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Review Article

Health Implications of 5G Radiofrequency Exposure on Respiratory Diseases: A Comprehensive Review

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Abstract:
The rapid advancement of fifth-generation (5G) wireless communication technology has significantly enhanced global connectivity, enabling faster data transmission, low latency communication, and the expansion of digital infrastructure. Despite these technological benefits, increasing concerns have been raised regarding the potential health effects associated with prolonged exposure to *radiofrequency electromagnetic fields (RF-EMFs)* generated by wireless communication systems. This review aims to summarize current scientific evidence on the possible health implications of 5G radiofrequency exposure on respiratory diseases and to discuss the biological mechanisms that may be involved. Radiofrequency radiation used in wireless communication belongs to the non-ionizing region of the electromagnetic spectrum and does not possess sufficient energy to directly damage DNA or ionize biological molecules. However, several experimental studies have suggested that RF-EMF exposure may influence important cellular processes, including *oxidative stress*, redox signaling, and inflammatory responses. Increased production of *reactive oxygen species (ROS)* and alterations in antioxidant defense mechanisms have been observed in both in vitro and in vivo studies, indicating potential oxidative damage at the cellular level. These biological changes may contribute to mitochondrial dysfunction, tissue injury, and activation of inflammatory pathways associated with respiratory disorders such as asthma, *chronic obstructive pulmonary disease (COPD)*, and *pulmonary inflammation*. Nevertheless, the overall scientific evidence remains inconsistent due to variations in exposure conditions, experimental models, and study methodologies. Therefore, further well-designed experimental, epidemiological, and mechanistic studies are necessary to better understand the relationship between RF-EMF exposure and respiratory health outcomes.

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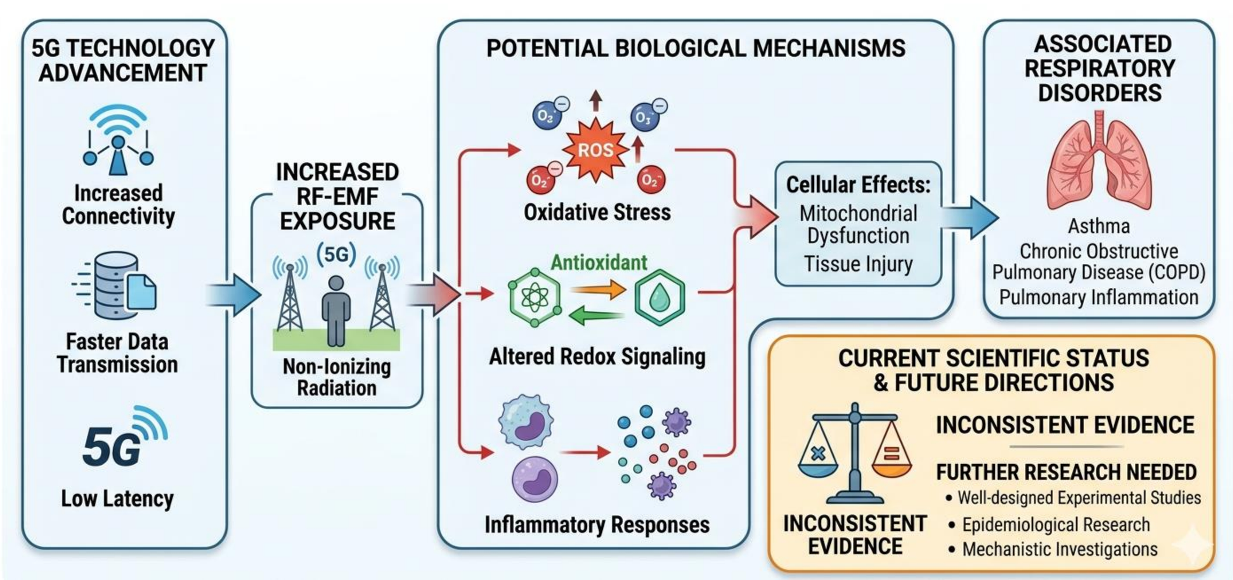
Graphical Abstract



1. Introduction

The rapid evolution of wireless communication technologies has significantly transformed modern society by enabling faster connectivity, improved data transmission, and widespread digital integration (1–3). As wireless communication technologies have progressively evolved to meet increasing demands for speed, connectivity, and data capacity, the emergence of fifth-generation (5G) technology represents a significant advancement that builds upon and extends the capabilities of earlier network generations. Among these technological advancements, fifth-generation (5G) wireless communication represents a major milestone in telecommunications (4). 5G technology offers enhanced network capacity, ultra-low latency, and higher data transfer rates compared with previous generations such as 3G and 4G (5,6). These advantages have facilitated the expansion of applications including smart cities, telemedicine, autonomous vehicles, and the Internet of Things (IoT). However, the deployment of 5G infrastructure has also raised concerns regarding potential health effects associated with increased exposure to (RF-EMFs) (7–9). Radiofrequency radiation used in wireless communication systems operates within the non-ionizing portion of the electromagnetic spectrum (10,11). Unlike ionizing radiation such as X-rays or gamma rays, RF radiation does not possess sufficient energy to directly break chemical bonds or ionize biological molecules (12,13). Nevertheless, continuous and long-term exposure to RF-EMFs generated from mobile phones, base stations, routers, and other wireless devices has led to growing scientific interest regarding its potential biological effects. With the introduction of 5G technology, the frequency range has expanded to include both sub-6 GHz bands and higher millimeter-wave frequencies, which may alter exposure patterns and biological interactions (10,12,13). Beyond technological advancements, it is equally important to consider the potential biological and health implications associated with increased RF-EMF exposure.

One area of increasing attention is the potential impact of radiofrequency exposure on the respiratory system. The respiratory tract is highly sensitive to environmental stimuli, including pollutants, allergens, and electromagnetic radiation (14–16). Respiratory diseases, such as asthma, chronic obstructive pulmonary disease (COPD), pulmonary inflammation, and allergic airway disorders, represent major global health challenges. According to global health statistics, respiratory diseases significantly contribute to morbidity and mortality worldwide. Therefore, understanding the environmental factors that may influence respiratory health is essential (17–19).

