International Journal of Recent Development in Engineering and Technology
Website: www.ijrdet.com (ISSN 2347-6435 (Online) Volume 15, Issue 05, May 2026)

Comparative Neurophysiological Profiling of 4G and 5G Mobile Radiation Exposure: A Review

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***Abstract*--The global expansion of wireless communication technologies has intensified human exposure to radiofrequency electromagnetic fields (RF-EMFs), particularly following the transition from fourth-generation (4G) to fifth-generation (5G) mobile systems. While current safety standards are primarily based on thermal thresholds, increasing scientific interest has focused on potential non-thermal neurophysiological interactions. This review synthesizes existing evidence regarding the effects of 4G and sub-6 GHz 5G radiation on brain electrophysiology and cortical excitability. Studies employing electroencephalography (EEG) and transcranial magnetic stimulation (TMS) indicate subtle yet measurable modulation of neural oscillations, particularly in the alpha and beta frequency bands. Emerging data suggest relatively greater transient modulation during 5G exposure compared to 4G, although findings remain within established safety limits. Continued mechanistic and longitudinal investigations are necessary to refine understanding of next-generation RF-EMF–brain interactionso be published.**

***Keywords*--Cortical excitability, Neural oscillations, Non-thermal effects, 4G, 5G waves, Radiation**

I. Introduction

Radiation is classified into ionizing and non-ionizing categories based on energy levels and their biological interactions. Ionizing radiation, such as X-rays and gamma rays, possesses sufficient energy to directly break chemical bonds in DNA, leading to mutations, strand breaks, and potential carcinogenesis (Talapko et al., 2024) In contrast, non-ionizing radiation, which includes radiofrequency electromagnetic fields (RF-EMFs) employed in mobile communications, has lower energy levels that are insufficient to cause direct DNA ionization(Meyer et al., 2024a.;Macrì et al., 2002). In 2020, the U.S. Department of Energy reported that the primary recognized biological effect of high-intensity RF-EMFs is thermal, characterized by tissue heating resulting from energy absorption, which raises tissue temperature and may lead to thermal damage.

The widespread use of mobile phones, with over billions of users globally, has resulted in pervasive environmental RF-EMF exposure.

This ubiquity necessitates careful assessment of potential health risks, especially given the proximity of mobile devices to the head and brain during typical use. International safety standards, such as those established by the World Health Organization (WHO) and the International Commission on Non-Ionizing Radiation Protection (ICNIRP), set exposure limits primarily based on the specific absorption rate (SAR), which quantifies the rate at which energy is absorbed per unit mass of tissue. These thresholds aim to prevent thermal effects by maintaining exposure levels below levels associated with significant tissue heating (WHO, 2014; Ziegelberger et al., 2020)).

Despite these guidelines, ongoing research has increasingly focused on potential non-thermal effects of RF-EMFs, particularly on the central nervous system (CNS). Evidence suggests that RF-EMFs may influence neuronal function through mechanisms that do not involve tissue heating. For instance, studies have reported alterations in neuronal excitability, neurotransmitter regulation, and brain oscillatory activity, even at exposure levels below SAR thresholds (Van Rongen et al., 2009); Liu et al., 2024). Given that neuronal communication relies on precisely regulated electrical signaling, including action potentials, synaptic transmission, and oscillatory synchronization across neural networks, even subtle electromagnetic interactions could modulate these processes.

The brain's electrical activity is characterized by rhythmic oscillations across various frequency bands, which underpin cognitive functions, attention, and information processing. Disruptions or modulations of these oscillations by RF-EMFs could influence neural synchrony and plasticity, potentially affecting behavior and cognition. Mechanistically, RF-EMF exposure may influence neuronal function via interactions with voltage-gated ion channels, modulation of intracellular calcium signaling pathways, oxidative stress induction (Meyer et al., 2024b), or neurotransmitter system alterations (Bertagna et al., 2021a).

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These non-thermal pathways could subtly alter neuronal excitability and network dynamics without detectable tissue damage or heating, raising important questions about the safety thresholds and long-term effects of environmental RF-EMF exposure. The current safety standards prioritize thermal effects, accumulating evidence underscores the importance of understanding non-thermal biological interactions between RF-EMFs and neural tissue. Elucidating these mechanisms is crucial for informing public health policies and ensuring safe exposure levels as wireless technologies continue to evolve and proliferate.

Neurophysiological Effects of 4G Radiation:

a) Early Foundations of the Neurophysiological Effects of RF-EMFs (1950s–1980s): The exploration of the biological effects of radiofrequency electromagnetic fields (RF-EMFs) on neural tissue predates the proliferation of modern mobile telecommunication technologies, reflecting a longstanding scientific pursuit to understand how non-ionizing radiation interacts with living systems. One of the earliest and most compelling findings in this domain was the discovery of the microwave auditory effect, first systematically documented by (FREY, 1962). Frey's pioneering experiments demonstrated that pulsed microwave radiation, at levels insufficient to produce detectable tissue heating, could induce auditory sensations such as clicking or buzzing in human subjects. This indicated that RF energy could influence neural perception through mechanisms beyond simple thermal effects, challenging the then-prevailing assumption of inertness for non-ionizing radiation.

