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Potential Health Implications of Fifth Generation (5G) Wireless Communication

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Abstract

Background: The implementation of global 5G wireless technology, having revolutionized telecommunications, has led to greatly increased speed and connectivity; however, there are concerns of potential health risks associated with exposure to radiofrequency electromagnetic field (RF-EMF), particularly at the new 5G frequencies (3.5–100 GHz). This has caused much discussion globally. One can see the focus on concerns regarding some public issues and also scientific concerns, which cover thermal and non-thermal effects, carcinogenicity, and other potential impacts on neurological, reproductive, and immunological systems.

Objective: To identify the research gaps around the potential health effects of 5G technology, the peer-reviewed literature was reviewed.

Methods: A systematic review of literature was undertaken from the years 2010-2024, using PubMed, Scopus, and Web of Science databases. Search terms for the search included and were limited to "5G technology," "RF-EMF," and "health effects." The studies reviewed evaluated health effects, were performed using human or animal models, and focused on targets related to 5G-specific frequencies. Review articles that were non-peer-reviewed were excluded from the review. A thematic analysis was conducted, with specific attention to biological and epidemiological findings.

Results: Thermal effects of 5G are minimal and within safety margins, and they impact skin primarily. Non-thermal effects, such as oxidative stress, have inconsistent in vitro and in vivo findings. Epidemiological data on carcinogenicity are limited, with very few 5G-specific studies. Some reproductive and neurological impacts suggest a possibility of risk; however, the available data are not sufficient to reach a conclusion. Regulatory guidelines consider thermal impacts but may not stipulate exposure through similar non-thermal mechanisms.

Conclusions: Although 5G appears to be safe within the parameters of regulatory guidelines, other consequences of 5G exposure in the long term and potential non-thermal exposure effects remain uncertain. Standard dosimetry and longitudinal studies are necessary to establish a course of research for public health risks, if any, from 5G.

Keywords: 5G technology, RF-EMF, health effects, non-thermal health effects, carcinogenicity.

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Introduction

The 5th generation (5G) wireless technology represents an important step towards global connectivity and enabling applications including the Internet of Things (IoT), autonomous vehicles, and smart cities (Andrews et al., 2014). The primary differences with 5G from previous generations (2G, 3G, and 4G) specifically are in the available bandwidth and operating frequencies. While the earlier generations only used low-band (less than 1GHz) and mid-band (1-6GHz) frequencies, 5G will be using high-band (millimeter waves) frequency ranges (e.g., 24GHz-100GHz) (Rappaport et al., 2013). The new higher frequencies and technologies, such as massive multiple-input multiple-output (MIMO) systems and beamforming, allow 5G to provide data rates 100 times faster than 4G and can also accommodate a very large number of devices (Shafi et al., 2017).

While 5G technology is all that it is reported to be technologically, it is important to recognize that there are also concerns related to potential health impacts of RF-EMF exposure, regarding the new use of millimeter waves and generally increased densification of networks (Wu et al., 2015). Public fears extend beyond carcinogenic effects to general impacts on the neurological, reproductive, and immunological systems (Hardell & Carlberg, 2017). Some regulatory agencies, like the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and the World Health Organization (WHO), will argue that 5G is within the public safety criteria (ICNIRP, 2020). Critics will argue that the 5G-specific frequencies are not sufficiently studied for long-term exposures, and research into the many potential health impacts must be prioritized (Russell, 2018).

This review attempts to provide an integrated synthesis of peer-reviewed evidence on potential health impacts of 5G technology, from biological mechanisms, epidemiology, and public health consequences. Thermal and non-thermal effects, carcinogenicity, and other health impacts are referenced. Research gaps are also noted, and future study directions are proposed to facilitate evidence-informed policy making.

1. Methods

A systematic review of the literature was conducted to find original, peer-reviewed research articles published between January 2010 - July 2024 concerning the health effects of RF-EMF exposure due to the technology used in 5G. The PubMed, Scopus, Web of Science, IEEE Xplore libraries were searched with key terms, including "5G technology", "radiofrequency electromagnetic fields", "millimeter waves", "health impact", and "biological effect". The inclusion criteria were studies investigating 5G-specific frequency bands (3.5–100 GHz), human or animal subjects, and biological or health effect-outcomes. The exclusion criteria were non-peer-reviewed publications, editorials, and studies with methodological errors. Data were thematically synthesized for thermal effects, non-thermal effects, carcinogenicity, reproductive health, neurological effects, and immunological effects.