Emerging experimental and epidemiological studies have suggested that RF-EMF exposure may influence biological processes, such as oxidative stress, inflammatory responses, cellular signaling pathways, and immune modulation (20–23). These biological mechanisms are closely associated with the pathophysiology of several respiratory disorders. Some in vitro and in vivo studies have reported that RF radiation can induce reactive oxygen species (ROS) production, alter gene expression, and affect cellular membrane permeability. These effects may contribute to airway inflammation, epithelial damage, or altered pulmonary function under certain exposure conditions (24,25). Furthermore, the densification of 5G networks requires the installation of a larger number of small-cell base stations in urban environments, which could lead to changes in population exposure patterns. Although international regulatory bodies, including the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and the World Health Organization (WHO), have established exposure guidelines to ensure safety, ongoing scientific evaluation is necessary to assess possible long-term health implications (26–28). In this context, understanding the underlying biological mechanisms is essential for evaluating potential health risks.

Despite increasing public concern, the available scientific evidence regarding the relationship between 5G radiofrequency exposure and respiratory diseases remains limited and inconsistent. Many existing studies focus primarily on neurological, reproductive, and carcinogenic outcomes, whereas comparatively fewer investigations address respiratory health effects. Therefore, a comprehensive and updated review of current research findings is essential to better understand the potential association between RF exposure and respiratory system alterations (29,30). Despite these emerging findings, significant gaps and inconsistencies remain in the current evidence.

This review aims to summarize recent scientific evidence regarding the health implications of 5G radiofrequency exposure in respiratory diseases. This highlights possible biological mechanisms, experimental findings, epidemiological evidence, and existing safety guidelines. By critically evaluating the current literature, this review seeks to provide a clearer understanding of the potential risks and identify research gaps that require further investigation. In light of these considerations, the following section discusses the role of RF-EMF exposure in inducing oxidative stress, which is a key mechanism underlying potential respiratory health effects.

2. RF-EMF Exposure and Oxidative Stress

Radiofrequency electromagnetic fields (RF-EMFs) generated from wireless communication technologies, including emerging 5G networks, have been widely investigated for their potential biological effects (Table 1) and (Figure 1). One of the most frequently proposed mechanisms underlying RF-EMF-induced health effects is oxidative stress, which results from an imbalance between ROS production and the antioxidant defense system. Oxidative stress is strongly associated with the pathogenesis of several respiratory disorders such as asthma, chronic obstructive pulmonary disease (COPD), pulmonary inflammation, and lung tissue damage. Experimental evidence suggests that RF-EMF exposure may influence cellular redox balance by increasing ROS production, altering antioxidant enzyme activity, and modifying oxidative stress biomarkers. A recent systematic review evaluating experimental in vivo and in vitro studies on RF-EMF exposure reported that several studies detected changes in oxidative stress markers, including lipid peroxidation products, oxidized DNA bases, and modified proteins following RF-EMF exposure. However, the magnitude and direction of the effects varied across studies, indicating that the overall certainty of evidence remains low due to heterogeneity in exposure conditions, frequency ranges, and biological models. Furthermore, RF-EMF exposure has been associated with mitochondrial dysfunction and altered cellular metabolism, which can enhance ROS generation. Increased ROS levels may trigger inflammatory signaling pathways, resulting in tissue damage and impaired respiratory function. Experimental studies have also demonstrated that electromagnetic field exposure can significantly influence antioxidant biomarkers and oxidative stress markers in biological tissues (31).

As oxidative stress plays a critical role in airway inflammation and lung injury, understanding the relationship between RF-EMF exposure and oxidative damage is essential for evaluating the potential respiratory health risks associated with modern wireless technologies (32). Building on the role of oxidative stress, the next section explores how RF radiation contributes to cellular oxidative damage at the molecular level in humans.

Table 1. Reported effects of RF-EMF exposure on oxidative stress biomarkers.

Experimental Model	Frequency / Exposure	Oxidative Stress Biomarkers Evaluated	Key Findings	References
Systematic review of in vitro and in vivo studies	100 kHz – 300 GHz RF-EMF exposure	Oxidized DNA bases, lipid peroxidation products, modified proteins	Evidence of oxidative stress was inconsistent across studies; heterogeneity in exposure conditions influenced results	(33)
Animal models and cultured cells	Various RF frequencies (mobile communication range)	ROS, antioxidant enzymes	RF-EMF exposure may increase ROS generation and disturb antioxidant defense systems	(34)
Experimental animal and cellular studies	Electromagnetic radiation exposure	Lipid peroxidation markers, SOD, CAT, glutathione	EMF exposure altered antioxidant enzyme activities and increased oxidative damage indicators	(35)
Meta-analysis of experimental studies	Low-intensity RF radiation	ROS levels, oxidative DNA damage	Majority of analyzed studies reported increased ROS production after RF exposure	(36)