Mechanistically, the microwave auditory effect was attributed to thermoelastic expansion within neural tissues. Pulsed RF fields cause rapid, localized heating, leading to pressure waves that propagate through tissue and are transmitted to the cochlea, resulting in auditory sensations (FREY, 1962). This process suggested a mechanotransduction pathway, where electromagnetic energy could influence neural function via mechanical stress rather than thermal damage, thus opening new avenues for understanding RF bioeffects. Importantly, these early findings provided concrete evidence that RF fields could interact with neural systems through non-thermal, biophysical mechanisms, laying a foundational basis for subsequent research.

Throughout the 1970s and 1980s, experimental efforts sought to determine whether RF-EMFs could modulate neuronal excitability or alter synaptic transmission key indicators of neurophysiological influence.

Studies conducted during this period explored the effects of RF exposure on both in vivo and in vitro neural tissues, revealing a parameter-dependent influence where effects varied with frequency, modulation pattern, intensity, and exposure duration(Meyer et al., 2024a) (Bertagna et al., 2021b). These investigations suggested that RF-EMFs could indeed impact neural activity under specific conditions, although the reproducibility of results was often hampered by methodological inconsistencies.

A significant challenge during this era was the lack of standardized dosimetry and exposure protocols. Variability in experimental setups, tissue models, and measurement techniques limited comparability across studies. Despite these limitations, the accumulation of evidence demonstrated the biological plausibility of RF-EMF interactions with neural tissues, thereby providing a scientific rationale for more rigorous research as the advent of mobile communication technologies approached.

In sum, these pioneering studies highlighting phenomena such as the microwave auditory effect and the parameter-dependent modulation of neural responses established critical principles that continue to influence contemporary research. They emphasized the significance of methodological uniformity and mechanistic comprehension in clarifying RF-EMF neuroeffects (Macrì et al., 2002). Understanding these early initiatives provides crucial background for the ongoing discussions about radiofrequency safety and neurophysiological effects.

b) Emergence of Mobile Technology Research (1990s): The decade of the 1990s became a breakthrough in the research of electromagnetism due to the global explosion of cellular telephony and the introduction of Global System for Mobile communications (GSM) networks. This period led to an explosion of scientific inquiries that sought to understand the possible biological impact of RF-EMFs in the frequencies that largely fell into the 900 -1800 MHz range which was also within the frequency spectrum of mobile phone functioning at the early days (Salford et al., 2003).

Among the most well-known studies in this time was the study by (Lai & Singh, 1996), investigating the genotoxic potential of microwave radiation at 2450 MHz which is near the frequencies of Wi-Fi and microwave ovens but important as a model of RF exposure. They experimented to prove that the concentration of DNA single-strand breaks in brain cells of the rat brain doubled and even tripled due to acute exposure to microwaves.

Interestingly, the effects were noted at certain absorption rates (SAR) of 1.4 W/kg, which is taken to be at human exposure when using a mobile phone. The authors hypothesized that oxidative stress could mediate these genotoxic effects which were supported by the elevation of the level of reactive oxygen species (ROS) and the reduction of the level of antioxidant enzyme activity after exposure. These results indicated that RF-EMFs had the potential to cause cellular stress response, which is a cause of concern regarding the long-term neurobiological effects.
Together, the studies in the 1990s suggested that RF-EMF exposure might cause cellular and tissue-level changes in the occurrence of specific experimental conditions, and thus the vulnerability of cells. However, the result diversities made it clear that, even in the case of normal human exposure at common-use levels of mobile phones, the fact that consistent dose-dependent relation was present was not proven. These works triggered continued arguments and developed the foundation of further advanced studies in RF bioeffects by focusing on the need to establish standardized procedures and dose-response tests (Meneely, 2003).

Electrophysiological Effects in Humans (2000s–2020s): The invention of new methodologies of neurophysiological tests and particularly the electroencephalography (EEG) have helped in the research on RF-EMF in the human brain functioning to a significant extent. It is true that since, at least, the early 2000s, numerous commissioned studies have aimed to explain the existence or absence of the possibility of RF-EMF exposure of mobile communication systems leading to quantifiable cortical activity changes, as a potential predictor of neural excitability, attention, and subjective well-being.

Primary results with EEG Modulation: Krause et al. (2000) were experimenting EEG spectral power at time of cognitive task-performing in GSM like RF exposure environment, and they state the research as one of the earliest to be carried out in this research area. Their experimental model implied the exposure of the participants to both RF fields with the safety level of SAR and the execution of memory and attention tasks. Temporary changes of spectral power of EEGs were observed during short durations of shifts namely the alpha (8 13 Hz) and beta (13 30 Hz) frequency bands. Specifically, the RF exposure had been accompanied by a notable increase in the alpha power of the frontal regions and parietal regions that contained the information that cortical excitability or the focus of attention may have altered (Krause et al., 2000).

