Non-thermal effects of radiofrequency fields

5LSN0 , Technlogy for care and cure - Q2

Full Name	Email address	Student ID
Venkata Pragna Nerella	v.p.nerella@student.tue.nl	2098830
Mahmut Can Aridasir	m.c.aridasir@student.tue.nl	1415956

Tutor Dr. Kemal Sumser

Eindhoven, January 25, 2025

Abstract

This study investigates the non-thermal effects of radiofrequency (RF) fields on human tissues, with a focus on their potential to stimulate neuronal activity and the role of modulation in these processes. RF fields, widely utilized in telecommunications and medical technologies, are predominantly associated with thermal effects due to tissue heating. However, emerging evidence suggests that non-thermal mechanisms may also significantly impact cellular functions, particularly at the neuronal level. Key findings from the literature indicate that RF fields can alter membrane properties, influence ion channel dynamics, and modulate neuronal excitability without a discernible rise in tissue temperature. The study further explores the role of frequency and amplitude modulation in enhancing these effects, which may hold therapeutic potential in neurostimulation and oncology. Ethical considerations and safety guidelines for RF exposure are also addressed to ensure responsible application in clinical settings. This review highlights critical gaps in understanding non-thermal RF mechanisms and proposes avenues for future research to optimize their medical applications.

Contents

1 | Introduction

Radio frequency (RF) waves, are a type of electromagnetic radiation in the frequency range from 30 KHz to 300 GHz, and are widely used in communication systems, industrial applications and especially medical devices. Compared to ionising radiation such as X-rays or gamma rays, RF waves do not have sufficient energy to ionise atoms or molecules, making them a safer option for medical applications [1, 2].

In the medical field, RF technology is the foundation of several essential devices and therapeutic techniques. Magnetic resonance imaging (MRI) uses RF waves to generate images of organs without using ionising radiation [3]. Similarly, RF hyperthermia uses controlled RF energy to raise the temperature of tissues, a method used in cancer treatment to improve the effectiveness of chemotherapy and radiotherapy [4]. RF ablation, another crucial application, uses RF-induced heating to destroy abnormal parts of tissues, such as tumours [5].

In addition to these known thermal applications, RF technologies are being actively investigated for their non-thermal effects, which do not involve significant tissue heating but interact with cellular and neurological processes [6, 7]. Recent studies have shown that non-thermal RF fields can affect the polarisation of cell membranes, modulate the activity of ion channels and alter intracellular signalling pathways. Moreover, RF-EMF exposure has shown potential non-thermal molecular effects on cancer cells, such as mitotic arrest and apoptosis, suggesting its possible role in cancer treatment [8] These effects can also offer promising opportunities for neuromodulation and innovative therapeutic interventions[6].

However, the existence of true non-thermal effects of RF fields remains controversial. Humans have been exposed to RF from natural and man-made sources for decades, but direct biological effects beyond thermal effects have not been conclusively established [9, 10]. Many studies show correlations between RF exposure and cellular responses, but the mechanisms behind these effects are not well understood and could still involve subtle thermal changes. This uncertainty raises important questions about the underlying processes and whether these responses are truly non-thermal.

Despite the wide use of RF technology in established medical applications, the potential of non-thermal effects to enable new therapies remains underexplored in neuroscience. This report addresses the following research questions:

- Do RF fields affect biological tissues beyond their thermal effects?
- Can RF fields stimulate neurons?
- What is the role of modulation in neuron stimulation by RF fields?

By addressing these questions, this report aims to explore the non-thermal RF effects and their potential for the development of innovative medical therapies. In particular, it looks at neuron stimulation, where RF fields interact with the electrical properties of neurons to regulate nerve activity. Multiple sources describe many applications of electromagnetic based technology in practical medical situations. Emerging research suggests that RF fields, especially when modulated, may offer new, non-invasive treatment options for neurological conditions.

