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Effects of radiation on humans due to the proximity of 5G wearable device

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Abstract

The integration of fifth generation (5G) wireless technology into wearable electronics marks a critical advancement in personal health monitoring and real-time data transmission. However, the continuous proximity of these devices raises concerns on their possible harmful effects to the human body, particularly in the context of millimeter wave (mmWave) emissions. This review critically evaluates current evidence regarding the health effects of radiofrequency electromagnetic radiation (RF-EMR) emitted by 5G wearable devices, emphasizing translational findings across mechanistic *in vitro* investigation, *In vivo* animal models, and human epidemiological observational studies. We focused on studies employing frequencies in the 6–100 GHz range, reflecting the operational spectrum of mmWave 5G devices. *In vitro* investigations reveal alterations in reactive oxygen species (ROS) balance, calcium flux, tight junction integrity, and heat- and stress-related protein expression, particularly in dermal cell lines. Animal studies suggest that chronic exposure to RF-EMR may elicit oxidative stress, neuroendocrine disruption, and behavioral changes, even at intensities below regulatory thresholds. While human data remains limited, preliminary studies suggest subtle physiological effects such as altered heart rate variability and increased skin conductance, during prolonged exposure to smartwatches. Further investigations such as long-term and large cohort studies are needed to better understand exposure profiles and cumulative emissions from multiple wearable, and implantable devices and their effects on human health.

Keywords: Millimeter wave; 5g technology; Electromagnetic radiation; Radio frequency; *In vivo*

1. Introduction

The rapid miniaturization of hardware and expansion of next-generation wireless communication have expanded the advent of wearable 5G-enabled devices [1]. These include smartwatches, biometric sensors, fitness trackers, and a large class of health-monitoring accessories, all of which rely on continuous proximity to the body. This introduces an unprecedented exposure to radiofrequency electromagnetic radiation (RF-EMR) to the human body, at previously underutilized frequency bands [2], and a novel paradigm into possible pathophysiological effects. Indeed, the exact biological consequences of this exposure remain poorly characterized.

Current 5G infrastructure employs a heterogeneous spectrum, spanning sub-1 GHz, mid-band frequencies (1–6 GHz), and millimeter-wave bands (24–100 GHz). Notably, the high-frequency millimeter wave (mmWave) component, though limited in penetration depth, has raised specific concerns due to its confinement to superficial tissues, such as the skin and peripheral nerve endings [3]. Thus, the chronic, skin-adjacent placement of wearables devices or even the chronic implantation of health trackers creates a biologically plausible risk profile, with unknown components compared to previous exposure standards. International guidelines on non-ionizing radiation, including those from the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [4] and the Institute of Electrical and Electronics Engineers (IEEE) [5], have set limits mostly based on thermal effects and from population-level averages, with limited emphasis on the emerging paradigm of low-intensity chronic dermal/neuronal exposure [6]. Furthermore, wearable devices are

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often evaluated for compliance in isolation, rather than in the context of multiple devices worn simultaneously or in high-density signal environments, where effects may cumulate into biologically relevant body responses.

As further discussed below, preclinical investigation of non-thermal biological effects of low-intensity RF fields point towards considerable effects on oxidative stress, membrane potentials, calcium homeostasis and hormonal imbalances [7-12]. Thus, it is essential to further investigate the biological effects of 5G wearable devices and potential cumulative effects into the short – and long-term biological effects and the elicited heat, stress and immune responses. The objective of this review is to critically evaluate the current scientific understanding on the pathophysiological effects of RF-EMR generated by wearable 5G devices, with a particular focus on studies that elucidate pathophysiological changes in skin, neural, endocrine, and immune systems. We adopted a translational approach, beginning with mechanistic *in vitro* and *In vivo* animal data, progressing to human epidemiological evidence. Our work aims at generating interest toward gaps in knowledge and encouraging a more comprehensive risk-benefit assessment of 5G wearable integration into human life.