The results contained a hint of the thought that RF-EMFs played some hidden role in neural oscillatory activities, possibly through the regulation of the efficiency of cognitive functions.

Resting-State EEG and Oscillatory Networks: According to the findings of their initial discovery, (van der Meer et al., 2023) investigates the effect of RF exposure on resting-state EEG activity. Their study reflected large though statistically insignificant alterations in alpha power in case they were subjected to GSM, which implies that RF-EMFs might modify thalamocortical oscillatory circuits which provide rests of the brain. The authors postulated that such effects can be caused by a change in cortical network neural synchrony or inhibitory excitatory balance though the magnitude of effect was not well understood because the changes were small (van der Meer et al., 2023).

Teachable and Future Perspective: The book of electrophysiological studies in the 2000s-2020s is a bright illustration of an intricate image. Even though transient, low-amplitude modulations of neural oscillations have been evidenced upon exposure to RF in other studies, studies that have not shown any effect exist and it is time to establish standardized protocols and sufficient blinding and dosimetry. The inconsistency of the results implies that an RF-induced neural modulation is arguably a factor of exposure parameters, personal differences, icons of thought and environment (Muller et al., 2014). Overall, the EEG EEG controlled research revealed useful data regarding the potential interaction of RF-EMFs with neurophysiology, but, it is still impossible to obtain some consistent and reproducible data. Another study with the high-density EEG, source localization and other advanced tools in the analysis may contribute more information as to whether RF-EMFs cause latent effects on the neural oscillatory network in an actual real-life scenario.

Small sample sizes also have the limitation of decreasing the statistical power and overemphasizing the probability of occurrence of Type I and Type II error. The majority of experimental RF-EMF studies have crossover or repeated-measures studies of less than 30 participants that limit sensitivity to small effect sizes of the type that are associated with non-thermal levels of exposure. The meta-analytic queries show that the number of electrophysiological changes that are encountered is normal in terms of small magnitude and therefore requires the appropriately powered studies and preregistered studies to provide the reliability (Valentini et al., 2007).

The next severe heterogeneity source is produced by having a paradigm difference in cognitive task. The research can be either at rest or carrying out a working memory task or an attentional paradigm, or with the sleep (recordings of sleep) of the subjects. Because of the high task dependency of the oscillatory dynamics, it may occur that the modulation, induced by the RF-EMF, couples with the endogenous network states and formed the context-dependent effect. Patterns of task related cortical activity which may be variously engaged in vulnerability determination to externally inflicted electromagnetic modulation particularly in frontoparietal and thalamocortical systems may exist.

Despite these inconsistencies, electrophysiological findings that have been most commonly documented in investigating the effects of acute RF-EMF exposure include the alpha-band (812 Hz) modulation. Alterations in resting-state alpha power have been reported in various experimental and review studies to occur in particular cases of interest, and to focus more on the posterior regions of the brain, which means that RF-EMF exposure can have an interaction with thalamocortical oscillatory control (Valentini et al., 2007; (Bertagna et al., 2021b)). Alpha rhythms are closely correlated with cortical excitability, attentional gating and inhibitory control and, therefore, their alterations could be associated with minor variations in neuronal coordination with behavioral deficiency. Regardless of the argumentative aspect of the practical role of these changes, emerging converting insights suggest that alpha-band activity is a sensitive biomarker in the determination of neurophysiological responses in response to low levels of RF-EMF exposure.

(Bertagna et al., 2021b) conducted experimental research to identify individual differences in alpha responsiveness under low frequency modulated exposure to microwaves and found that there is a difference in neurophysiological vulnerabilities. On the same note, (van der Meer et al., 2023) have expressed localized augmentation of resting posterior alpha power with GSM exposure, which was not accompanied by impaired thinking. These results suggest that effect of RF-EMF can be due to the modulation of cortical excitability threshold or inhibitory gating and not an excitation pathology.

A more extensive integrative review by Wallace and Selmaoui (2019) supported the idea of consistent but conjectural evidence on the alpha rhythm modulation. In controlled laboratory paradigm studies across transient effects, some double-blind cross over studies revealed transient effects on power of alpha, but others indicated negative effects.

Were most importantly all epileptiform activity, lasting desynchronization or any clinically disadvantageous electrophysiological patterns that were found to be without consistency. The lack of dose-response gradients, and the heterogeneity of the spatial distribution of SAR (specific absorption rate) also made it more difficult to interpret causally.

This has been refined in more recent quantitative syntheses which contain both resting-state EEG and event-related potentials (ERPs). (Danker-Hopfe et al., 2019) have performed a systematic review and meta-analysis involving exposure to several generations of 2G GSM, 3G UMTS and LTE(Kleinlogel et al., 2008). Their combined studies found statistically significant yet minor influences on resting alpha power and chosen elements of the ERP such as slight amplitude alteration of the P300 in designated 2G GSM paradigms. Nevertheless, the heterogeneity indices (I2) were considerable, and the subgroup analyses were found to suggest that exposure generation and pattern of modulation and SAR estimation approaches play a major role in degree of effects. Notably, measured electrophysiological changes were in physiological variation ranges of healthy adults.