2 | Physiology of RF fields applied to neurological processes

The interaction of radiofrequency (RF) fields with human tissue is a complex process that depends on both the physical properties of the RF waves and the physiological properties of the tissue. RF fields can affect biological systems through two primary mechanisms: thermal effects, in which the tissue is heated, and non-thermal effects, which do not cause a significant increase in temperature but interact directly with cellular and molecular structures.
Calcium ion channels play a fundamental role in cellular communication and are particularly critical in neuronal activity. These channels regulate the flow of calcium ions (Ca^{2+}) across the cell membrane, a process essential for various physiological functions, including neurotransmitter release, muscle contraction, and intracellular signaling. In neurons, calcium ion channels are responsible for the precise timing and control of synaptic transmission, which facilitates communication between neurons [6].
When an action potential reaches the presynaptic terminal, voltage-gated calcium channels open in response to changes in the membrane potential. This opening allows extracellular calcium ions to enter the cell, driven by a steep electrochemical gradient between the intracellular and extracellular environments. As illustrated in **Figure 2.1**, the intracellular calcium concentration is maintained at approximately 0.00001 mMol, while the extracellular concentration is about 1.3 mMol, creating a 10000:1 gradient. This provides a strong driving force for the calcium influx [11].
The influx of calcium ions into the presynaptic terminal triggers the fusion of synaptic vesicles with the membrane, releasing neurotransmitters into the synaptic cleft. This process enables signal transmission between neurons and is crucial for normal brain function. Any disruption in calcium ion channel activity can profoundly impact neuronal signaling, contributing to various neurological disorders.

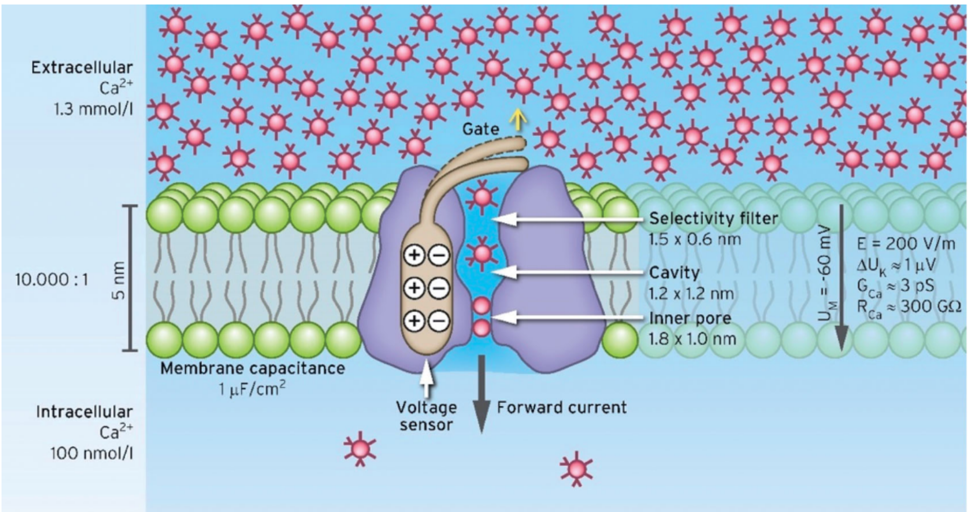

Figure 2.1: Structure and function of calcium ion channels. The electrochemical gradient drives calcium ion influx into cells, regulated by voltage sensors and gating mechanisms. RF fields are assumed to influence this process by modulating membrane potential, impacting intracellular calcium signaling and synaptic transmission ([6])

RF fields have been investigated for their potential to influence the activity of voltage-gated calcium channels (VGCCs). Non-thermal RF fields are assumed to modulate the membrane potential and gating behavior of these channels, potentially altering the flow of calcium ions. Experimental evidence supports this hypothesis, as studies have demonstrated that RF fields, such as GSM 900 MHz electromagnetic fields, can induce changes in calcium flux dynamics within neuronal cells, increasing intracellular calcium concentrations and affecting cellular signaling pathways [12, 13]. By impacting calcium dynamics, RF fields may influence synaptic transmission and neuronal excitability, offering opportunities for innovative approaches of neuromodulation and neurostimulation.

However, contrasting findings highlight the ongoing debate in the field. While some reviews suggest that currents induced by RF fields at levels compliant with safety guidelines are insufficient to affect VGCC gating, other studies have not conclusively ruled out this possibility. Furthermore, it remains unclear what specific levels of RF exposure might be required to achieve an effect, emphasizing the need for further investigation into the mechanisms involved [13].

3 | Basic Physics Principle

This chapter explores the physical principles underlying the effects of RF fields on biological systems, with a focus on their hypothesized ability to modulate membrane potentials and influence VGCC activity. These mechanisms are central to understanding how RF fields can enable non-invasive and therapeutic interventions for neurological disorders.

3.1 | Electromagnetic Properties of RF Fields

RF fields consist of two oscillating components: an electric field (E-field) and a magnetic field (B-field), which propagate perpendicular to each other and to the direction of wave travel [3]. These fields can penetrate biological tissues, inducing electric currents that interact with cellular components [13]. The strength of this interaction depends on factors such as frequency, intensity, and exposure duration. Unlike ionizing radiation, RF fields cannot break chemical bonds but can influence biological processes by modulating electrical properties of cell membranes [12].