2. Biological and Health Effects of Exposure to 5G

2.1. Thermal Effects

Radiofrequency electromagnetic fields (RF-EMF) produced by wireless communication technologies predominantly affect biological tissues by thermal mechanisms whereby electromagnetic energy absorbed is dissipated, as heat, and leads to local heating (Ziskin, 2013). For the fifth-generation (5G) wireless communications system, there are particularities associated with millimeter waves (24–100 GHz) because of the lower wavelengths and shallow penetration compared to the lower frequencies associated with the previous 2G, 3G, and 4G systems (Alekseev et al., 2018). High frequency waves interact primarily with the near-surface tissues in the body, e.g., skin and cornea, and have penetration depths less than 1–2 mm, which severely limits interaction with deeper structures (Foster et al., 2017; Figure 1).

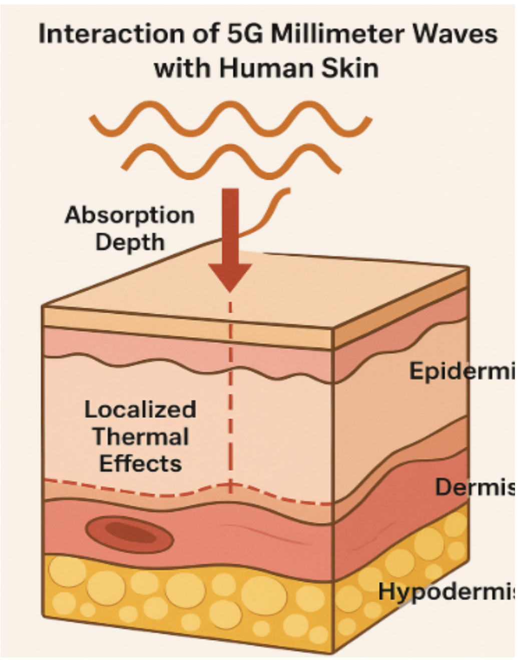


Figure 1: Penetration Depth of 5G Frequencies in Human Tissue.

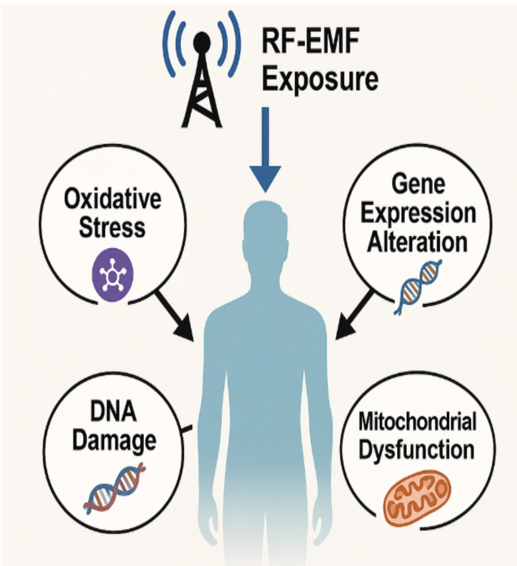
Experimental studies using animal models, e.g., rodent models, have shown that millimeter wave exposure by the acute route does not increase temperature by more than 1°C, and results were safely within the exposure guidelines mandated by the International Commission on Non-Ionizing Radiation Protection (ICNIRP, 2020). Wu et al. (2019) used a combination of rats that were exposed to 60 GHz millimeter wave exposure, and did observe heating of superficial skin, but no evidence or significant signs of damage or abnormalities were produced (i.e., normal physiological signs).

Despite these findings, ongoing concerns persist about the potential for cumulative thermal effects from high-density 5G exposure, such as in high-density urban environments, e.g., locations with high density of small cells and base stations (Neufeld & Kuster, 2018). 5G network rollout involves the placement of a greater number of antennas and deployment of beamforming technology, which focuses RF energy into directional beams, potentially increasing localized power density (Colombi et al., 2020). Computational modeling shows that under specific circumstances, e.g., long exposure to beams of high-power density, skin temperature can exceed safety levels, particularly in exposure situations involving close proximity to 5G antennas (Neufeld & Kuster, 2018). Although human studies are limited, early reports suggest that thermal effects (typical of 5G exposure) are below safety limits, and that there is no risk for immediate thermal injury (Betzalel et al., 2018; Figure 1). However, the long-term effects of a history of low-level thermal exposure under realistic exposure conditions, e.g., the urban environment (where pervasive 5G networks are present) are poorly researched, and these potential effects must be a focus of further study to determine compliance with safety recommendations.