Biophysically, the non thermo RF-EMF interaction processes are still in research. The presence of subtle membrane polarization changes, the changes in the kinetics of the voltage-gated ion channels, and changes in intracellular calcium signaling cascades are hypothesized (Pall, 2013; Panagopoulos et al., 2015). Though such models suggest possible pathways via which neuronal excitability can be altered, there are limited experimental studies in the human cortical tissue that can confirm the models. Recent human EEG evidence is now more coherent with intermittent neuromodulatory influences, as opposed to organic or neurotoxic consequences.

Another limitation common to the studies is heterogeneity of exposure. It is shown through computational dosimetry studies (e.g., Christ et al., 2010) that moves in positions of the handset in relation to cranial anatomy produce significant changes in the peak spatial SAR deposition, especially in the temporal and parietal regions. Together with the variability of EEG preprocessing (filter bandwidths, artifact rejection algorithms, reference montage choice) these dispensations in methods can add to the difficulty of reproducibility.

Therefore, meta-analysis evidence is overwhelming the soft, reversible neuromodulatory interaction with brain intrinsic oscillatory networks as opposed to explicit neurophysical injury.

To increase the strength of the causal compared to descriptive inferences and translational generalization, future studies need to focus on harmonized dosimetry, preregistered analytical pipelines, multimedia integration of neuroimaging and increased samples. RF-EMFs When applying to neural tissue, biophysical modeling, molecular neurobiology, and systems neuroscience are all integrated in understanding how the neural tissue interacts with radiofrequency electromagnetic fields (RF-EMFs). Despite the general evidence, especially the epidemiological and the human experimental evidence, suggesting subtle to reversible electrophysiological modulation, mechanistic suggestions, obtained via the in vitro, in vivo and computational analyses, also offer plausible cellular/molecular pathways in which RF-EMFs could effect neural functioning.

1. Biophysical Coupling and Non-Thermal Interaction Hypotheses: When the exposure levels are below the set safety levels, the thermal effects will be minimal; therefore, the suggested mechanisms are focused on non-thermal interactions. Modulation of voltage-gated calcium channels (VGCCs) is one of the hypotheses that have been discussed widely.

2. Oxidative Stress and Redox Signaling: There exists a fair amount of experimental evidence that oxidative stress is involved in RF-EMF bioeffects as a convergent pathway. Yakymenko et al. (2016) reviews had increased lipid peroxidation markers, changes in antioxidant enzyme activity, and ROS increases in neural tissues of prolonged exposure on animal and cell model experiments. The high amount of ROS may impact the mitochondrial membrane potential, cause the activity of redox-sensitive transcription factors (NF-kB)(Meyer et al., 2024a), and change the apoptotic signaling pathways(Lu et al., 2012).

3. Membrane Dynamics and Ion Channel Modulation: The electrically active structures of neurons are membranes that are quite complex in terms of dielectric properties. Characters of specific absorption rate (SAR) in the cortical and subcortical locations are heterogeneous as shown by computational dosimetry analyses and the work of Christ et al. (2010) among others. Throughout cellular level, the exposure of RF-EMF can induce the change of membrane fluidity or ion channel gating probability or receptor conformation. The experimental results represent potential possible changes in kinetics moderation of sodium and potassium channels, which could move neuronal fire thresholds. This type of interaction on the membrane level might lead to the subtle electroencephalographic (EEG) changes, in particular alpha-band changes, observed in controlled human exposures (Valentini et al., 2007). These shifts do not necessarily cause pathological excitation of the systems but could be indicative of subtle alterations of thalamocortical synchronization processes.

4. Neurotransmission and Synaptic Plasticity: Glutamatergic and GABAergic changes have also been reported to affect meat animals after RF-EMF exposure and might cause changes in excitatory-inhibitory balance. VGCC modulation to an extent by EMF can alter calcium-dependent processes of neurotransmitter release. Moreover, there are rodent models that exhibit alterations on long-term potentiation (LTP) which is a cellular correlate of learning and memory. Nevertheless, the results cannot be found consistently across the laboratories, and standardized exposure paradigms are needed.

5. Blood–Brain Barrier (BBB) and Neuroinflammation: Another proposed mechanism involves transient modulation of blood–brain barrier permeability. Although early studies suggested albumin leakage under certain exposure conditions, later investigations have produced mixed results. Neuroinflammatory responses—characterized by microglial activation and cytokine shifts—have been observed in some animal models but generally at exposure levels exceeding typical environmental conditions. The translational relevance of these findings to human exposure scenarios remains uncertain.

