ISSN 2231-3478 (Print)
JUSPS-B Vol. 38(7), 85-97 (2026). Periodicity-Monthly
Section B
ISSN 2319-8052 (Online)

JOURNAL OF ULTRA SCIENTIST OF PHYSICAL SCIENCES
An International Open Free Access Peer Reviewed Research Journal of Physical Sciences
website:- www.ultrascientist.org
Estd. 1989

Biological Interactions and Health Implications of 5G Radiofrequency Electromagnetic Radiation: Review of Current Evidence

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DOI:- http://dx.doi.org/10.22147/jusps-B/380702

Acceptance Date 10th July 2026 Online Publication Date 18th July 2026

Abstract

The rapid development of fifth-generation (5G) wireless communication technology has increased data transmission speed, network capacity, and connectivity for modern digital systems. Unlike earlier mobile communication generations, 5G operates over a wider radiofrequency electromagnetic field (RF-EMF) spectrum, including sub-6 GHz frequencies and high-frequency millimeter waves. While 5G offers notable advantages, concerns have emerged about the potential biological and health effects linked to long-term RF-EMF exposure.

This review investigates the current scientific evidence on interaction mechanism of 5G radiation with biological systems and its potential health implications. Key interaction mechanisms discussed include thermal absorption, dielectric interaction, oxidative stress generation, ion-channel modulation, and possible genotoxic effects. Experimental studies have shown biological responses such as oxidative stress, neurological changes, reproductive effects, cellular damage, and superficial tissue heating after RF exposure. However, the findings are inconsistent, and many effects have not been clearly demonstrated in realistic exposure situations.

The review also analyzes epidemiological and experimental evidence regarding neurological disorders, reproductive toxicity, DNA damage, and cancer risk. While some lab and animal studies suggest possible biological effects, large-scale human studies are limited and often inconclusive. There are still significant research gaps, including a lack of long-term studies, inconsistent dosimetry, insufficient examination of vulnerable populations, and no standardized experimental protocols.

Overall, current scientific evidence does not definitively show severe adverse health effects from 5G radiation within recommended exposure limits. However, more multidisciplinary research is needed to clarify the long-term biological and health implications of 5G RF-EMF exposure.

Key words : 5G wireless communication, SAR, biological effects, RF radiation, millimeter wave.

1. Introduction

The rapid growth of wireless communication technologies has transformed modern society by allowing high-speed connectivity, real-time communication, and the integration of digital systems into daily life. Fifth-generation (5G) mobile communication technology marks a significant leap forward compared to earlier wireless network generations, offering much faster data transmission, reduced latency, greater network capacity, and better support for emerging technologies like the Internet of Things (IoT), autonomous vehicles, smart cities, and artificial intelligence systems. Unlike previous systems, 5G technology uses both standard sub-6 GHz frequencies and higher-frequency millimeter-wave (mmWave) bands that range roughly from 24 GHz to 100 GHz [11].

The rollout of 5G infrastructure has rapidly expanded across the globe due to rising demands for faster and more reliable communication systems. However, the introduction of dense antenna networks, beamforming technologies, and millimeter-wave frequencies has sparked significant scientific and public concern about the possible biological and health effects of radiofrequency electromagnetic field (RF-EMF) exposure. While RF radiation is non-ionizing and doesn't have enough energy to directly ionize biological molecules, some researchers propose that long-term or repeated exposure could lead to biological effects through both thermal and non-thermal mechanisms[18].

Research into the biological effects of electromagnetic radiation has been a topic of interest for decades. Previous generations of mobile communication technologies, such as 2G, 3G, and 4G, have been studied for their potential health impacts, including oxidative stress, neurological changes, reproductive effects, DNA damage, and cancer risk[17,33,30]. However, scientific findings remain inconsistent, with some studies showing harmful biological effects and others reporting little or no significant health risks under regulated exposure conditions.

The shift to 5G technology has intensified this debate because the exposure characteristics of 5G differ significantly from those of earlier wireless systems. Millimeter waves penetrate tissues only slightly and require a dense infrastructure of small-cell antennas throughout urban areas[22].

This review critically examines current scientific evidence regarding the biological and health effects of 5G mobile radiation. The article discusses how RF-EMF interacts with biological tissues, summarizes experimental and epidemiological findings, evaluates scientific uncertainties, and points out important research gaps that need further exploration.