2.2. Non-Thermal Effects

Non-thermal RF-EMF effects that occur without the heating of tissue are an even more contentious and poorly researched area of study (Pall, 2018). These effects could potentially be driven by functions such as oxidative stress, DNA damage, effects on cellular signalling mechanisms, and gene expression, with implications for cellular function and general health (Figure 2). In vitro studies of 5G frequencies derived from non-thermal RF-EMFs have not produced congruent findings (e.g., these kinds of interactions are complex). Belyaev et al. (2019) reported increased oxidative stress after subjects of customary human fibroblast cell lines underwent 26 GHz millimeter wave exposures, suggesting that it is possible to generate reactive oxygen species (ROS) that could elicit cellular injury. Consistent oxidative stress would disrupt cellular homeostasis, resulting in long-term health implications. On the other hand, Wood et al. (2021) reported de novo experiments (with the same exposures) whereby they detected no measurable change in function or viability of the cells, demonstrating the range of experimental outcome variability due to differences in exposure parameters, cell types, and study designs.

Figure 2: Biological Pathways Potentially Affected by 5G Non-Thermal RF-EMF Exposure.



Animal studies have brought further complexity to the understanding of non-thermal effects. Altered gene expression was reported in mice exposed to 5G-relevant frequency in studies cited by Kostoff et al. (2020), with an inference of potential stress responses at the molecular level affecting physiological processes. The findings raise the cause for concerns regarding subtle, long-term non-thermal effects. Alternatively, studies conducted by Elder and Chou (2020) failed to show consistent evidence for non-thermal effects at exposure levels within ICNIRP guidelines, where exposure intensity and duration of exposure proved to be key evidence of significance. One of the key limitations in this line of research is the lack of standardized exposure protocols and dosimetry models that complicate the comparison of the results of studies (Vijayalaxmi & Prihoda, 2019). Non-thermal effects are further complicated by the variability in frequency bands, modulation schemes, and exposure durations, and stricter, standardized studies need to be conducted to demonstrate the biological importance of non-thermal effects.

2.3. Carcinogenicity

The possible carcinogenicity of RF-EMF exposures has created scientific controversy since the International Agency for Research on Cancer (IARC) classified RF-EMF as a "possible agent" (Group 2B) in 2011 due to limited evidence, including studies of 2G and 3G technologies (IARC, 2011). The National Toxicology Program (NTP) further demonstrated carcinogenic activity in rats following high-intensity RF-EMF exposures, which included gliomas (brain tumors), schwannomas (nerve tissue tumors) (NTP, 2018). These findings are disputed, however, based on exposure rates used that were far in excess of exposures in typical human environments, casting their applicability to actual 5G exposure into doubt (Falcioni et al., 2018).

5G-specific information is especially scarce, as much of the epidemiologic data has been targeting previous wireless technologies. Hardell and Carlberg (2020) speculated that 5G's increased frequencies and beamforming may pose novel risks, either adding to the risk of DNA damage or cell stress due to the concentrated nature of the radiation. A cohort study by Choi et al. (2021) did not find a correlation between long-term mobile phone use and brain tumors, though it was not targeting 5G-specific frequencies. Lack of long-term epidemiological evidence concerning 5G-specific exposures underscores the need for long-term studies to determine potential carcinogenic hazards (Miller et al., 2019). Large-scale, prospective cohorts are needed because of the widespread deployment of 5G networks in order to determine whether the unique aspects of 5G, including millimeter waves and further network densification, pose a carcinogenic hazard.

2.4. Reproductive Health

Concerns have surfaced regarding the potential for RF-EMF exposure to adversely affect reproductive parameters, particularly male fertility, as the reproductive health of men is, unfortunately, the "canary in the coal mine" of environmental destruction. A number of in vitro and animal studies have indicated RF-EMF exposure to be positively correlated with reduced sperm motility, viability, and morphology through a variety of mechanisms, including oxidative stress and heat (e.g., Houston et al., 2019). Houston et al. (2019) indicated that the reduced sperm motility attributed to exposure to 3.5 GHz RF-EMF resulted from increased ROS, causing detrimental effects. There have also been findings of these effects on the exposure of human semen to RF-EMF, but with limited studies covering exposure to 5G frequencies (Agarwal et al., 2018). These findings would have relevance in the context of the potential for 5G exposure affecting male fertility, especially in proximity to devices or infrastructure emitting 5G for a prolonged timeframe.

The study of female reproductive health outcomes is less extensive but equally important. There is evidence that RF-EMF exposure may have effects on ovarian function or pregnancy via interfering with hormonal signaling or embryonic development, albeit to a limited degree (Divan et al., 2017). The evidence reviewed is inconsistent, and importantly, there are no studies that specifically target 5G frequencies, reflecting a significant evidence gap in regard to 5G. Adams et al. (2014) stressed the need for focused research to evaluate the impact of RF-EMF on female reproductive health, especially in relation to new and forthcoming modalities, such as 5G. As 5G technologies are increasingly rolled out across the country, it is important to cautiously evaluate both male and female reproductive outcomes to establish potential risks and inform public health policy.