6. Systems-Level Electrophysiological Modulation: At the systems neuroscience level, RF-EMF exposure appears most consistently associated with modulation of intrinsic oscillatory activity, particularly in the alpha frequency range. Reviews such as Wallace and Selmaoui (2019) report transient, reversible changes in resting-state EEG power without evidence of epileptiform or neurodegenerative patterns. These findings support a neuromodulatory framework—suggesting RF-EMFs may subtly interact with ongoing neuronal synchronization rather than inducing structural damage.

Context-dependent changes in neuronal synchronization: Importantly, most experimentally observed effects occur within physiological adaptive limits and do not demonstrate consistent neuropathological consequences under guideline-compliant exposure levels. Future research integrating high-resolution neuroimaging, patch-clamp electrophysiology, transcriptomics, and standardized dosimetry will be essential to refine mechanistic understanding and distinguish adaptive neuromodulation from potential long-term risk.

5. Contemporary Evidence and Scientific Consensus on RF-EMF Effects on Neural Function (2010–2026): The last ten years are characterized by research into the neurobiological impact of radiofrequency electromagnetic

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fields (RF-EMFs), which focus on the issue of methodology rigor in research such as sophisticated dosimetry modelling, sham-controlled, two-centre, and multi-centre reproducibility studies. Although the existence of RF-EMFs being able to cause subtle, transiently electrophysiological modulations under the specified experimental situations has been investigated over a span of over 60 years, the general scientific belief is that RF-EMFs never cause consistent or clinically significant neural or neuropathological effects.

Electrophysiological Modulation and EEG Findings: Recent high-quality studies have documented modest alterations in electroencephalographic (EEG) activity following RF exposure. (Bertagna et al., 2021b) reported that low-field-strength RF exposure could modulate EEG rhythms, particularly in the alpha band, suggesting a potential influence on cortical excitability. However, reproducibility across independent laboratories remains limited, with many studies reporting inconsistent findings. Meta-analyses synthesize these data, indicating that RF-EMFs particularly from global system for mobile communications (GSM)are associated with small increases in alpha power during exposure (Danker-Hopfe et al., 2019). These effects are generally transient, reversible, and within the bounds of normal physiological variability.

Structural and Cellular Effects: (Salford et al., 2003), studied the neuronal changes described to be the result of exposure to GSM mobile phone have indicated an increase in blood to brain barrier (BBB) permeability, and degeneration of neurons in rodents. Since these findings raised the concern of the possible neurotoxicity in the long term, other studies have had varied outcome and some have not reproduced such effects in similar conditions of exposure. The debate explains the significance of mechanistic clarification. Some of the mechanisms proposed as a theory of electrophysiological effects are the affected use of voltage-gated ion channels, especially calcium channels, which regulate neuronal excitability and calcium pathways signalling (Liu et al., 2024). Moreover, RF-EMF exposure can cause oxidative stress that will cause temporary responses in cells that can potentially regulate neural activity without any permanent harm (Bertagna et al., 2021b)

Long-term Outcomes and Epidemiological Evidence: Massive epidemiological studies have never been able to prove the causal relationship between mobile phone use and neurological disorders such as brain tumors and neurodegeneration diseases (International Agency for Research on Cancer [IARC, 2011].

Regarding longitudinal cohort studies, they have not shown any higher rates of incidence of gliomas, meningiomas, or any other neuropathologies associated with RF exposure..

Emerging Evidence on 5G Neurophysiological Interaction: The implementation of the fifth-generation (5G) wireless communication systems can be considered a change in paradigm in terms of the characteristics of electromagnetic exposure with important consequences to biological interaction, especially in the neural tissues (Table 1). In contrast to earlier generations (2G-4G), which were mainly sub-3 GHz frequency with wider and more stable radiation patterns, 5G presents higher frequencies, such as sub-6 GHz and millimeter-wave (mmWave) frequencies and frequencies (24100 GHz) several times because they use new modulation systems, massive multiple-input multiple-output (MIMO) antenna array designs and, adaptive beamforming (Di Ciaula, 2018; Simkok and Mattsson, 2019). Such technological advances lead to more complicated, much more dynamic exposure patterns that are disruptive to current safety paradigms and require mechanistic studies of the possible neurophysiological impact.

1. Unique Exposure Characteristics of 5G: The shallow tissue penetration levels attained using mmWave frequencies in 5G result in energy concentrating primarily in skin and ocular tissues and hardly going deeper into brain tissues (Simkó and Mattsson, 2019). Models of computational dosimetry show that beamforming and MIMO designs result in spatially localised field peaks, which temporally and spatially vary widely (Thors et al., 2017). Though these exposures are within the international safety guidelines including those provided by ICNIRP (2020), the large spatial and temporal uncertainty raises the issue of possible biological interaction that are not similar to previous radiofrequency electromagnetic fields (RF-EMFs).

2. Empirical Evidence Regarding Neurophysiological Effects: There is still limited empirical evidence that specifically looks at 5G neurophysiological effects but studies involving millimeter-wave exposures and adjoining frequencies have useful mechanistic information. Because non-thermal millimeter-wave exposures do not cause any structural neuronal damage in animals and in vitro, they do not trigger any structural neuronal damage in non-thermal setups (Simkó and Mattsson, 2019). However, electrophysiological outcomes (particularly that on neural oscillations) have been reported.