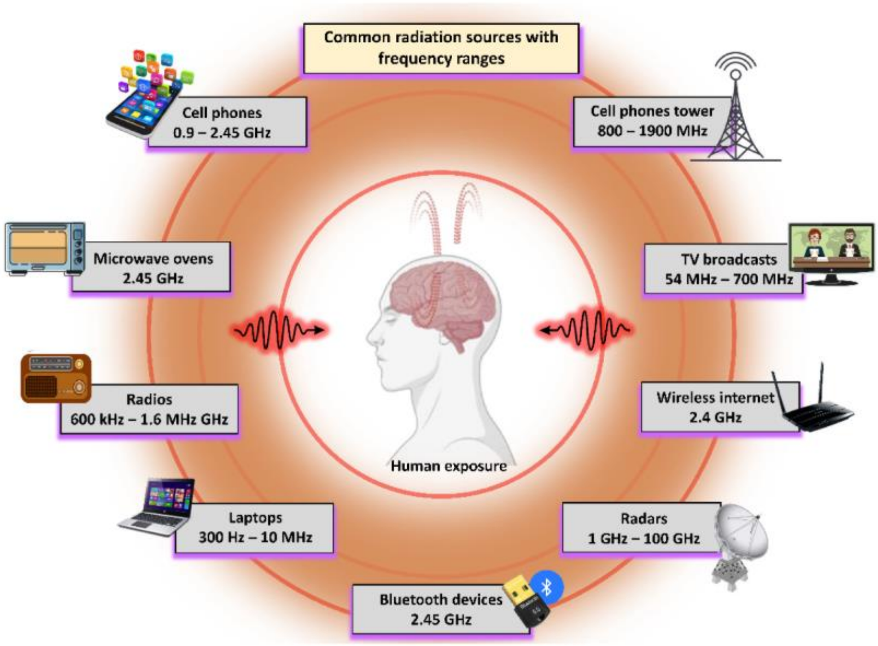


Figure 1. Biological effects of RF-EMF exposure on cells

3. RF Radiation and Cellular Oxidative Damage

Radiofrequency (RF) radiation emitted from wireless communication devices can influence cellular biochemical processes, particularly through the generation of. ROS are highly reactive oxygen-containing molecules, such as superoxide radicals, hydroxyl radicals, and hydrogen peroxide, which are normally produced during cellular metabolism. When ROS production exceeds the antioxidant defense capacity of cells, **oxidative stress occurs**, leading to damage to lipids, proteins, and deoxyribonucleic acid (DNA). Experimental studies have demonstrated that exposure to electromagnetic fields (EMFs), including RF radiation, increases ROS levels and promotes oxidative damage in biological systems. Increased ROS production can trigger lipid peroxidation, alter membrane fluidity, disrupt membrane transport, and impair enzymatic activity within cells. These changes may contribute to cellular dysfunction and inflammation (37,38).

In the review, numerous experimental studies were analyzed to evaluate the effects of EMF exposure on antioxidant defense systems. The authors reported that RF radiation can disturb the balance between pro-oxidant and antioxidant systems, resulting in oxidative stress in the tissues. Such oxidative damage may ultimately affect cellular structures and contribute to chronic diseases (39).

ROS-mediated oxidative damage is particularly important because reactive oxygen species can oxidize cellular macromolecules, such as lipids, proteins, and nucleic acids. Therefore, persistent oxidative stress can lead to mitochondrial dysfunction, inflammatory signaling activation, and programmed cell death pathways. These molecular mechanisms are considered key contributors to chronic inflammatory disorders and tissue injuries. The effects of RF radiation on cellular oxidative stress biomarkers are shown in Table 2. and Figure 2. Building on the role of oxidative stress, the next section explores how RF radiation contributes to cellular oxidative damage at the molecular level of the cell.

Table 2. Effects of RF radiation on cellular oxidative stress biomarkers

Experimental Model	RF Frequency / Exposure	Oxidative Damage Biomarkers	Key Findings	References
Review of animal and cellular studies	Various RF-EMF frequencies used in mobile communication	ROS production, lipid peroxidation, antioxidant enzymes (SOD, CAT, GPx)	RF radiation may disturb the oxidant–antioxidant balance and increase oxidative stress in biological tissues	(39)
Meta-analysis of experimental studies	Low-intensity RF radiation	ROS, oxidative DNA damage	Majority of analyzed studies reported increased ROS generation following RF exposure	(36)
In vitro and in vivo experimental studies	RF-EMF from mobile communication devices	Oxidative stress biomarkers, antioxidant enzyme activity	RF exposure may induce oxidative damage and alter cellular redox balance	(34)
Mechanistic review	RF-EMF exposure from wireless technologies	ROS production, calcium signaling pathways	RF radiation may activate voltage-gated calcium channels leading to oxidative stress and cellular damage	(40)

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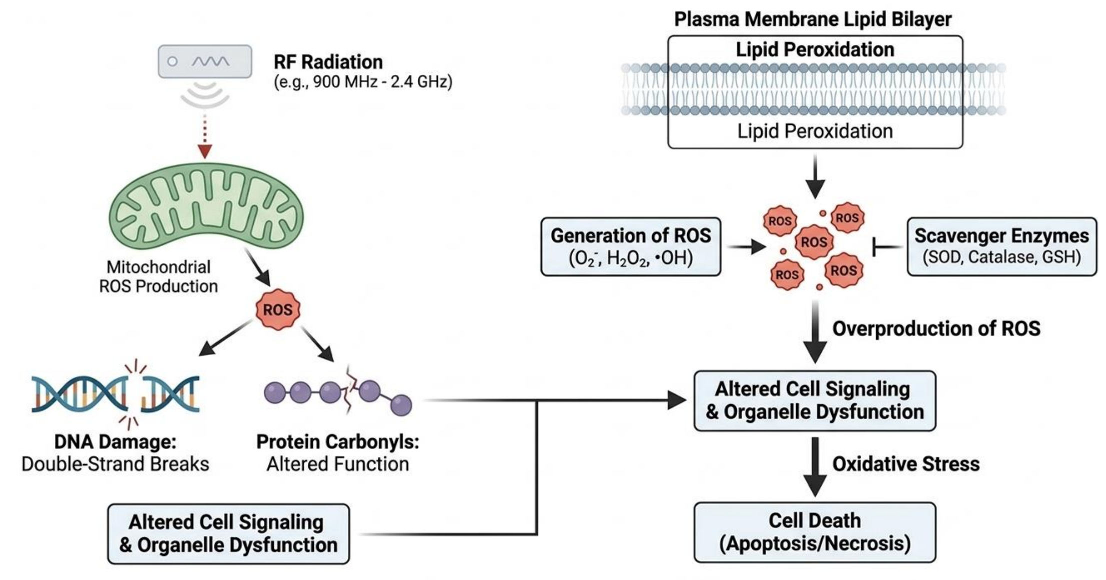

Figure 2. RF radiation–induced generation of reactive oxygen species and cellular oxidative damage

4. Oxidative Stress in Lung and Other Organs

Exposure to radiofrequency (RF) radiation, particularly in the 900 MHz frequency range used by mobile communication systems, has been reported to induce oxidative stress in several organs, including the lungs, heart, liver, and reproductive tissues. Oxidative stress occurs when the production of ROS exceeds the antioxidant defense capacity of cells, leading to cellular and molecular damage. Experimental animal studies suggest that RF radiation may influence oxidative balance by increasing lipid peroxidation and altering antioxidant enzyme activity. These alterations may result in tissue injury and inflammatory responses, particularly in organs with high metabolic activity, such as the lungs.