3.2 | Interaction with Voltage-Gated Calcium Channels

VGCCs are critical for neuronal signaling, synaptic transmission, and intracellular communication. RF fields are hypothesized to modulate VGCC activity by altering the membrane potential or interacting with voltage sensors. Experimental studies show that RF fields can influence ion channels, including artificial and natural systems, by affecting ion transport and gating mechanisms [12]. While evidence for VGCC-specific effects is still emerging, findings suggest RF fields may modulate membrane electrical properties, potentially altering calcium dynamics and affecting neuronal excitability and downstream signaling.

3.3 | Mechanisms of RF Field Interaction

The mechanisms by which RF fields affect biological systems include:

- **Membrane Potential Modulation**: RF-induced electric fields may cause depolarization or hyperpolarization of cell membranes, altering the activity of VGCCs [12].
- **Voltage Sensor Interaction**: Oscillating electric fields from RF exposure may interact with the voltage-sensitive domains of VGCCs, modulating their gating behavior [12].
- **Intracellular Signaling Changes**: Increased intracellular calcium levels triggered by RF exposure can activate signaling pathways involved in gene expression, enzyme regulation, and synaptic plasticity [12].

3.4 | Comparison to Established Neuromodulation Techniques

Transcranial magnetic stimulation (TMS) is a well-established neuromodulation technique that uses rapidly changing magnetic fields to induce electric currents in brain tissue. Unlike RF fields, which operate via indirect mechanisms such as calcium ion modulation, TMS directly induces neuronal firing through electromagnetic induction based on Faraday's Law [13]. While TMS provides immediate and targeted effects, RF fields present a potential for focused, non-invasive, and targeted stimulation. This capability could open new point of view for neuromodulation, particularly in treating conditions such as mental disorders, by providing an alternative mechanism with distinct advantages [12].

3.5 | Discussion: Controversies and Future Direction

The interaction of RF fields with biological tissues remains a subject of debate. Reviews such as Wood and Karipidis (2021) [13, 14] argue that the electric currents induced by RF fields at levels compliant with safety guidelines are insufficient to affect VGCC gating. However, this is relevant for safety considerations, as therapeutic applications could use RF field levels that exceed these guidelines. The key question remains whether such levels would produce the desired effects without causing significant thermal effects. Experimental studies, including those by Kim et al [12] (2011), suggest RF exposure modulates calcium dynamics, with discrepancies likely due to variations in experimental design, exposure intensity, or cell types studied. Resolving these controversies requires further investigation and a deeper understanding of the molecular mechanisms involved.

4 | Processing and Interpretation of Technology

The processing and interpretation of non-thermal RF technology for medical applications, particularly in neuronal stimulation, focus on how RF signals are generated, delivered, and optimized for safe and effective treatment. Below, we discuss the delivery methods, challenges, and developmental needs for advancing this technology.

4.1 | RF Signal Delivery for Treatment

Non-thermal radiofrequency technique relies on accurate delivery to target tissues without causing unwanted side effects.

4.1.1 | Delivery Mechanisms

- **Frequency and Wavelength Matching:** Selecting RF frequencies that match the dielectric properties of brain tissues is essential for efficient energy delivery and effective interaction with cellular components like ion channels and membranes [1] [15] .
- **Microwave Focusing:** Harid et al. (2023) demonstrated that phased array systems could focus RF energy into deep tissues by creating constructive interference patterns at the target site. This allows precise stimulation of specific brain regions while avoiding thermal effects or damage to surrounding areas [16].
- **Pulse Modulated RF Signal:** Pulse modulation introduces breaks in RF energy delivery, which can prevent tissue heating and enhance compatibility with natural neuronal firing patterns. Pulse-modulated RF has been shown to increase selectivity in targeting specific neuronal circuits while minimizing unintended effects. This approach can also mimic physiological signaling frequencies, making it an important design consideration for neuromodulation devices [7].

4.1.2 | Challenges in RF Delivery

Delivering RF fields with millimeter precision is critical for applications like DBS. [16]. Ensuring that RF delivery does not cause unintended heating or off-target effects is a major challenge. Pulse modulation and careful frequency selection are often used to mitigate these risks [1] [6].