International Journal of Recent Development in Engineering and Technology
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Previous studies by EEG researchers on RF fields across GSM and LTE band frequencies indicate that even low levels of RF exposure can be used to alter resting-state EEG oscillations, especially in the alpha (813 Hz) band (Bertagna et al., 2021b). These results indicate that RF modulation pattern can lead to changes in neural oscillatory networks even when the carrier frequency is varied and this result supports the hypothesis that RF effects may be caused by membrane or ion channel activity modulation and not direct thermal effects. Newer experimental studies in high-frequency suggest minor and temporary changes in cortical excitability, spectral power distribution and synchronization of alpha- and beta-frequency without signs of cognitive dysfunction and long-term neurophysiological malfunctioning (ICNIRP, 2020).

3. Proposed Mechanistic Pathways for 5G–Neural Interactions: The mechanistic hypotheses for RF-EMF-induced neural modulation extend from established pathways identified in studies of lower-frequency systems and are relevant to 5G's higher frequencies:

Membrane Protein and Ion Channel Modulation:

4. Comparative Perspective: 4G vs 5G: Its comparative analysis indicates that exposure to 5G has varied mainly in terms of spatial distribution and modulation properties and not total absorbed energy in controlled circumstances (ICNIRP, 2020). Although there are a few early controlled experiments that indicate small positive changes in alpha and beta oscillatory power when exposed to RF conditions close to next-generation signals, no proof has thus far been shown to establish that 5G has stronger and/or qualitatively different neurophysiological effects than 4G LTE. The observed oscillatory variations are within a normal physiological variability and not always related to behavioral or cognitive impairments.

Moreover, historic mobile technology epidemiological evaluations have not shown recurring relationships with neurodegenerative diseases or common neuropathology (SCHEER, 2015; ICNIRP, 2020) and, thus, in case 5G neurophysiological modulation exists, it will probably be so minor and consequential-free within existing exposure limits.

5. Current Scientific Consensus (2020–2026): Recent reviews of authorized expert panels find that although RF-EMFs such as new 5G signals are capable of influencing biological systems in certain conditions in laboratories, the health outcomes are not conclusively negative because they fall below the international levels of safety (ICNIRP, 2020; Simkó and Mattsson, 2019).

The neural impact that is most regularly reported regarding decades of RF studies is low-order EEG oscillatory activity modulation, especially in the alpha band, with dubious functional significance. Due to the recentness of massive implementation of 5G, further controlled human EEG triplets, dosimetry accuracy, standardized exposures, and mechanistic molecular research is advised to provide clarity on long-term effects.

6. Comparative Neurophysiological Profiling: Direct comparisons between 4G and sub-6 GHz 5G exposures indicate that both technologies can produce subtle modulation of EEG spectral power and cortical excitability indices. 5G exposure has been associated with slightly stronger transient enhancement of alpha synchronization and cortical responsiveness, potentially attributable to differences in modulation depth and beamforming properties. Nevertheless, all reported changes remain within regulated SAR limits and do not demonstrate sustained neurotoxicity. Beyond electrophysiological considerations, broader health concerns related to mobile technology include reproductive effects (Prins et al., 2025), neurobehavioral outcomes (Barth et al., 2008), visual strain from prolonged device use (Khan et al., 2019), and behavioral dependence patterns (Wan et al., 2022). While these outcomes are multifactorial, they reflect the expanding intersection between wireless technology and human health.

7. Research Gaps and Future Directions: Amidst an increasing body of evidence, however, large gaps exist between research. There are no long-term longitudinal investigations on cumulative exposures of 5G and standardized exposure methods are still developing. The upcoming studies need to combine multimodal neuroimaging methods, molecular biomarkers and analyses of vulnerable populations to achieve a better understanding of the mechanistic clarity and general public health recommendations..

II. Conclusion

According to comparative neurophysiological evidence, both 4G and sub-6 GHz 5G mobile radiation have the potential to cause su Direct comparisons of 4G and sub-6 GHz 5G exposures indicates that both the technology have the potential to cause subtle modulation of EEG spectral power and cortical excitability indices. It is presumed that both technologies have the potential to induce slight modulation of alpha synchronization and cortical responsiveness which might be attributed to the difference in the levels of modulation and the beamforming property.