In experimental studies involving rodents exposed to 900 MHz pulse-modulated RF radiation, researchers observed increased oxidative stress biomarker levels in lung tissues (Table 3). These changes include elevated levels of lipid peroxidation markers, such as malondialdehyde (MDA), and decreased activity of antioxidant enzymes, such as superoxide dismutase (SOD) and catalase (CAT). The imbalance between ROS generation and antioxidant defense systems suggests that RF radiation exposure may contribute to oxidative damage in respiratory tissues (41).

Furthermore, oxidative stress induced by RF radiation has been linked to mitochondrial dysfunction, activation of inflammatory signaling, and cellular apoptosis. As oxidative stress is a key contributor to respiratory diseases, such as asthma, chronic obstructive pulmonary disease (COPD), and pulmonary fibrosis, these findings raise concerns regarding the potential respiratory health implications associated with long-term RF exposure. Therefore, several experimental studies have emphasized the importance of evaluating the biological effects of RF radiation on multiple organs, including the lungs (41). RF radiation–induced oxidative stress in the lungs and other organs is shown in Figure 3. These organ-level effects highlight the importance of understanding the underlying signaling mechanisms, which are addressed in the subsequent section on redox signaling pathways.

Table 3. Experimental studies reporting oxidative stress in organs following RF radiation exposure

Experimental Model	RF Frequency / Exposure	Organs Examined	Oxidative Stress Biomarkers	Key Findings	References
Rat model	900 MHz RF radiation exposure	Lung, heart, liver, testis	MDA, SOD, CAT	RF exposure increased lipid peroxidation and	(42)

				altered antioxidant enzyme activity in several organs including lung tissues	
Rat model	GSM base station radiation	Brain, lung and systemic tissues	Nitric oxide, antioxidant enzymes	Chronic RF exposure increased oxidative stress indicators and affected cellular antioxidant systems	(43)
Experimental rat model	Mobile phone RF radiation	Brain and peripheral tissues	Lipid peroxidation markers, ROS	RF radiation increased oxidative damage markers in tissues exposed to electromagnetic radiation	(44)
Meta-analysis of experimental studies	Low-intensity RF radiation	Multiple organs including lung	ROS production, oxidative DNA damage	Majority of reviewed studies reported increased ROS generation following RF exposure	(36)

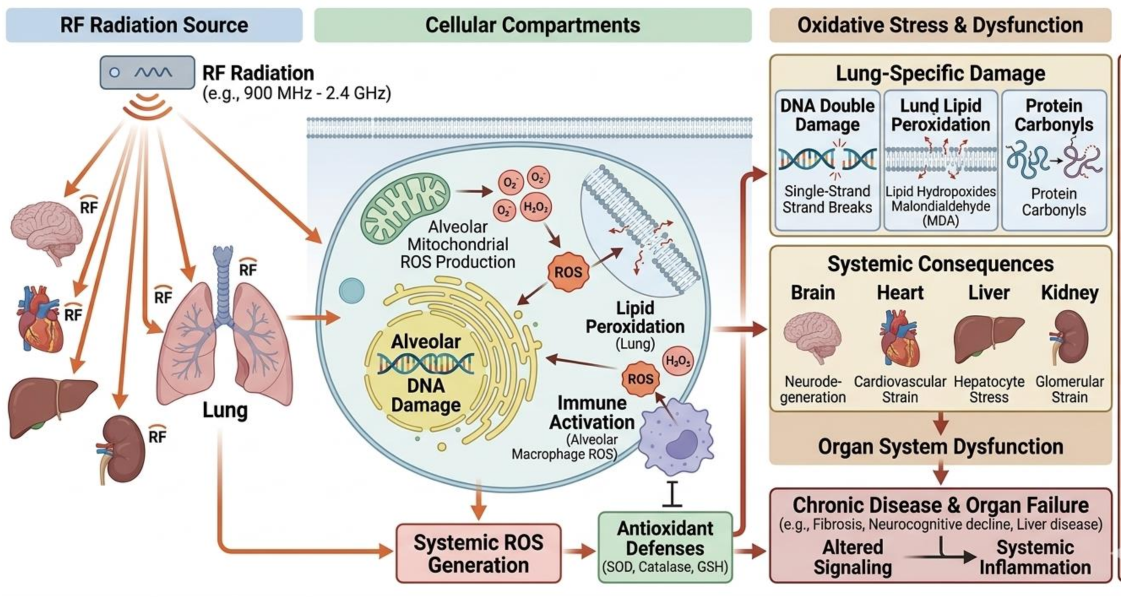

Figure 3. RF radiation–induced oxidative stress in lung and other organs

5. RF-EMF and Cellular Redox Signaling

Environmental stressors, such as (RF-EMF) can influence the cellular redox balance by modulating ROS production and antioxidant defense mechanisms (Figure 4). ROS are normally produced during cellular metabolism and play an important role in redox signaling, where low concentrations act as signaling molecules that regulate cellular processes such as proliferation, differentiation, and immune responses. However, excessive ROS generation can disrupt redox homeostasis and trigger oxidative stress, leading to damage to lipids, proteins, and deoxyribonucleic acid (DNA).

Recent experimental evidence indicates that RF-EMF exposure activates redox-dependent signaling pathways, resulting in oxidative damage, inflammatory responses, and different forms of programmed cell death. The review by analyzed experimental studies evaluating the biological effects of environmental pollutants, such as black carbon and RF-EMF. The authors reported that exposure to RF-EMF can induce oxidative stress and activate several cellular death pathways, including apoptosis, necrosis, autophagy, pyroptosis, and ferroptosis, depending on the cell type and exposure conditions (45).