2.5. Neurological Outcomes

The neurological effects of RF-EMF exposure are also an emerging area of interest focused on cognition, brain function, and neurodevelopment. There is emerging evidence for neurological function changes following RF-EMF exposure, especially as reported in animal studies. Marino et al. (2019) reported alterations in electroencephalogram (EEG) patterns in RF-EMF-exposed rodents, with potential implications for brain function and neural transmission. These changes have implications for the cognitive processes of attention and memory, but their relevance to human effects remains uncertain.

Human investigations of neurological impacts have produced mixed outcomes. No cognitive impairment was found in adults exposed to RF-EMF from mobile phones in a cross-sectional study by Thomas et al. (2020), with little effect under typical exposure levels. Some minor effects on memory and attention were reported in a minority of studies, however, e.g., Barth et al. (2012), where the level of exposure was high. The potential for neurodevelopmental effects in children is especially of concern, given the vulnerability of developing nervous systems (Foerster et al., 2018). Epidemiologic studies on earlier wireless technologies have implicated RF-EMF exposure in potential linkages with children's behavioral disturbances, but not for 5G (Calvente et al., 2016). Sage and Carpenter (2019) suggest the use of the precautionary principle until evidence is more robust, advocating for longitudinal studies assessing the neurological outcomes of 5G exposure, in particular, in vulnerable groups such as children and adolescents.

3. Immunological Effects and Public Health Implications of 5G Exposure

3.1. Immunological Effects

The study of radiofrequency electromagnetic field (RF-EMF) exposure effects on immune function has developed into a leading research agenda with the introduction of fifth generation (5G) wireless technology. Current evidence suggests that exposure to RF-EMF can modify immune system response, but has also been shown to impact cytokine production, immune cell function, and the balance of immune function, which may enhance susceptibility to infection or encourage the pattern of inflammatory disease (Yakymenko et al., 2015). Cytokines, which are the signaling agents critical to the regulation of immunity, are sensitive to changes induced by RF-EMF. Yakymenko et al. (2015) predicted that RF-EMF exposure would produce oxidative stress, resulting in an abnormal balance of cytokines between the proinflammatory cytokines and anti-inflammatory cytokines, which could result in impaired immune function. That prediction is consistent with animal studies such as those by Megha et al. (2018), where exposure to RF-EMF at frequencies related to earlier wireless technology produced significant alterations in immune markers, such as changes in the level of interleukin-6 (IL-6) and tumor necrosis factor-alpha (TNF-α) in the rats. The findings show a shift towards immune dysregulation, though direct applicability to 5G's higher frequency ranges, particularly millimeter waves (24–100 GHz), remains uncertain in the absence of targeted studies at these frequencies.

Human studies of RF-EMF and immune function are extremely limited, and existing evidence is insufficient to allow for firm conclusions on 5G's immunologic impacts (Simkó & Mattsson, 2019). Simkó and Mattsson (2019) conducted a comprehensive review and found that while some in vitro experiments suggest RF-EMF may affect immune cell proliferation or differentiation, the lack of replicable outcomes and the use of non-5G frequencies limit the inferences of the research. The complexity of the immune system, with its extensive network of cell and molecular interactions, also complicates the untangling of RF-EMF-specific outcomes. Heterogeneity of exposure parameters, frequency, intensity, and duration also makes the interpretation of immunologic effects complex. As 5G cellular infrastructure becomes increasingly ubiquitous, controlled human studies are needed to determine if chronic exposure to 5G-specific frequencies will adversely impact immune function, especially in populations that are especially vulnerable due to pre-existing immune dysregulation.

3.2. Public Health and Regulatory Considerations

Recommendations from the International Commission on Non-Ionizing Radiation Protection (ICNIRP, 2020) and the Federal Communications Commission (FCC, 2019) form the basis for regulatory limits to the rollout of 5G. The recommendations specify exposure limits set to safeguard against adverse thermal effects (e.g., tissue heating) based on considerable evidence related to RF-EMF and biological tissue interactions (Foster & Moulder, 2013). ICNIRP (2020) for example provides maximum permissible exposure limits for RF-EMF such that the SAR remains below levels that create thermal increases in temperature. Regulatory authorities and the majority of the experts involved deem these guidelines to be precautionary in nature, based on multiple decades of scientific evidence identifying thermal effects as the primary means of RF-EMF generated harm at frequencies classified as non-ionizing (Foster & Moulder, 2013).