4.2 | Needs for Development

4.2.1 | Advanced Device Design

Devices must allow for precise control over RF signal parameters, including frequency, amplitude, and waveform [16]. To enhance clinical usability, RF devices need to be compact, cost-effective, and user-friendly [17].

4.2.2 | Standardized Protocols

For various therapeutic objectives, including neurological conditions, pain management, and cancer treatments, protocols must be customised. For example, the RF parameters effective for DBS may differ significantly from those used for cancer therapy [1] [16] . By predicting how RF fields would interact with different anatomies, computational models might enhance targeting and lessen adverse effects. Techniques like microwave focusing rely heavily on these models for success [6] [16].

4.2.3 | Computational Modeling and Simulation

- **Patient-Specific Customization**: Computational models can predict how RF fields interact with individual anatomies, improving targeting and reducing side effects. Techniques like microwave focusing rely heavily on these models for success [6] [16].

5 | Risks and Limitations

The use of non-thermal effects of radiofrequency (RF) fields in medical applications presents both challenges and ambiguities, primarily due to the limited number of comprehensive studies available on the topic. Recent studies and research indicate that this technology is associated with numerous potential risks.

- **Biological Risks**
  While non-thermal effects have shown promising short-term results, there is insufficient data for the long-term understanding of this concept. Due to this, the long-term safety and prolonged exposure remain unanswered. Non-thermal radiofrequency energy may inadvertently alter undesirable brain pathways, leading to off-target consequences or abnormal neuronal activity. Prolonged exposure may result in cumulative cellular effects, such as changes in membrane potential, ion transport dysregulation, or unintended interference with normal neuronal plasticity. The literature review [18] reports on the importance of choosing the right frequencies for cancer treatments. Studies indicate that RF fields can alter ion channel activity, including calcium flux, which may disrupt intracellular signaling pathways. These disruptions could affect critical processes such as synaptic transmission and neuronal health [1] [6]. A notable risk associated with non-thermal RF technologies is **electromagnetic hypersensitivity (EHS)**, also referred to as microwave syndrome. Individuals with EHS report adverse physiological and psychological effects following exposure to RF fields, even at intensities far below established safety thresholds. Although the exact prevalence is unclear, it has been documented in numerous case studies and surveys [14] [19].

- **Technical Limitations**
  Achieving precise spatial targeting of RF fields remains a significant technical challenge. This is particularly critical for deep brain stimulation (DBS), where unintended stimulation of surrounding brain regions could lead to adverse effects [6] [20]. The therapeutic efficiency of non-thermal RF fields depends on specific frequency and waveform parameters. Variations in these parameters across devices or environments can lead to inconsistent results [1]. The development of reliable and scalable devices for non-thermal RF applications requires advanced engineering. Factors like power efficiency, signal stability, and biocompatibility must be addressed for widespread clinical use RF fields may interact with other implanted or external medical devices, such as pacemakers or cochlear implants, potentially causing malfunctions or reduced efficiency [1].

- **Ethical and Regulatory Risks and Limitations**
  The novelty of non-thermal RF technologies raises ethical concerns in conducting human trials. Participants may face risks that are not fully understood or documented. Robust informed consent and strict oversight are essential to mitigate these concerns [13]. Trials involving patients with neurological disorders, such as Parkinson's or depression, raise ethical questions about exposing vulnerable populations to experimental therapies with uncertain outcomes [20]. Gaining regulatory approval for non-thermal RF technologies is challenging due to the lack of standardized practices and inconsistent evidence on efficiency. Regulatory bodies require comprehensive evidence of safety and effectiveness, which is currently limited.

Differentiating non-thermal effects from thermal side effects remains a challenge in ensuring safety. Small amounts of heating, even when unintended, can complicate the interpretation of observed effects. It is also possible for RF fields to interfere with nearby medical devices, such as pacemakers or brain stimulators leading to device malfunction.

While non-thermal RF fields hold promise for innovative therapeutic applications, these risks and limitations underline the need for rigorous research, robust regulatory frameworks, and ethical considerations. Addressing these challenges through systematic studies and optimized device development is critical to the safe and effective implementation of this technology in clinical settings.

6 | Development of technology as Medical Device

The development of medical devices using the non-thermal effects of RF fields for neuronal stimulation is at an early but promising stage. Research has demonstrated that RF fields can modulate cellular and neuronal activities without significant heating, offering a potential alternative to traditional invasive brain stimulation techniques. Here, we summarize the current state of development and the challenges associated with translating this research into clinical applications.