At the molecular level, RF-EMF-induced oxidative stress may activate key signaling pathways, such as NF-κB, MAPK, and Nrf2, which regulate inflammatory responses and antioxidant defense systems. Activation of these pathways can lead to increased expression of pro-inflammatory cytokines and stress-response proteins, ultimately influencing cell survival or death. Moreover, mitochondrial ROS generation plays a critical role in initiating these signaling cascades and may trigger apoptosis or autophagy when oxidative stress levels are excessive (46).

As redox signaling is closely linked to inflammation and cellular injury, RF-EMF-induced disturbances in redox balance may contribute to the development of chronic diseases affecting multiple organs, including the respiratory system. Therefore, further experimental and epidemiological studies are required to better understand the relationship between RF-EMF exposure and redox-mediated cellular responses (46). The redox signaling pathways associated with RF-EMF exposure are listed in Table 4. In addition to biological mechanisms, it is essential to consider technological factors influencing exposure, such as the expansion of 5G frequency bands, which are discussed in the next section.

Table 4. Redox signaling pathways associated with RF-EMF exposure

Experimental Model	RF-EMF Frequency / Exposure	Cellular Redox Pathways Affected	Biological Effects Observed	References
Review of in vitro and in vivo studies	Environmental RF-EMF exposure	ROS-mediated redox signaling pathways	Oxidative stress, activation of inflammatory pathways and programmed cell death mechanisms	(47)
Cellular and animal experimental models	RF-EMF from wireless communication systems	ROS generation, Nrf2 antioxidant pathway	Disturbance of cellular redox balance and increased oxidative stress biomarkers	(44)
Mechanistic review	RF radiation from wireless devices	Voltage-gated calcium channel activation, ROS signaling	Increased intracellular Ca^{2+} leading to oxidative stress and inflammatory signaling	(36)
Meta-analysis of experimental studies	Low-intensity RF radiation	ROS production and oxidative signaling	Elevated ROS levels and activation of oxidative stress pathways	(36)

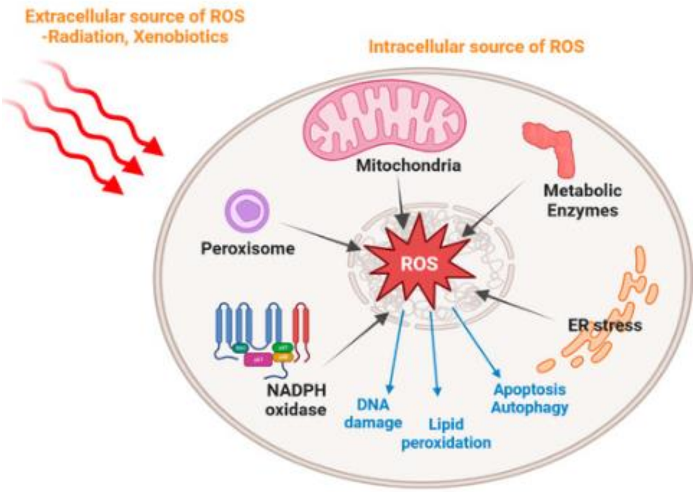

Figure 4. Mechanism of RF-EMF–induced redox signaling pathways

6. Expansion of 5G Frequency Bands

The development of 5G wireless communication technology has introduced a significant expansion in the range of radiofrequency (RF) spectrum used for mobile networks compared with previous generations, such as 3G and 4G (Table 5). Unlike earlier systems that primarily relied on frequencies below 3 GHz, 5G operates across multiple frequency bands, including low-band, mid-band (sub-6 GHz), and high-band millimeter-wave frequencies, which increases the diversity of RF exposure in the environment. The 5G New Radio (NR) standard defined by the 3rd Generation Partnership Project (3GPP) categorizes operational frequencies into two main ranges: Frequency Range 1 (FR1) and Frequency Range 2 (FR2). The FR1 band includes frequencies below approximately 7 GHz, commonly referred to as sub-6 GHz, and supports wide coverage with moderate data speeds. FR2 corresponds to millimeter-wave (mm Wave) frequencies ranging from approximately 24 to 71 GHz, which provide extremely high data transfer rates but operate over shorter distances owing to signal attenuation and limited penetration through obstacles.

The adoption of these additional frequency bands enables 5G networks to support high-capacity data transmission, ultra-low-latency communication, and massive device connectivity required for emerging technologies such as the Internet of Things (IoT), smart cities, and autonomous systems. However, the utilization of both sub-6 GHz and millimeter-wave frequencies means that populations may be exposed to a broader range of RF electromagnetic fields than earlier mobile communication systems (48).

Sub-6 GHz frequencies provide wider coverage areas and better signal penetration through buildings, making them suitable for nationwide 5G deployments. In contrast, millimeter-wave frequencies deliver extremely high bandwidth and multi-gigabit data speeds but require dense infrastructure, such as small-cell base stations, because signals attenuate rapidly with distance and obstacles.

From a biological and environmental perspective, the expansion of the RF spectrum in 5G networks raises questions regarding the possible health implications associated with exposure to different frequency ranges. Although the current exposure limits established by international regulatory bodies aim to ensure safety, ongoing scientific evaluation is necessary to understand the potential biological interactions with these diverse RF frequency bands (48). These technological advancements have also raised public health concerns, which are critically examined in the following sections.

Table 5. Frequency ranges used in 5G communication technology

Frequency Band	Frequency Range	Key Characteristics	Applications / Network Use	Reference s

Low-band 5G	<1 GHz	Wide coverage area, strong penetration through buildings, lower data speed	Rural coverage and nationwide connectivity	(49)
Mid-band (Sub-6 GHz)	1–6 GHz	Balanced coverage and capacity, moderate latency	Urban mobile broadband and general 5G services	(49)
Millimeter-wave (mmWave)	24–100 GHz	Very high data speed, limited propagation distance, requires dense base stations	High-capacity urban networks, stadiums, smart cities	(50)
5G New Radio spectrum	Multiple frequency ranges including FR1 and FR2	Supports ultra-low latency, massive device connectivity, and high bandwidth	Internet of Things (IoT), autonomous systems, high-speed wireless communication	(51)

7. Public Health Concerns Regarding 5G Deployment

The rapid deployment of fifth-generation (5G) wireless communication technology has generated considerable debate among scientists, public health experts, and policymakers regarding its potential biological and environmental effects (Table 6) and (Figure 5). Unlike earlier generations of wireless communication, 5G networks use new frequency ranges, advanced antenna technologies, and dense networks of small-cell base stations. Because of these technological changes, some researchers have argued that 5G infrastructure has been implemented globally before a comprehensive evaluation of its long-term health effects (48).