2. Principles of wearable 5G technology and Radiofrequency Electromagnetic Radiation (RF-EMR)

The fifth generation (5G) of wireless technology represents a structural leap in telecommunications, not only in terms of data transmission, speed and latency reduction, but in its reorganization of the electromagnetic spectrum. Unlike prior generations, 5G integrates a triad of frequency ranges: low-band (sub-1 GHz), mid-band (1–6 GHz), and high-band millimeter waves (24–100 GHz). Electromagnetic radiation emitted by 5G devices is non-ionizing in nature, meaning it lacks sufficient quantum energy to directly disrupt covalent molecular bonds or induce DNA strand breaks [13]. Nevertheless, it exhibits the capacity to induce biological alterations through dielectric heating, modulation of ion channels, and perturbation of oxidative balance [14-16]. Most existing safety thresholds, such as those defined by ICNIRP and IEEE, are predicated on bulk tissue heating (thermal effects), as quantified by the Specific Absorption Rate (SAR). For frequencies above 6 GHz, however, SAR becomes less physiologically representative, and power density (measured in W/m^2) is adopted as the regulator, making penetration depth a critical determinant of its biological impact [17]. Indeed, millimeter waves possess high atmospheric and dermal attenuation, typically limited to the superficial stratum corneum of the skin and upper dermis [18]. Although this limited penetration might appear innocuous, superficial layers of skin host a dense network of unmyelinated nociceptive fibers (type C), Langerhans cells, sweat glands, and microvascular loops, each of which can serve as a primary target for RF-EMR-induced stress responses [19]. Furthermore, the epidermis acts as a neuroimmune sentinel organ, translating environmental insults into systemic physiological responses [20]. In wearable applications, the proximity between the radiating element and the skin surface is typically <1 cm, and often in continuous contact. In contrast to mobile phones, whose radiation is intermittent and localized primarily to the head or hip, wearables emit low-power signals persistently and across varied anatomical sites such as wrist, chest, ear, and ankle, exposing multiple tissue compartments [21]. The expansion of 5G technology into the millimeter-wave domain of RF-EMR introduces a novel potential disruptor of biophysical systems with unprecedent knowledge on its safety and tolerability during chronic localized exposures [22].

Another dimension of complexity arises from beamforming and massive MIMO (Multiple Input, Multiple Output) technologies employed in 5G. These features dynamically focus radiation toward connected devices, optimizing energy delivery and spectral efficiency, but potentially creating localized hotspots on the skin and subdermal tissue with variable field intensities over time [23]. The biological response to these complex multi-stimulatory conditions may elicit nonlinear responses, amplification cascades, and cross-talk with intrinsic electric signaling mechanisms, yet to be fully understood [24].

3. Correlating Macro-/Small-Cell Exposure Limits to Wearable Devices: Distance Extrapolation Approach

To compare regulatory exposure thresholds for high-power macro- and small-cell transmitters with those for wearable devices, we assume power density "S" at distance "d" follows the inverse square law for isotropic sources:

$$S(d) = \frac{P_{out}}{4\pi d^2}$$

where P_{out} is the radiated power (W). International standards set limits for public exposure to prevent thermal effects, typically S_{lim} = 10 W/m^2 for frequencies above 6 GHz [4, 17, 25]. Macro- and small-cells operate at up to P_{out} = 60 dBm = 1000 W, while smartwatches emit at much lower power, producing measured skin-level densities of S_{watch} = 58 mW/m^2.

For macro-cells, the minimum safe distance d_{cell} for a given exposure limit S_{lim} is derived from

$$d_{cell} = \sqrt{\frac{P_{out}}{4\pi S_{lim}}}$$

For a wearable at power P_{watch}, the equivalent distance d_{watch} yielding the same S_{lim} becomes

$$d_{watch} = \sqrt{\frac{P_{watch}}{4\pi S_{lim}}}$$

The ratio:

$$\frac{d_{watch}}{d_{cell}} = \sqrt{\frac{P_{watch}}{P_{out}}}$$

provides the distance scaling between macro-cell and wearable exposures. Substituting P_{out} = 1000 W and P_{watch} = 58 × 10^{-3} W,

$$\frac{d_{watch}}{d_{cell}} = \sqrt{\frac{58\ x\ 10^{-3}}{1000}} \approx 0.0076$$

Thus, if d_{cell} = 10 m meets safety limits for a macro-cell, the equivalent permissible distance for a smartwatch is:

d_{watch} = 10 × 0.0076 = 0.076 m = 7.6 cm.