Studies have shown that non-thermal RF fields influence ion channels, alter membrane potentials, and induce resonance-based neuronal modulation. These effects have been explored for their potential to stimulate deep brain regions non-invasively. MIRS (Mid-Infrared Stimulation) has demonstrated potential for selectively targeting neuronal activity via resonance phenomena without thermal damage [**liu2021nonthermal**].

6.1 | Clinical Translation and Valorization

The broader field of non-thermal RF technologies is in the early stages of clinical translation. While certain devices, such as the gammaCore™ vagus nerve stimulator, have been approved for specific therapeutic applications like migraine and cluster headaches [17], most technologies using non-thermal RF effects remain experimental. Significant progress in clinical validation and device standardisation is necessary to go from research to proven medicinal therapies.

6.2 | Development of Technology for Medical Devices

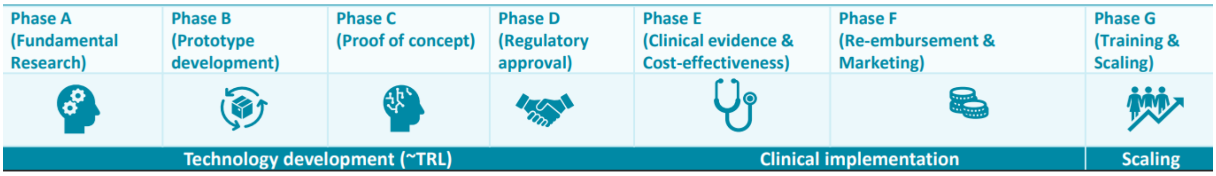

Figure 6.1: Technology Readiness Level

Fig 6.1 outlines a framework for the progression of medical device development, from fundamental research (Phase A) to training and scaling (Phase G). For non-thermal RF-based neuronal stimulation, the technology is primarily positioned between Phase A (Fundamental Research) and Phase B (Prototype Development), with some early efforts in Phase C (Proof of Concept). Below, we map the current state of the technology to the stages in the diagram and identify key steps required for further advancement.

6.2.1 | Phase A: Fundamental Research

Current Status:
Non-thermal RF effects, particularly their potential for neuronal stimulation, are still under investigation. Early studies have provided foundational evidence that RF fields can modulate neuronal activity through non-thermal mechanisms such as altering membrane polarization and regulating ion channels like voltage-gated potassium and sodium channels. These findings form the basis for understanding how RF energy interacts with brain tissues, as seen in work by Doyle et al. (1998) on potassium channel behavior and Kim et al. (2011) on artificial ion channel [11] [12]. However, the precise biophysical interactions remain incompletely understood. Advances in computational modeling and experimental methods, such as the use of metal-free environments to study neuronal activity under RF stimulation (Yaghmazadeh et al., 2022), are helping to clarify these mechanisms. This phase has laid the groundwork for exploring therapeutic applications in neuromodulation, oncology, and drug delivery [4] [7].

Needs for Advancement:
Studies like "Mechanisms for Interaction Between RF Fields and Biological Tissue" [1] highlight the need to understand how non-thermal RF fields interact with neural tissues at molecular and cellular level.

Laboratory experiments should focus on validating non-thermal effects across diverse neuronal models to build a robust evidence base.

6.2.2 | Phase B: Prototype Development

Current Status:
Early prototypes for non-thermal RF-based stimulation devices have been developed, showcasing the potential to target deep brain regions and other tissues non-invasively. One such technology involves microwave focusing, which uses computational modeling and constructive interference to deliver energy precisely to targeted areas while minimizing off-target effects. This approach has demonstrated high spatial resolution and non-destructive capabilities in initial studies [1] [16].

Needs for Advancement:
However, these devices remain experimental and are not yet ready for clinical deployment. Challenges include improving their safety, reliability, and precision. For example, while early studies show promise, ensuring that RF energy does not cause unintended heating or off-target effects is critical for further development [15] [16] . Additionally, existing prototypes must be adapted to account for inter-individual variability in brain anatomy and electromagnetic field interactions, which requires advanced computational modeling and further testing [1] [17].

6.2.3 | Phase C: Proof of Concept

Current Status:
Initial proof-of-concept studies have provided encouraging evidence for the feasibility of non-thermal RF-based technologies, particularly for neuromodulation and other medical applications. These studies highlight the non-invasive, reversible, and non-thermal nature of the approach, making it a promising candidate for clinical applications in neurology and beyond [17]. Similarly, microwave focusing has been validated as a non-destructive method for precise RF delivery, providing high spatial resolution while minimizing damage to surrounding tissues [16].