One of the major concerns raised by researchers is that the existing safety guidelines for (RF-EMF) are primarily based on thermal effects, meaning biological damage caused by tissue heating. However, some experimental studies have suggested the possibility of non-thermal biological effects, including oxidative stress, DNA damage, and changes in cellular signaling pathways. These findings have led some scientists to argue that the current exposure guidelines may not fully account for the potential biological effects associated with chronic low-level RF exposure. In 2017, more than 390 scientists and medical professionals signed an appeal to the European Union, requesting a temporary moratorium on 5G deployment until independent research could better assess the potential health and environmental impacts. The appeal emphasized the need for comprehensive risk assessment and unbiased scientific evaluation before the large-scale implementation of the technology (48).

Another factor contributing to public concern is the classification of radiofrequency radiation by the International Agency for Research on Cancer (IARC) as a “possible human carcinogen” (Group 2B). Although this classification was based mainly on earlier mobile communication technologies, it has intensified calls for further investigation of long-term RF exposure, especially with the introduction of new 5G frequencies and infrastructure components.

Despite these concerns, international health organizations, such as the World Health Organization (WHO), state that, based on current evidence, no confirmed adverse health effects have been established from exposure to radiofrequency fields within the recommended safety limits. Nevertheless, researchers have emphasized the need for continued monitoring and long-term epidemiological studies to better understand the possible biological interactions associated with emerging wireless technologies (52). Beyond general concerns, specific biological effects, such as inflammatory responses, are discussed in detail in the next section.

Table 6. Major public health concerns associated with 5G deployment

Concern Category	Description of Issue	Potential Public Health Implications	References
Rapid deployment of 5G infrastructure	Global implementation of 5G technology before comprehensive long-term biological safety evaluation	Possible unknown long-term health effects due to chronic RF-EMF exposure	(49)
Increased environmental RF exposure	Expansion of wireless infrastructure including dense networks of small-cell base stations	Increased cumulative RF radiation exposure to the population	(53)
Non-thermal biological effects	RF radiation may induce biological responses beyond thermal heating mechanisms	Possible oxidative stress, cellular signaling changes, and inflammatory responses	(50)
Ecological and environmental concerns	Increased electromagnetic radiation may affect human health and biological systems	Potential neurological, reproductive, and immune system effects	(54)

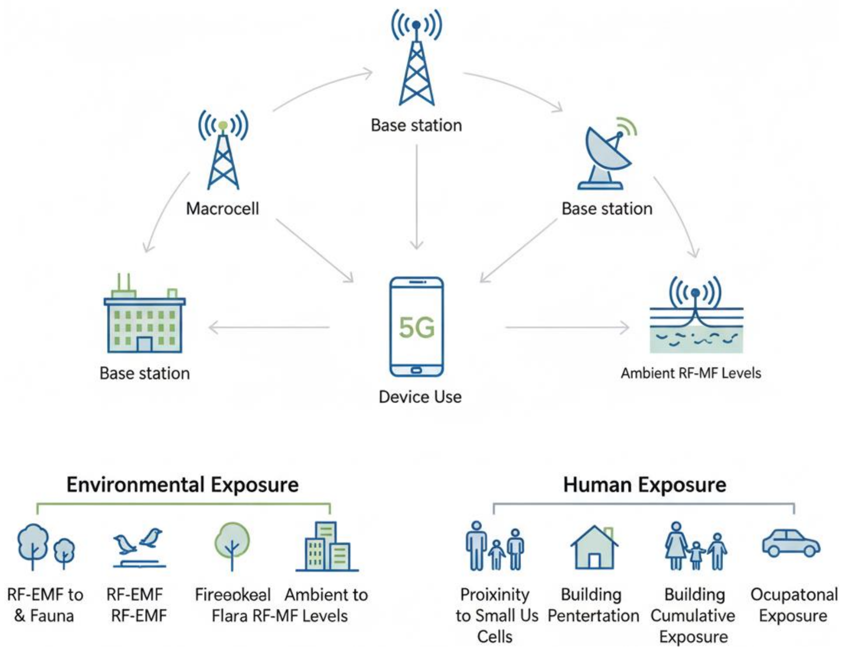

Figure 5. Infrastructure and exposure pathways associated with 5G deployment

8. RF-EMF Effects on Inflammatory Processes

Exposure to (RF-EMFs) has been reported to influence inflammatory signaling pathways involved in the development of several chronic diseases (Figure 6). Inflammation is a complex biological response triggered by cellular stress, infection, or environmental stimuli and plays a crucial role in the pathogenesis of respiratory diseases, such as asthma and chronic obstructive pulmonary disease (COPD). Environmental stressors, including RF-EMF exposure, may alter the cellular signaling networks that regulate inflammatory mediators and immune responses. Recent experimental evidence indicates that RF-EMF exposure can induce oxidative stress and redox-dependent signaling pathways, which are closely linked to inflammatory responses. This review summarized several experimental studies demonstrating that environmental stressors, such as RF-EMFs, can produce oxidative damage in cells and activate molecular pathways associated with inflammation and cell death. These pathways include apoptosis, necrosis, necroptosis, autophagy, and ferroptosis, which are often triggered by excessive reactive oxygen species (ROS) generation and inflammatory signaling (45).

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In addition, experimental cellular studies have shown that electromagnetic field exposure can enhance the production of pro-inflammatory cytokines, such as tumor necrosis factor-α (TNF-α), interleukin-1β (IL-1β), and interleukin-6 (IL-6). Increased cytokine production is associated with the activation of transcription factors, such as NF-κB and NFAT, which regulate inflammatory gene expression. These molecular events suggest that EMF exposure may amplify inflammatory responses in immune cells and tissues (55).