Given that smartwatches rest directly on the skin (d ≈ 0), cumulative thermal and non-thermal effects become plausible despite low power.

4. 5G *In vitro* and *ex-vivo* mechanistic studies

In vitro studies are essential to identify pathways and cellular defense mechanism activated during exposures to frequencies in the 6–100 GHz range. Among the most consistently observed phenomena is the induction of oxidative stress. Cultured human keratinocytes exposed to 60 GHz RF fields exhibited a significant increase in intracellular ROS production, mitochondrial depolarization, and suppression of catalase activity, all in the absence of measurable thermal elevation [26]. Similar findings were replicated in neuronal cell lines, where low-intensity mmWave exposure provoked alterations in calcium homeostasis, microtubule integrity, and expression of heat shock proteins [27]. Heat shock proteins are master regulators of the proteome, the total intracellular content of proteins, and by stabilizing the folding of proteins and proteasomal degradation of irreversible damaged proteins, guarantee cellular survival towards environmental stressors [28-30]. These stress-related protein responses reflect the cell's attempt to preserve homeostasis, even under non-thermal non-ionizing radiation, highlighting the importance of activated cellular dysfunction and defense mechanisms under this type of exposure. In a recent pre-print (2025), three-dimensional skin models (organotypic epidermal cultures) exposed to mmWave fields have shown changes in epidermal permeability, cytokine expression, and tight junction protein integrity, suggesting a possible compromised barrier function [31].

Additional studies have also outlined potential genotoxic effects of mmWaves. Comet assays and micronucleus tests performed on exposed fibroblasts, lymphocytes and leukocytes have yielded variable results, with some studies reporting increased DNA strand breaks or caspase-mediated apoptotic signaling under specific modulation patterns, while others failed to replicate these findings [32-35]. These inconsistencies may be attributable to frequency, exposure duration, waveform characteristics, and cell type heterogeneity. Indeed, biological effects arising from mmWave exposure may depend on cell cycle phase, antioxidant buffering capacity, and extracellular matrix context [36], making the establishment of exact dose-response curves challenging. Importantly, additional differences arise from cell-to-cell specificity, with reproductive cells showing the highest sensibility to non-ionizing radiation. Indeed, plenty of authors have investigated the effects of 4G phone-related radiations, identifying increased risks of defects during spermatogenesis, blood-testis barrier dysfunction and reduction of semen quality [37]. Although, other investigators have found that sperm motility is significantly impaired only when samples are located in proximity of a wi-fi source, and minimally when 4G or 5G RF-EMR is applied. In the same report, various effects were observed depending on distance from emitting source and also from the type of mobile phone cover utilized, increasing the complexity of developing standard dosimetry curves [38]. Given that the skin is the primary interface for wearable devices, it will be

essential to understand whether these effects on spermatogenesis observed *in vitro*, also replicate *In vivo*, thus suggesting that the 5G-related disruption of skin immunological and structural roles could translate into systemic effects.

Taken together, these studies provide compelling mechanistic plausibility for biological responses to 5G-relevant frequencies, particularly at the skin-tissue interface and reproductive systems. These findings warrant further exploration through integrative omics, high-content phenotyping, and co-culture systems, i.e. 3D cultures or organoids, that better approximate human physiology.

5. Preclinical investigation of 5G RF-EMR effects

Animal studies represent a foundational bridge between theoretical EMR biophysics and human translational relevance. Controlled *In vivo* models with rodent and non-rodent mammals have provided insight into organ-specific susceptibility, inflammatory cascades, neurobehavioral changes, and potential genotoxicity following radiofrequency electromagnetic radiation (RF-EMR) exposure [39-41]. Rodents exposed to RF-EMR within 900 MHz to 2.4 GHz bands (comparable to 2G-4G technologies) have exhibited histopathological changes in the testes, adrenal glands, liver, and brain, suggestive of tissue stress and endocrine disruption [42]. Notably, chronic low-level exposure increases the overall levels of lipid peroxidation, elevation of 8-OHdG, and perturbation of glutathione redox, which in turn may provoke oxidative DNA damage [43, 44]. The harmful effects on ROS production are further highlighted by the fact that the use of melatonin, a strong anti-oxidant compound [45], results in the mitigation of RF-EMR via inhibition of ferroptosis and Nrf2 pathway activation [46]. Some reports indicate that non-thermal RF-EMR are able to activate the hsp27/p38MAPK pathway in endothelial cells resulting in inhibition of caspase-3 apoptotic signaling and increase brain-blood barrier permeability and inflammation [47].