2. Fundamentals of 5G Mobile Radiation :

5G communication systems use electromagnetic waves within the radiofrequency spectrum.

These systems are meant to provide better mobile broadband, ultra-reliable low-latency communication, and massive machine-type communication (Figure 1).

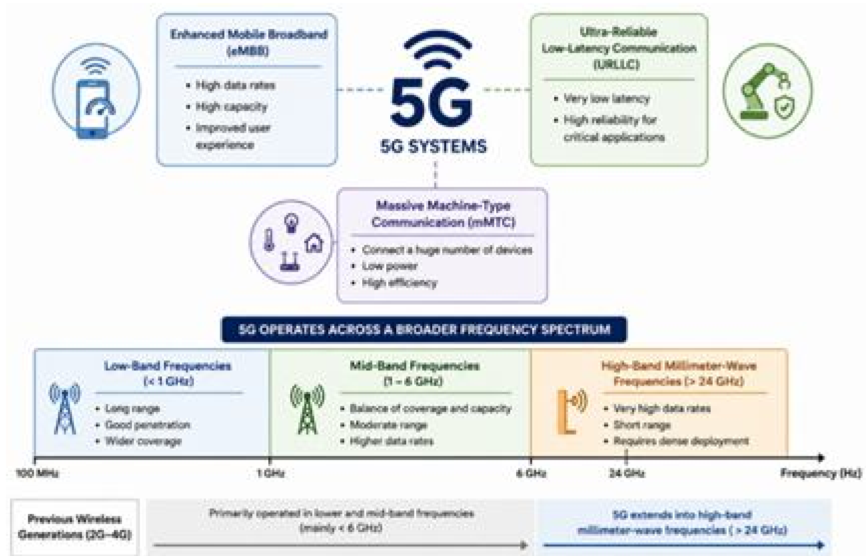

Figure 1. Overview of 5G Communication Systems and Frequency Spectrum

Compared to earlier wireless generations, 5G technology employs a wider frequency spectrum that includes low-band frequencies (<1 GHz), mid-band frequencies (1–6 GHz), and high-band millimeter-wave frequencies (>24 GHz).

Millimeter waves have shorter wavelengths and higher frequencies than traditional microwave frequencies. This allows for faster data transfer rates but reduces how far the signals can travel and how deeply they can penetrate. Therefore, 5G systems need a denser infrastructure with small-cell antennas spread across urban environments.

The way RF radiation interacts biologically depends on multiple physical factors, including frequency, power density, exposure duration, polarization, modulation pattern, and the dielectric properties of tissues[14].

The energy absorbed by biological tissues is measured using the Specific Absorption Rate (SAR), which is expressed in watts per kilogram (W/kg). The SAR relationship is expressed as:

$$SAR = \frac{\sigma E^2}{\rho}$$

where σ represents tissue conductivity, E is electric field strength, and ρ represents tissue density.

At lower RF frequencies, electromagnetic waves can penetrate relatively deeply into biological tissues. However, millimeter waves used in 5G systems mainly deposit energy in superficial tissues like the skin and cornea because of their limited penetration depth.

3. Mechanisms of Interaction Between 5G Radiation and Biological Tissues :

3.1. Thermal Mechanisms :

Thermal interaction is the most understood way that RF radiation affects biological tissues. When electromagnetic energy is absorbed by tissues, some of that energy turns into heat. Excessive heating in tissues can change cellular function, enzyme activity, membrane permeability, and protein structure.

How much RF energy is absorbed and the thermal effects in biological tissues depend on the dielectric properties of the tissue, which include water content, electrical conductivity, exposure frequency, and the strength of the electric field[2,30]. Highly hydrated tissues like muscle absorb RF energy more effectively than fat tissues. Thermal effects are especially significant for tissues with limited heat dissipation, like the eyes and testes[18].

Millimeter-wave exposure primarily impacts superficial tissues because penetration depth reduces with increasing frequency. This relationship can be described as (Gandhi & Riazi, 1986; Gabriel et al., 1996):

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$

Where δ is penetration depth, ω is angular frequency, μ is magnetic permeability, and σ is electrical conductivity. This equation shows that higher-frequency millimeter waves penetrate less deeply into tissues.