Inflammatory signaling pathways activated by RF-EMF exposure are particularly relevant to respiratory health because chronic inflammation plays a central role in airway remodeling, mucus hypersecretion, and tissue damage in diseases such as asthma and COPD. Therefore, understanding how RF-EMF influences inflammatory signaling networks is essential for evaluating the potential health implications of long-term exposure to electromagnetic radiation(32). The experimental evidence linking RF-EMF exposure with inflammatory signaling pathways is shown in Table 7. Despite these observed biological effects, inconsistencies in the evidence necessitate critical evaluation, as presented in the following section.

Table 7. Experimental evidence linking RF-EMF exposure with inflammatory signaling pathways

Experimental Model	RF-EMF Frequency / Exposure	Inflammatory Markers / Pathways	Key Biological Effects	References
Review of in vitro and in vivo experimental studies	RF-EMF exposure from environmental sources	ROS-mediated signaling, NF-κB activation	Oxidative stress and activation of inflammatory signaling pathways	(56)
Macrophage cell line (RAW 264.7)	ELF-EMF exposure	TNF-α, IL-1β, IL-6 cytokines	Increased inflammatory cytokine production and immune activation	(57)
Microglial cell cultures	Pulsed electromagnetic field exposure	MAPK pathway, inflammatory cytokines	Modulation of inflammatory signaling and immune responses	(58)
Meta-analysis of experimental studies	Low-intensity RF radiation	ROS generation, oxidative inflammatory pathways	Increased ROS production linked to inflammatory responses	(36)

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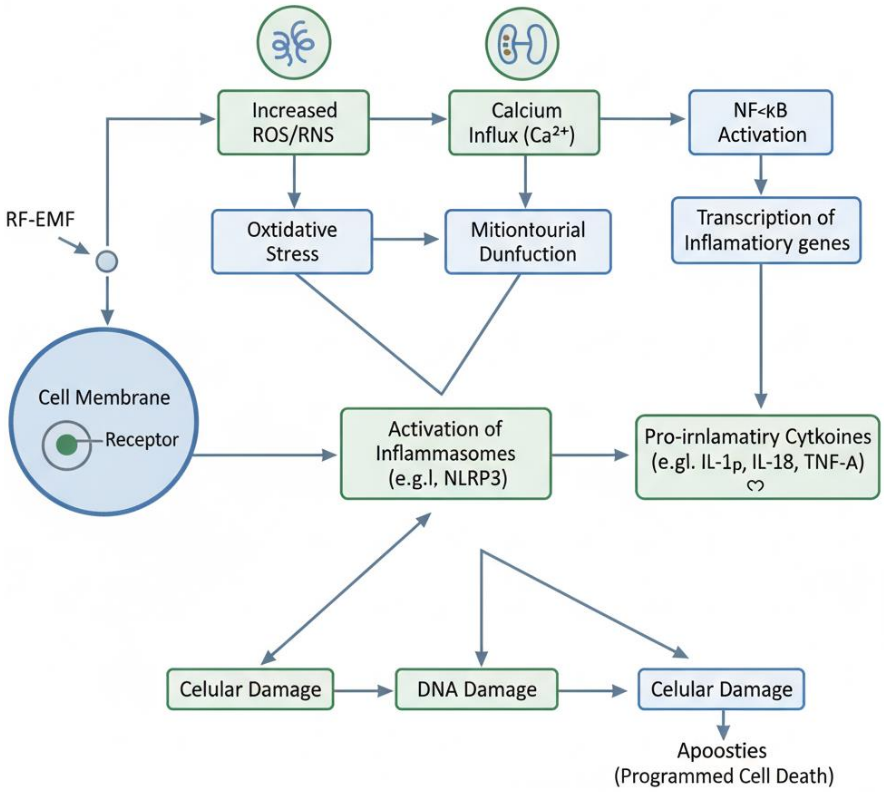

Figure 6. RF-EMF-induced inflammatory signaling mechanisms

9. Evidence Uncertainty in RF-EMF Health Studies

Scientific investigations evaluating the biological and health effects of radiofrequency electromagnetic field (RF-EMF) exposure have produced inconsistent and sometimes contradictory results (Table 8) and (Figure 7). Systematic reviews have indicated that the overall certainty of evidence linking RF-EMF exposure to oxidative stress and other biological effects remains low. These inconsistencies are mainly attributed to variations in the experimental design, exposure conditions, biological models, and measurement techniques used in different studies. A systematic review evaluated experimental in vitro and in vivo studies investigating the relationship between RF-EMF exposure and biomarkers of oxidative stress across the frequency range of 100 kHz–300 GHz. The review initially screened more than 12,000 publications and ultimately included 56 experimental studies (45 in vivo and 11 in vitro). These studies investigated oxidative stress biomarkers, such as oxidized DNA bases, modified proteins, oxidized lipids, and hydrogen peroxide production (32).

The results demonstrated considerable heterogeneity across the studies. For example, the effects on oxidative stress biomarkers in the rodent brain varied widely, ranging from strong decreases to large increases, depending on the exposure conditions and experimental design. Similar inconsistencies have been observed in studies examining the liver, blood, and reproductive tissues.

The systematic review concluded that the certainty of evidence linking RF-EMF exposure to oxidative stress biomarkers is very low, largely because many studies showed a high risk of bias, inconsistent methodologies, and insufficient characterization of exposure parameters. These methodological limitations make it difficult to draw definitive conclusions regarding the biological effects of RF-EMF exposure.