Other animal models have demonstrated alterations in behavioral domains, including increased anxiety-like behaviors, reduced locomotor activity, and disturbed circadian gene expression following exposure to high-frequency EMR [48]. Exposure to 700 and 3500 MHz 5G frequencies was also related to the persistence of anxiety-like behavior that was related to a decrease in acetylcholinesterase activity [49]. Mice exposed to asymmetric head exposures to 5G-3.5 GHz signals, do not display behavioral changes or memory impairment but in thorough examination provoke mild transcriptomics alterations [50]. There are also some studies that for similar radiation doses (60GHz, 8 weeks) have found no significant behavioral or systemic changes in either males of females mice [51].

The collection of contrasting results may arise from the few challenges normally faced during the preclinical investigation for RF-EMR toxicity. First, animals such mice and rats have shorter lifetimes, and may be unable to display the long-term effects of non-ionizing radiation. Indeed, changes in the transcriptome observed in the work of Lameth et al. may reflect alterations not yet visible clinically and that require longer experimental windows or larger *sample sizes* [50]. Another relevant limitation lies in the dosimetry translation. Rodent surface-to-volume ratios, metabolic rates, and thermal dissipation characteristics differ from humans [52, 53]. Nonetheless, the presence of dermal and subdermal alterations in these models raises legitimate concerns about long-term, skin-adjacent exposure from wearable devices operating at mmWave, with the potential for subclinical effects that may escape overt histological detection but alter biological signaling in subtle, chronic, and cumulative ways.

6. Human exposure and epidemiological surveillance studies to RF-EMR

Direct evidence of health effects from 5G wearable exposure in humans remains scarce. Most available human studies have assessed exposure to RF-EMR from mobile phones and base stations operating below 6 GHz, rather than wearable 5G devices utilizing millimeter waves [54, 55]. However, these datasets offer an essential foundation for hypothesis generation and risk extrapolation. Occupational studies, particularly among military personnel display increased prevalence of headaches, fatigue, memory impairment, and changes in EEG patterns following long-term exposure to high-frequency EMR [56]. Although these systems operated at higher power levels than wearable devices, the chronicity and cumulative burden of EMR exposure remain comparable. Similar results were found in a cross-sectional studies performed in a high school where phone cell users identified symptoms such as concentration difficulties, fatigue, sleep disturbances and warming of the hear in a dose-response matter [57]. Importantly, beside few initial studies linking phone usage with increased risk of being diagnosed with glioma or neurinoma [58, 59], large and prospective cohort studies on more than 250,000 participants have excluded a causative effects between phone use and development of brain tumors [60].

In a small double-blind crossover trial, participants wearing active and sham smartwatches showed no significant differences in acute cardiovascular or thermoregulatory parameters; however, subtle variations in skin conductance and cortisol levels were observed [61]. These findings underscore the potential for EMR to modulate autonomic tone and stress-related pathways, even in the absence of an identified physiological injury. Additionally, 5G devices have been available for limited time which limits the latency period required for chronic events, such as cancer of neurodegeneration, to manifest.

An area of concern is the usage of wearable device in patients with cardiac implantable electronic device (CIED), deep brain stimulators or others. While earlier smartphones seemed to not interfere with CIED functionality [62, 63], recent iPhone Promax 12 with MagSafe technology can cause magnet interference on CIEDs, during direct skin contact in the proximity of the CIED pocket [64, 65].

Taking together these findings highlight a potential risk arising from 5G continuous exposure. Wearable device, differently from phones, create continuous localized exposures, allowing for a stronger causative investigation into their dermatological- and neuronal-related biological effects. However, it will be important to establish large-scale, prospective, and device-specific investigations, particularly for vulnerable populations. These should integrate wearable exposure dosimetry, physiological biomarkers, and digital phenotyping to capture both acute, chronic and longitudinal health trajectories [66]. Additionally, with the increasing use of implantable cardiac, neuronal or stimulatory device, prospective multi-cohort studies are needed to establish safe guidelines and avoid dramatic complication from the interference between devices.