Critics will assert that these regulatory regimes may not provide adequate determination of possible non-thermal means of effects which have much less clear pathways for causation, and which might correlate to possible chronic exposures that are generally low level defined by use of 5Gs networks. The higher frequency and beamforming aspect of anticipated clues within 5G and the inclusive RF power concentration of focused beam exposure technology provides new exposures to the public which might not be adequately represented in the existing guidelines (Russell, 2018). Emergent concerns for updating the current exposure limits to include possible non-thermal pathways including; oxidative stress, as well as interference of signalling of cellular processes, should provide a rationale, as possible long-term or cumulative health impact potential. Thus, public health policy must achieve a balance in sight of the revolutionary advancements of 5G networks, such as improved telehealth services for the sick, monitored healthcare technologies for those with fragile health and rapid response systems in the event of an emergency events, whilst at the same time addressing the reasonable possibility of health affections to human health (Lin, 2020). 5G-enabled telemedicine could improve healthcare access for rural populations, but public trust in these technologies can be eroded in the absence of credible safety evidence. It is also critical to ensure effective public health measures include the community at every stage of the process, and that there is transparency in communicating to the community to reduce fears related to 5G safety and clear up validation concerns raised around misinformation (Wiedemann et al., 2013).

Misinformation, which is sometimes based on anecdotal evidence or unverified observation, has stoked public fear surrounding 5G, including assertions of widespread health damage. In this context, Wiedemann et al. (2013) argue that risk communication must be evidence-based, transparent, and participatory in order to build confidence and mitigate irrational fears. Initiatives like the World Health Organization's International EMF Project play a crucial role in providing evidence-based advice and facilitating global cooperation to assess RF-EMF health hazards (WHO, 2021). 5G-specific advice remains in development, however, since most existing guidelines are based on research on earlier wireless technologies. Continued efforts to add to these frameworks 5G-specific evidence is needed to protect public health as well as encourage technological development.

4. Gaps in Knowledge and Future Directions

The current evidence base surrounding the health implications of fifth generation (5G) wireless technology outlines multiple areas of sufficient evidence gaps. The lack of long-term epidemiological studies is a fundamental limitation, as most prevalence studies reflect outcomes based on short-term exposures to radiofrequency electromagnetic fields (RF-EMF), and not chronic or long-term exposures subject to longer follow-ups. Long-term follow-up cohort studies in diverse populations, over decades, are required to investigate potential chronic risks, which might include risk of carcinogenicity, neurological disease, or other chronic health impacts occurring after prolonged exposures to 5G networks, which take decades of long exposure to develop. Standard dosimetry models are another source of challenge in that they introduce exposure measurement complexities that are not captured by existing methodology.

The biological mechanisms of non-thermal effects including oxidative stress, DNA damage, or disruption of cellular signaling pathways have yet to be established, especially at 5G-specific frequencies. Research within vulnerable subpopulations, including children, pregnant women, and individuals with pre-existing disease, would be important to identify if exposure to 5G RF-EMF has 8 unique effects and whether such effects warrant targeted public health responses. The interaction of the 5G RF-EMF exposure with other environmental exposures has not been well-studied and would be important in order to present a more comprehensive picture of 5G's impact to health. Any future studies should include interdisciplinary collaboration by integrating biophysics, epidemiology, and toxicology to more completely provide the health impact of 5G.

5. Conclusion

The introduction of 5G mobile technology has the potential to yield transformative advances in connectivity and drive new applications in healthcare, transport, and communications. However, as compelling as those advances are, we must also keep in mind the attendant concerns about the potential health effects of 5G technology, specifically potential immunological, carcinogenic, reproductive, and neurological effects when conducting future research. Existing evidence demonstrates that 5G is within the safe thermal limits of exposure published by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and the Federal Communication Commission (FCC). However, the potential non-thermal effects, as well as long term effects of 5G technology on human health due to a lack of 5G-specific health research data, remains unknown. The thermal exposure limits and guidelines lend some measure of assurance of credibility to safety, but it is imperative that exposure limits also be revised to take into account new knowledge about other non-thermal processes and impact of exposure over long periods. Transparency in communication and stakeholder participation should be a key focus of public health initiatives to build public trust and reduce the spread of misinformation. However, interdisciplinary research will be instrumental in closing the gaps to assure the safe adoption of 5G technology and related network changes. With increased public dialogue between scientists, policymakers, and the public, it may be possible to reap the maximum benefits of 5G technology while minimizing public health implications.

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