In addition, heterogeneity in exposure duration, frequency ranges, specific absorption rate (SAR), and biological models further complicates the comparisons between studies. Consequently, researchers have emphasized the need for improved experimental design, standardized exposure systems, and validated biomarker measurements in future investigations (32). Considering these uncertainties, there remains a clear need for focused research on respiratory outcomes, which we discuss in the next section. Overall, a comparative analysis of the reviewed studies indicates that most experimental in vitro and in vivo investigations consistently report increased ROS production and alterations in antioxidant defense mechanisms following RF-EMF exposure. Animal and cellular studies have frequently demonstrated oxidative stress–mediated cellular damage, mitochondrial dysfunction, and activation of inflammatory signaling pathways. However, systematic reviews and meta-analyses have highlighted considerable variability in the magnitude and direction of these effects, primarily due to differences in exposure conditions, frequency ranges, and biological models. While mechanistic studies support a potential link between RF-EMF exposure and oxidative and inflammatory responses, the overall certainty of the evidence remains low, emphasizing the need for standardized methodologies and well-designed long-term studies to establish definitive conclusions.

Table 8. Factors contributing to uncertainty in RF-EMF health research

Exposure Conditions	Biological Models Used	Major Limitations Identified	Key Conclusions	References
RF-EMF exposure ranging from 100 kHz to 300 GHz	In vitro and in vivo experimental studies	Variability in exposure conditions and inconsistent biomarker measurements	Evidence linking RF-EMF exposure to oxidative stress biomarkers remains of very low certainty	(32)
RF radiation from wireless communication devices	Animal and cellular experimental models	Heterogeneity in experimental design and exposure parameters	Mixed evidence regarding oxidative stress and biological responses	(32)
Environmental RF-EMF exposure from mobile technologies	Review of experimental and epidemiological studies	Differences in exposure duration, intensity, and biological endpoints	Further standardized research is required to clarify health effects	(50)
RF-EMF exposure from wireless devices	Human and animal experimental studies	Methodological variability and limited long-term data	Current evidence does not conclusively demonstrate harmful biological effects	(33)

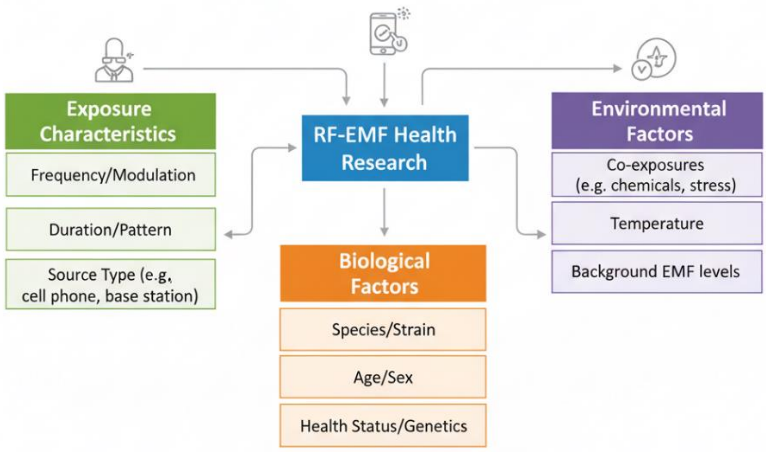

Figure 7. Sources of variability in RF-EMF health research

10. Need for Further Research on Respiratory Outcomes

Despite the rapid expansion of 5G wireless communication networks, the available scientific evidence directly linking radiofrequency electromagnetic field (RF-EMF) exposure to respiratory disease remains limited. Most studies evaluating the biological effects of RF-EMF have primarily focused on neurological, reproductive, or carcinogenic outcomes, while relatively few have specifically examined the respiratory system. Consequently, the potential impact of 5G RF exposure on respiratory health outcomes, such as asthma, chronic obstructive pulmonary disease (COPD), pulmonary inflammation, and airway remodeling, remains poorly understood. Current experimental evidence suggests that RF-EMF exposure may influence biological processes, such as oxidative stress, inflammation, and cellular signaling pathways, which are known to play important roles in respiratory disease pathogenesis. However, most of these findings originate from in vitro cellular studies or short-term animal experiments, and their direct relevance to human respiratory health remains unclear. Additionally, most existing studies were conducted using earlier mobile communication frequencies rather than the newer millimeter-wave frequencies used in 5G networks (48). Another limitation of the current literature is the lack of long-term epidemiological studies investigating the relationship between RF-EMF exposure and respiratory health outcomes in human populations. Epidemiological research is essential for evaluating real-world exposure conditions, long-term health risks, and potential interactions with other environmental factors, such as air pollution and occupational exposure. Furthermore, differences in exposure intensity, frequency bands, and duration make it difficult to compare the results across existing studies (59).

To address these knowledge gaps, future research should focus on well-designed longitudinal epidemiological studies, standardized exposure assessment methods, and mechanistic investigations that explore how RF-EMF exposure affects respiratory tissues and immune responses. Advanced experimental models, including organoid systems and animal models mimicking human respiratory diseases, may provide valuable insights into the potential biological interactions between RF radiation and lung tissues.

Overall, although current scientific evidence does not conclusively demonstrate a direct association between 5G RF exposure and respiratory diseases, the limited availability of targeted research highlights the need for comprehensive long-term studies to better understand the potential respiratory health risks (52). These research gaps collectively inform the conclusions presented in the final section.

11. Conclusion

In conclusion, the rapid expansion of 5G wireless communication has intensified scientific interest in the potential biological effects of radiofrequency electromagnetic field (RF-EMF) exposure. Although RF radiation is non-ionizing and does not directly damage DNA, accumulating experimental evidence suggests its involvement in oxidative stress, redox imbalance, and inflammatory responses associated with respiratory disorders, such as asthma and COPD. These effects are primarily mediated by increased reactive oxygen species (ROS) production and altered antioxidant defense mechanisms. However, the overall evidence remains inconsistent because of variability in study design, exposure conditions, and biological models. Moreover, respiratory health outcomes remain underexplored compared with other systems. Therefore, well-designed long-term epidemiological and mechanistic studies are required to clarify the potential impact of RF-EMF exposure on respiratory health.

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Conflict of Interest

The authors declare no conflict of interest.

Authors' Contribution

Conceptualization; methodology; software; validation; formal analysis; investigation; resources; data curation; writing—original draft preparation; writing—review and editing; visualization; supervision; project administration by Phanindra Erukulla and Pericharla Venkata Narasimha Raju. All authors have read and agreed to the published version of the manuscript.

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