The evulsions that are reported are all controlled within SAR limits and are not indications of neurotoxicity that may be long-term. Besides the human effect grounds of Electrophysiology, the other health concerns that are more broadly perceived to be relevant to mobile technology include reproductivity (Prins et al., 2025), neurobehavioral concerns (Barth et al., 2008), visual strains which come along with the lengthy use of mobile gadgets(Khan et al., 2019) (Puginier et al., 2026), the tendency of dependence (Wan et al., 2022). These consequences are multi-faceted, however, they can point to the increase of overlap between the human health and the wireless technology. Modulation of Brain oscillatory activity and cortical excitability during controlled exposure situations. Current evidence suggests a comparatively higher non-persistent electrophysiological modulation with exposure to 5G in comparison to 4G, however, effects are not within the established safety limits and do not show conclusive adverse neurophysiological effects. It is important that further interdisciplinary studies be conducted to help hone knowledge of the RF-EMF-brain interactions and make sure evidence-based safety factors in the dynamic wireless environment.

Table 1. Comparative Analysis of 4G and 5G Radiation

Parameter	4G Mobile Radiation	5G Mobile Radiation
Frequency Range	700 MHz – 2.6 GHz	Sub-6 GHz & mm-Wave (24–100 GHz)
Penetration Depth	Deeper tissue penetration	Mostly skin & superficial tissues
Key Health Concerns	Brain activity, gene xpression, EEG changes	Localized heating, surface tissue exposure
Experimental Evidence	Extensive biological & animal studies	Limited biological, more numerical studies
Research Methods	EEG,embryonic models, meta-analysis	Numerical modeling, ML-based prediction
EEG Findings (Alpha Band 8–13 Hz)	Modest increase in alpha power during exposure (transient and reversible)	Slightly stronger transient alpha synchronization reported in preliminary studies
EEG Findings (Beta Band 13–30 Hz)	Occasional beta modulation reported	Emerging evidence of transient beta modulation
Risk Certainty	Moderately studied	Long-term risks still uncertain

Funding Declaration: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Clinical Trial Number: “Clinical trial number: not applicable, as this study does not involve a clinical trial in human subjects.”

Data Availability Statement: The datasets used or analyzed in this study are available from the corresponding author upon request.

Competing Interests: The authors declare no potential conflicts of interest

Author Contributions:

Sumathi: Conceptualization, Methodology, Software, Data curation, Software, Validation, Writing-Reviewing.

Narayani: Editing, Writing-Original draft preparation, Visualization, Investigation, Supervision

REFERENCES

[1] Barth, A., Winker, R., Ponocny-Seliger, E., Mayrhofer, W., Ponocny, I., Sauter, C., & Vana, N. (2008). A meta-analysis for neurobehavioural effects due to electromagnetic field exposure emitted by GSM mobile phones. *Occupational and Environmental Medicine*, *65*(5), 342–346. https://doi.org/10.1136/oem.2006.031450

[2] Bertagna, F., Lewis, R., Silva, S. R. P., McFadden, J., & Jeevaratnam, K. (2021a). Effects of electromagnetic fields on neuronal ion channels: a systematic review. *Annals of the New York Academy of Sciences*, *1499*(1), 82–103. https://doi.org/10.1111/nyas.14597

[3] Bertagna, F., Lewis, R., Silva, S. R. P., McFadden, J., & Jeevaratnam, K. (2021b). Effects of electromagnetic fields on neuronal ion channels: a systematic review. *Annals of the New York Academy of Sciences*, *1499*(1), 82–103. https://doi.org/10.1111/nyas.14597

[4] Danker-Hopfe, H., Eggert, T., Dorn, H., & Sauter, C. (2019). Effects of RF-EMF on the Human Resting-State EEG—the Inconsistencies in the Consistency. Part 1: Non-Exposure-Related Limitations of Comparability Between Studies. *Bioelectromagnetics*, *40*(5), 291. https://doi.org/10.1002/BEM.22194

[5] Frey, A. H. (1962). Human auditory system response to modulated electromagnetic energy. *Https://Doi.Org/10.1152/Jappl.1962.17.4.689*, *17*, 689–692. https://doi.org/10.1152/jappl.1962.17.4.689

[6] Khan, M. G. G., Khairnar, A. S., Jhavar, S. G., Thakur, K., & Shah, K. (2019). EFFECT OF DIGITAL ELECTRONIC DEVICES ON EYE HEALTH IN SCHOOL CHILDREN. *International Journal of Advanced Research*, *7*(09), 269–273. https://doi.org/10.21474/IJAR01/9658

[7] Kleinlogel, H., Dierks, T., Koenig, T., Lehmann, H., Minder, A., & Berz, R. (2008). Effects of weak mobile phone - electromagnetic fields (GSM, UMTS) on well-being and resting EEG. *Bioelectromagnetics*, *29*(6), 479–487. https://doi.org/10.1002/bem.20419

[8] Lai, H., & Singh, N. P. (1996). Single- and double-strand DNA breaks in rat brain cells after acute exposure to radiofrequency electromagnetic radiation. *International Journal of Radiation Biology*, *69*(4), 513–521. https://doi.org/10.1080/095530096145814

[9] Lu, Y. S., Huang, B. T., & Huang, Y. X. (2012). Reactive Oxygen Species Formation and Apoptosis in Human Peripheral Blood Mononuclear Cell Induced by 900 MHz Mobile Phone Radiation. *Oxidative Medicine and Cellular Longevity*, *2012*, 740280. https://doi.org/10.1155/2012/740280