7. Wearable devices and standards guidelines

Current regulatory frameworks for RF-EMR exposure are largely predicated on thermal safety limits. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) and IEEE establish exposure limits based on SAR for frequencies up to 6 GHz and power density for higher frequencies [4, 6, 17]. These thresholds are designed to prevent tissue heating, assuming exposure occurs intermittently and at a distance from the body. However, wearable devices are neither intermittent nor distant. They are in direct contact with the skin for extended durations, often 24 hours per day. Compliance testing for wearables typically uses phantom models with uniform tissue conductivity, which do not recapitulate the heterogeneity of human skin, subcutaneous fat, and microvasculature [25]. Furthermore, beamforming and adaptive power control technologies introduce spatial and temporal fluctuations in radiation patterns that are not adequately addressed by static testing protocols. These factors challenge the validity of current compliance strategies and suggest that real-time dosimetry, accounting for anatomical location and individual physiology, may be necessary for accurate risk estimation.

The Federal Communications Commission (FCC) and European agencies have yet to establish dedicated exposure metrics for wearables emitting in the mmWave spectrum [67]. Regulatory gaps also exist for individuals using multiple RF-emitting devices simultaneously (e.g., smartwatch, Bluetooth earbuds, chest monitor). These amassed exposures may exceed safety thresholds locally, even if each individual device remains compliant. In light of these limitations, we believe that regulatory approaches should incorporate adaptive thresholds, device-specific anatomical models, and post-market surveillance mechanisms capable of detecting subclinical or rare adverse effects.

8. Future directions and research gaps

The scientific interrogation of 5G wearable device-related radiation effects is just at its beginning. Several critical knowledge gaps impede comprehensive risk assessment and the development of strong recommendations and rational guidelines. Indeed, there is an urgent need for animal studies designed to replicate chronic, localized, low-power exposure, mimicking wearable usage. These should integrate behavioral assays, molecular profiling, and imaging modalities to capture subtle phenotypic changes, otherwise untraceable. Particular emphasis should be placed on dermal immune responses, neurocutaneous interfaces, and endocrine feedback mechanisms. For these studies, it will be important not only to use small animals with replicable data, but also to expand investigation in large size animals, that more strongly resemble the hormonal fluctuations of human beings. Mechanistic studies must evolve from single-cell cultures to organotypic co-culture systems that include fibroblasts, keratinocytes, nerve terminals, and immune cells within a 3D scaffold. Such models would offer a closer approximation of the human skin microenvironment and allow exploration of paracrine signaling, extracellular matrix remodeling, and EMR-induced neuroimmune crosstalk.

Prospective cohort studies that stratify by device type, usage duration, anatomical site, and signal frequency are needed. These studies will offer real-time exposure quantification, wearable-integrated biosensors, and digital health metrics

(e.g., sleep, HRV, galvanic skin response). Lastly, interdisciplinary collaboration between telecommunications engineers, bio electromagnetics researchers, dermatologists, and regulatory scientists will be essential. Without such cross-sector coordination, the pace of wearable innovation may outstrip our ability to evaluate its long-term safety.

9. Conclusions

The integration of 5G technology into wearable devices constitutes a major advance in continuous health monitoring and personalized data acquisition. Yet, this innovation introduces a new form of sustained electromagnetic exposure for which biological effects remain poorly characterized. *In vitro, ex vivo and In vivo* studies have pointed towards few biological effects arising from 5G RF-EMR, mostly related to oxidative stress, disruption of membrane dynamics, and altered gene expression, even in the absence of thermal injury. Human studies, while limited, suggest potential modulation of autonomic and endocrine pathways.

While definitive causal links to adverse health outcomes remain elusive, there is an unmet clinical need for the further understanding of wearable-specific safety limits, cumulative exposure guidelines, and development of real-time dosimetry tools. We urge the scientific and regulatory community to adopt a precautionary approach grounded in evidence-based medicine including the development of longitudinal studies, refinement of exposure assessment technologies, and recalibration of regulatory thresholds to reflect real-world use patterns.

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