3.2. Dielectric Interaction and Molecular Oscillation :

Biological tissues contain water molecules, ions, and charged biomolecules that have dielectric properties. Alternating electromagnetic fields cause these charged particles and dipoles to continuously oscillate, resulting in molecular rotation, ionic displacement, dielectric polarization, and energy loss (Gabriel et al., 1996; Foster & Schwan, 1989). Water molecules are particularly important because they are highly polar, and the oscillation of water dipoles significantly contributes to microwave absorption and tissue heating (Gandhi & Riazi, 1986). Differences in dielectric properties among tissues explain why various organs absorb electromagnetic energy differently (Gabriel et al., 1996).

3.3. Oxidative Stress Mechanism :

One of the most commonly suggested non-thermal mechanisms is the induction of oxidative stress. Multiple studies indicate that RF radiation exposure may raise levels of reactive oxygen species

(ROS), leading to cellular oxidative imbalance. Increased ROS production may cause lipid peroxidation, mitochondrial dysfunction, protein oxidation, DNA damage, and inflammation. The formation of superoxide radicals can be represented as:

$$O_2 + e^- \rightarrow O_2^{-\cdot}$$

Kesari and Behari[16] reported higher oxidative stress markers in rat brain tissue after microwave exposure. Kumar *et al*.[23] also found oxidative stress-related reproductive changes in animal models. Oxidative stress remains one of the most discussed mechanisms as it may indirectly clarify several reported biological effects linked to RF exposure.

3.4. Membrane and Ion Channel Effects :

Cell membranes hold voltage-gated ion channels responsible for managing electrical and biochemical signals. Some researchers suggest that electromagnetic fields may affect membrane permeability and the activity of ion channels, especially voltage-gated calcium channels.

According to Pall[27], RF-EMFs can activate voltage-gated calcium channels, leading to higher intracellular calcium levels. Increased calcium can stimulate nitric oxide production, oxidative stress pathways, and altered neurotransmitter release. Possible consequences include neuronal hyperactivity, changed synaptic signaling, enzyme activation, and cellular stress responses.

3.5. DNA and Chromatin Interaction :

Although RF radiation does not possess enough energy to directly break chemical bonds, indirect genotoxic mechanisms have been proposed. These mechanisms include oxidative DNA damage, changes in chromatin structure, impaired DNA repair, and altered gene expression.

Shckorbatov *et al.*[29] found structural changes in chromatin in exposed cells, while Hintzsche *et al*.[12] did not observe notable genomic damage under terahertz exposure. Because experimental results are inconsistent, the direct genotoxic potential of 5G radiation remains disputed.

4. Scientific Evidence on Health Effects of 5G Radiation :

4.1. Oxidative Stress and Cellular Damage :

Many experimental studies have looked into oxidative stress responses following RF exposure. Several investigations noted increased ROS levels and antioxidant imbalances in exposed tissues.

Kesari and Behari[16] found oxidative stress in rat brain tissue after microwave exposure. Kumar *et al*.[23] reported reproductive oxidative damage in male rats exposed to microwave radiation. Kostoff *et al*.[18] suggested that current lab studies may downplay biological effects because they often do not match real-world exposure conditions involving multiple environmental stressors. Sousouri *et al.*[31] showed that 3.6 GHz 5G modulates NREM sleep spindle frequency exclusively in CACNA1C

T/C genotype carriers, implicating voltage-gated calcium channels. Michelant *et al*.[25] found no EEG changes under 26 GHz mmWave exposure in 31 healthy adults, confirming neurological safety at mmWave frequencies under ICNIRP limits.

However, despite many positive findings, inconsistencies in exposure methodology, frequency selection, and dosimetry limit the ability to establish definitive causal relationships.

4.2. Neurological Effects :

The nervous system is one of the most sensitive biological targets of electromagnetic exposure. Proposed neurological effects include neurotransmitter imbalance, changes in neuronal activity, sleep issues, behavioral shifts, and disruption of the blood-brain barrier[16,27,18,32]. Several animal studies have reported changes in electrical activity and biochemistry after prolonged RF exposure[16,23]. However, large-scale studies involving humans have not consistently shown strong links between cellphone use and neurological diseases[30,2]. The differences between lab findings and human studies are an important topic of scientific debate.