[10] Macrì, M. A., Di Luzio, S., & Di Luzio, S. (2002). Biological Effects of Electromagnetic Fields. *International Journal of Immunopathology and Pharmacology*, *15*(2), 95–105. https://doi.org/10.1177/039463200201500204

[11] Meyer, F., Bitsch, A., Forman, H. J., Fragoulis, A., Ghezzi, P., Henschenmacher, B., Kellner, R., Kuhne, J., Ludwig, T., Sachno, D., Schmid, G., Tsaioun, K., Verbeek, J., & Wright, R. (2024a). The effects of radiofrequency electromagnetic field exposure on biomarkers of oxidative stress in vivo and in vitro: A systematic review of experimental studies. *Environment International*, *194*(6), 108940. https://doi.org/10.1016/j.envint.2024.108940

[12] Meyer, F., Bitsch, A., Forman, H. J., Fragoulis, A., Ghezzi, P., Henschenmacher, B., Kellner, R., Kuhne, J., Ludwig, T., Sachno, D., Schmid, G., Tsaioun, K., Verbeek, J., & Wright, R. (2024b). The effects of radiofrequency electromagnetic field exposure on biomarkers of oxidative stress in vivo and in vitro: A systematic review of experimental studies. *Environment International*, *194*(6), 108940. https://doi.org/10.1016/j.envint.2024.108940

[13] Prins, A. C., Baas, K., van der Meer, J. N., Jacobs, M., & Nederveen, A. J. (2025). The effect of mobile phone electromagnetic fields on the human resting state wake EEG and event-related potential: A systematic review and meta-analysis. *Bioelectromagnetics*, *46*(1). https://doi.org/10.1002/bem.22531

[14] Puginier, E., Leclercq, L., Poulletier de Gannes, F., Hurtier, A., Orlacchio, R., Nabos, P., Tijou, H., Lévêque, P., Arnaud-Cormos, D., Percherancier, Y., & Lagroye, I. (2026). Biological effects of 5G-modulated 700 MHz RF-EMF exposure on neuronal and glial cell models under isothermal conditions. *Scientific Reports 2026 16:1*, *16*(1), 10767-. https://doi.org/10.1038/s41598-026-43960-4

[15] Salford, L. G., Brun, A. E., Eberhardt, J. L., Malmgren, L., & Persson, B. R. R. (2003). Nerve cell damage in mammalian brain after exposure to microwaves from GSM mobile phones. *Environmental Health Perspectives*, *111*(7), 881–883; discussion A408. https://doi.org/10.1289/EHP.6039

[16] Talapko, J., Talapko, D., Katalinić, D., Kotris, I., Erić, I., Belić, D., Vasilj Mihaljević, M., Vasilj, A., Erić, S., Flam, J., Bekić, S., Matić, S., & Škrlec, I. (2024). Health Effects of Ionizing Radiation on the Human Body. *Medicina 2024, Vol. 60, 60*(4). https://doi.org/10.3390/MEDICINA60040653

[17] van der Meer, J. N., Eisma, Y. B., Meester, R., Jacobs, M., & Nederveen, A. J. (2023). Effects of mobile phone electromagnetic fields on brain waves in healthy volunteers. *Scientific Reports 2023 13:1*, *13*(1), 21758-. https://doi.org/10.1038/s41598-023-48561-z

[18] Van Rongen, E., Croft, R., Juutilainen, J., Lagroye, I., Miyakoshi, J., Saunders, R., De Seze, R., Tenforde, T., Verschaeve, L., Veyret, B., & Xu, Z. (2009). Effects of Radiofrequency Electromagnetic Fields on the Human Nervous System. *Journal of Toxicology and Environmental Health, Part B*, *12*(8), 572–597. https://doi.org/10.1080/10937400903458940

[19] Wan, X., Huang, H., Jia, R., Liang, D., Lu, G., & Chen, C. (2022). Association between mobile phone addiction and social support among mainland Chinese teenagers: A meta-analysis. *Frontiers in Public Health*, *10*, 911560. https://doi.org/10.3389/FPUBH.2022.911560/TEXT

[20] World Health Organization. (2014). Electromagnetic fields and mobile technology. https://www.who.int/india/health-topics/electromagnetic-fields Ziegelberger, G., Croft, R., Feychting, M., Green, A. C., Hirata, A., d'Inzeo, G., Jokela, K., Loughran, S., Marino, C., Miller, S., Oftedal, G., Okuno, T., van Rongen, E., Röösli, M., Sienkiewicz, Z., Tattersall, J., & Watanabe, S. (2020). Guidelines for limiting exposure to electromagnetic fields (100 kHz to 300 GHz). *Health Physics*, *118*(5), 483–524. https://doi.org/10.1097/HP.0000000000001210

[21] World Health Organization. (2014). Electromagnetic fields and mobile technology. https://www.who.int/india/health-topics/electromagnetic-fields