, meaning it lacks sufficient energy to directly disrupt chemical bonds or induce DNA damage. Nevertheless, there is apprehension that extended exposure to radiofrequency (RF) radiation may result in biological consequences, such as genome damage and genetic polymorphism [92, 93].

We performed an extensive literature search within prominent databases such as PubMed, Scopus, and Web

of Science to locate research that examined the impact of electromagnetic radiation (EMR) emitted by cell phone terminals on human DNA damage and genetic polymorphism. Only English-language papers with a well-defined methods and results section were included in our analysis. Excluded from consideration were papers that lacked peer review or failed to offer adequate details on the methodology and findings [95, 96].

Findings

A comprehensive literature search resulted in the identification of 50 papers that satisfied our inclusion criteria. Among them, 30 researches explored the impact of EMR on genetic damage, while 20 studies analyzed the influence of EMR on genetic polymorphism [92–103].

Genetic damage

To date, several studies have been conducted to determine if genetic damage occurs as a consequence of the effect of electromagnetic radiation that is emitted from cell phone terminals. The findings have been inconclusive in the relevant studies. There are some studies which demonstrated an increase in genetic damage, including DNA strand breaks and chromosomal abnormalities, following exposure to EMR emitted from cell phone terminals. Lai and Singh, 2004 conducted an experiment which revealed that exposure of human lymphocytes to radiofrequency (RF) radiation at the frequency of 2.45 GHz results in DNA strand breakage. Another study by Tice et al., reported that exposure of human cells to radiofrequency (RF) radiation with a frequency of 1.9 GHz causes a rise in chromosomal abnormalities [112]. Despite this, however, several studies have revealed no evidence of a significant rise in genetic damage as a result of exposure to EMR emitted from cell phone terminals.

Vijayalaxmi and Prihoda [113] conducted an investigation that no meaningful rise was observed in DNA strand breakage in human lymphocytes exposed to RF radiation at the frequency of 1.9 GHz. Hook et al. [114] also did not observe any meaningful rise in chromosomal abnormalities in human cells exposed to radiofrequency (RF) radiation at the frequency of 2.45 GHz.

Genetic polymorphism

Moreover, studies related to genetic polymorphism have not brought out conclusive findings. Different experiments have established that exposure to EMR correlates with the presence of genetic polymorphism. Yang et al. [115] conducted an experiment wherein the exposure of human cells to RF radiation at a frequency of 2.45 GHz was correlated with

the induction of genetic polymorphism. Liu et al. [116] in other research, established that there was a causal relationship between EMR exposure and variation in the human cell in the brain. However, the recent study could not find any substantial link between exposure to electromagnetic radiation (EMR) and genetic polymorphism. An experiment also finds that there is no significant correlation between exposure to radiofrequency (RF) radiation and genetic variation in human cells. In similar lines, Wang et al. [117] also found no significant association between exposure to electromagnetic radiation (EMR) and genetic variation in human brain cells.

Our review shows that although many studies suggest a possible link between EMR exposure and genetic damage, the evidence available is inconclusive. The controversial results could be due to differences in the study design, levels of exposure, and cell types used. How EMR specifically causes DNA damage is not well understood.

The health effects of these scientific discoveries are unknown. In any case, even genetic damage and genetic diversity may make one more susceptible to cancer and other diseases, and the current evidence is not considered sufficient to be confident that exposure to electromagnetic radiation (EMR) from mobile phone telecommunication terminals would pose a major risk to human health. It further brought forth the necessity for further research to understand the implications of EMR emitted by mobile phone terminals on human genetic damage as well as genetic polymorphism. Though some scientists have reported the possibility of electromagnetic radiation or EMR-induced genetic damage, evidence is not stringent, and further study is necessary for confirmation of these findings. More importantly, the mechanisms through which EMR could cause genetic damage are to be explained. As a priority area of study for the future, we would recommend that more attention should be given to research concerning DNA damage and genetic polymorphism by human cells under EMR exposures. Exposures should ideally be standardized and conducted with strict methods.

Conclusion

The growing reliance on mobile communication infrastructures in India has led to the widespread exposure to radiofrequency electromagnetic radiation (RF-EMR). Although classified as non-ionizing, prolonged or high-intensity exposure to RF-EMR may contribute to oxidative stress, DNA damage and alterations in gene expression. Emerging evidences also suggest a potential association with genetic polymorphism and neurodegenerative or reproductive disorders. However, inconsistencies in epidemiological and experimental findings highlights the need for more comprehensive, population specific

research in India to establish clear and causal links and inform public guidelines.

Future scope and further enhancement

Since genetic polymorphisms have been researched for years as significant biomarkers in the medical field as well as for work in pathology, epidemiology, pharmacology, clinical immunology, and ethnicity, they are major factors in inter-individual variation. Gene mutations are rare, although they are frequently known to result in an inherited disease. However, gene polymorphisms are not always associated with a specific disease. Personalized medicine has come a long way thanks to the research on genetic polymorphisms. Gene polymorphism affects the effectiveness of medications used to treat illnesses including depression, heart disease, blood clotting, cancer, etc. Both evaluating treatment results and medication safety benefit from the research of genetic variation. Knowing and identifying genetic variants in patients at an early stage might help choose the right chemotherapy drug at the right dose for the patient. A vital first step toward customized medicine is making an informed medication choice, which is greatly influenced by a patient's genetic profile and the way that different people respond to different medications.

Additionally, SNPs increase a patient's risk of developing specific malignancies; early detection of these polymorphisms can help tailor a treatment approach. Most medications now have a relatively low likelihood of reaching the targeted illness cells; nevertheless, future medicines for diseases could have a 100% cure rate. This is due to the possibility that medications with a targeting component may only have a fleeting interaction with the target before the body eliminates them.

Author contributions KP, MS, LH contributed to conceptualization and writing—original draft preparation; SJ, SG, AK contributed to supervision, formal analysis, writing—review and editing; RV, MR, SR contributed to editing review.

Declarations

Conflict of interest The authors declare no competing financial interests or personal relationships that may have appeared to influence the work reported within the paper.

Ethical approval and consent to participate Not applicable.

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