Table 1. Reported Biological Effects Associated with RF-EMF and 5G Radiation

Biological System	Reported Effects	Proposed Mechanism	Evidence Status	Key References
Nervous system	Neurotransmitter alteration, behavioral changes, oxidative stress, sleep disturbances	ROS generation, calcium signaling disruption, membrane interaction	Inconclusive	Kesari & Behari (2009); Pall (2013); Kostoff *et al*. (2020); Sousouri *et al.* (2025); Michelant *et al*. (2026)
Skin	Tissue heating, irritation, membrane permeability changes	Superficial millimeter-wave absorption and dielectric heating	Moderate evidence for thermal effects	Simkó & Mattsson (2019); Dabouis *et al.* (2016)
Eyes	Corneal heating, cataract concerns	Thermal accumulation in poorly vascularized tissues	Limited evidence	Simkó & Mattsson (2019); Kostoff *et al.* (2020); Adekola *et al.* (2025)
Reproductive system	Reduced sperm motility, oxidative stress, hormonal changes	DNA fragmentation, oxidative stress, mitochondrial dysfunction	Mixed evidence	Kumar *et al*. (2010); Kesari & Behari (2009)

Cellular DNA	Chromatin alteration, possible DNA strand effects, altered gene expression	Oxidative stress pathways and chromatin interaction	Contro-versial	Shckorbatov *et al.* (2009); Hintzsche *et al.* (2012); De Amicis *et al*. (2015); Kalantaryan *et al*. (2010)
Cardiovascular system	Changes in heart rate variability and autonomic regulation	Electromagnetic interaction with autonomic nervous system	Weak evidence	Kostoff *et al*. (2020)
Immune system	Inflammatory responses and altered immune signaling	Oxidative imbalance and cellular stress pathways	Preliminary evidence	Simkó & Mattsson (2019); Kostoff *et al.* (2020)
Cellular membrane and ion channels	Altered membrane permeability and calcium channel activation	Voltage-gated calcium channel stimulation	Moderate experimental evidence	Pall (2013); D'Agostino *et al.* (2018)
Genotoxicity and stress response	Stress protein induction and cellular response alterations	Non-thermal cellular stress mechanisms	Inconsistent evidence	Koyama *et al.* (2016); Franchini *et al.* (2018)

4.3. Reproductive Effects :

Research on reproductive health effects has found reduced sperm motility, changes in sperm shape, oxidative stress in reproductive tissues, and hormone disturbances (Adams et al., 2014). Kesari and Behari[16] and Kumar *et al*.[23] also noted reproductive changes in animal models exposed to microwave radiation. Possible mechanisms include oxidative stress, mitochondrial dysfunction, and DNA damage. However, the current evidence is inconsistent and not enough to confirm reproductive toxicity in humans.

4.4. Skin and Ocular Effects :

Millimeter waves mainly affect superficial tissues, making the skin and eyes primary targets of 5G exposure. Potential effects include localized heating, changes in membrane permeability, inflammation, and corneal heating[30,18]. Adekola *et al*.[1] reported corneal penetration of 4–7 μm and full attenuation at dental enamel at 24–45 GHz. Some researchers suggest that human sweat ducts may act as helical antennas that interact with millimeter-wave radiation, possibly affecting how electromagnetic energy is absorbed in the skin[8,10,30]. However, these ideas need more experimental support. Most of the reported skin and eye effects occur at exposure levels much higher than current public safety limits.

4.5. Genotoxicity and DNA Damage :

Several studies have looked into whether RF radiation can cause DNA damage or changes in chromosomes. Shckorbatov *et al*.[29] noted changes in chromatin related to microwave exposure, while De Amicis *et al*. (2015) found cellular changes after terahertz radiation exposure. In contrast, Hintzsche *et al*. [12] did not find significant genomic damage in controlled experiments. Currently, the scientific evidence on the genotoxicity of cellphone radiation is inconclusive.

4.6. Cancer and Carcinogenicity :

The International Agency for Research on Cancer (IARC) classified RF electromagnetic fields as "possibly carcinogenic to humans" (Group 2B) in 2011. Some animal studies reported more tumors after high-level RF exposure (National Toxicology Program, 2018; Falcioni et al., 2018). Epidemiological studies looking at long-term mobile phone use and brain tumors have produced mixed results (Interphone Study Group, 2010; Hardell & Carlberg, 2015; Röösli et al., 2019). (Mevissen et al., 2025,) reviewed 52 animal studies and found high-certainty evidence linking RF radiation to brain gliomas and cardiac schwannomas—tumor types mirroring human epidemiology. However, current evidence is not enough to confirm a clear link between 5G radiation and cancer development.

5. Research Gaps and Limitations :

Despite extensive research on the biological and health effects of radiofrequency electromagnetic fields (RF-EMFs), several uncertainties and limitations persist. One major limitation is the lack of long-term studies specifically focused on 5G exposure, as the large-scale rollout of 5G technology is relatively new. Most available evidence comes from earlier wireless communication technologies like 2G, 3G, and 4G, which differ significantly from 5G networks. Moreover, few experimental studies have examined millimeter-wave exposure conditions that truly represent actual 5G environments, especially regarding beamforming technologies and dense small-cell setups.

Another challenge is the inconsistency in exposure methods and dosage across studies. Differences in frequency, power, modulation patterns, exposure duration, distance from the source, and biological model selection make comparing results difficult. In many instances, poor dosimetric characterization reduces the reliability of reported biological effects. Additionally, the non-thermal mechanisms of RF interactions with biological tissues are still not well understood. While oxidative stress, calcium channel activation, membrane disruption, and altered cell signaling have been suggested as possible mechanisms, experimental evidence is inconsistent and debated.

Current research has also not sufficiently explored the impact of combined environmental stressors. In real life, human exposure occurs alongside multiple physical, chemical, and psychological stress factors, yet many lab studies only examine RF radiation in isolation under controlled conditions. This gap may limit the relevance of laboratory findings to real exposure situations. Furthermore, the lack of standardized experimental protocols across labs contributes to conflicting results and challenges in interpreting scientific data.

Another significant limitation is the relatively few studies on vulnerable populations, such as children, adolescents, pregnant women, and those with existing medical conditions. Children may absorb RF radiation differently due to their developing tissues, thinner skulls, and longer total exposure time. However, there is not enough long-term research on pediatric exposure. Finally, the rapid development of wireless communication technologies poses ongoing challenges for scientific evaluation. Constant changes in antenna design, modulation techniques, carrier frequencies, and network architecture make it hard for long-term health studies to keep up. Therefore, there is a clear need for more thorough, multidisciplinary research that uses standardized methods, realistic exposure scenarios, long-term monitoring, and advanced dosimetric analyses to better understand the potential health impacts of 5G radiation exposure.

6. Conclusion

5G mobile communication technology marks a significant step forward in wireless connectivity and digital infrastructure. However, concerns about the possible biological and health effects of RF-EMF exposure continue to spark considerable scientific discussion. Current evidence shows that RF radiation can interact with biological tissues through both thermal and proposed non-thermal mechanisms, including oxidative stress, membrane interactions, ion channel changes, and dielectric heating. Experimental studies have reported oxidative stress, reproductive changes, neurological alterations, and cellular responses under certain exposure conditions. However, epidemiological evidence remains mixed, and many biological effects reported lack reliability.

Most well-established effects of RF radiation are thermal, while non-thermal effects are still debated and not fully understood. Existing global safety guidelines mainly aim to prevent harmful thermal exposure, although uncertainties exist regarding long-term low-level exposure and chronic millimeter-wave exposure. Overall, the current evidence does not conclusively show that 5G radiation leads to serious health issues under regulated exposure conditions. However, significant research gaps remain, underscoring the need for rigorous long-term multidisciplinary studies that focus on realistic exposure environments and standardized methods.

7. Scope for Future Research :

Although considerable research has been conducted on the biological effects of radiofrequency electromagnetic fields, several questions regarding the health implications of 5G technology remain unanswered. Since 5G has only recently been deployed on a large scale, there is a clear need for long-term epidemiological studies to evaluate the possible health effects associated with prolonged exposure under everyday conditions. Much of the available evidence is based on previous generations of wireless technology, making it difficult to directly extrapolate those findings to 5G networks. Future experimental studies should better replicate realistic exposure scenarios by incorporating features unique to 5G, such as millimeter-wave frequencies, beamforming, and dense small-cell deployments.

Standardized exposure protocols and improved dosimetric techniques would also help reduce variability among studies and improve the reliability of reported findings.

Further research is needed to better understand the biological mechanisms underlying RF-EMF interactions. In addition, greater attention should be given to vulnerable populations, including children, pregnant women, and older adults, who may respond differently to RF exposure. Investigating the combined influence of RF-EMFs with other environmental stressors would also provide a more realistic assessment of potential health risks. Continued collaboration among researchers from physics, biology, medicine, engineering, and public health will be essential for generating robust scientific evidence and supporting the development of future evidence-based safety guidelines.

Funding
This research received no external funding.

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