Needs for Advancement:
By conducting small-scale clinical trials to test efficacy in specific applications, such as treating Parkinson's disease or chronic pain. By validating RF parameters (frequency, intensity, modulation) across multiple experimental settings to ensure consistency. Clarifying the specific molecular and cellular mechanisms via which RF fields work should be the main goal of proof-of-concept investigations. This is important for both clinical translation and regulatory approval [1] [20].

6.2.4 | Phase D: Regulatory Approval

Future Requirements:
To progress to this stage, developers must demonstrate safety and efficacy according to standards set by agencies like the FDA or EMA, provide evidence on chronic exposure effects through extended trials and establish protocols for device manufacturing and quality control.

6.2.5 | Phase E: Clinical Evidence and Cost-Effectiveness

Future Requirements:
Clinical evidence and cost-effectiveness can be achieved by performing randomised, controlled trials to confirm therapeutic efficacy for specific indications. By evaluating cost-effectiveness compared to alternative therapies, accessibility for patients and healthcare providers is assessed.

6.2.6 | Phase F: Reimbursement and Marketing

Future Requirments:
This can be achieved by developing marketing strategies to position the device competitively in the medical technology landscape and collaborating with insurers and healthcare systems to ensure reimbursement pathways.

6.2.7 | Phase G: Training and Scaling

Future Requirments:
By teaching doctors about device use and safety procedures, training and scaling can be accomplished. Global Accessibility can be achieved by adapting device design and pricing to ensure accessibility in diverse healthcare systems worldwide.

Current Position in Development

Non-thermal RF-based neuronal stimulation remains between Phases A and B, with early-stage research transitioning into prototype development. Significant advancements are required across all subsequent phases to translate this technology into an established medical intervention.

7 | Conclusion

In conclusion, research into the non-thermal effects of radiofrequency (RF) fields presents a promising avenue for medical research, with possible uses ranging from innovative cancer treatments to brain stimulation. Unlike traditional thermal applications, non-thermal effects focus on subtle mechanisms such as membrane polarization, changes in intracellular signaling, and the role of modulation in stimulation, which may open doors to innovative, non-invasive treatments. Research, including studies on metal-free rodent brains and therapeutic uses in oncology, demonstrates potential benefits but also underscores the complexity and knowledge gaps in this area.

Studies show that RF fields affect biological tissues in ways other than their thermal impacts, which helps in our ability to respond to the study questions that were presented. . They regulate cellular responses and neural signalling by influencing calcium ion motions and other ion fluxes [15]. We can also observe alterations in cell membrane properties, such as permeability and dielectric characteristics which are linked to RF field exposure [1]. Studies like [20] have also answered the question if RF fields can stimulate neurons by showing that high-frequency RF fields can interfere to create a low-frequency envelope, selectively stimulating deep brain regions without affecting surrounding tissue. It has been demonstrated that RF fields affect membrane potential and ion channel dynamics, two essential components of neuronal excitation [6] [13]. In response to the last research question, studies from [17] demonstrate that frequency selection has a crucial role in determining the specificity and depth of neuronal targeting, which is a crucial component for modulation in neuron stimulation. Modulation plays a critical role in achieving targeted and effective neuron stimulation with RF fields.

As discussed in the ”Development of Technology for Medical Devices” section, the journey of non-thermal RF technologies spans multiple stages. These include fundamental research (Phase A), prototype development (Phase B), and early proof-of-concept validation (Phase C). The technology currently resides in the early stages, requiring further optimization of device design, standardization of protocols, and comprehensive preclinical and clinical evaluations. Despite its promising potential, the adoption of RF-based medical technologies must account for challenges such as electromagnetic hypersensitivity (EHS). Individuals with EHS may experience non-specific symptoms like headaches and fatigue even at low RF exposure levels, emphasizing the need for personalized treatment protocols and careful safety assessments [14] [19]. Addressing these gaps will be critical to advancing the technology through later stages, such as regulatory approval, clinical evidence generation, and widespread adoption.

Expanding our understanding of the non-thermal effects of RF fields could revolutionize treatments for neurological disorders, cancer, and other medical conditions. However, achieving this vision will require sustained investment in research, standardized methodologies, and close collaboration between engineers, clinicians, and biologists.

General/References

Bibliography

[1] LJ Challis. "Mechanisms for interaction between RF fields and biological tissue". In: *Bioelectromagnetics* 26.S7 (2005), S98–S106.

[2] Iqram Hussain et al. "Quantifying physiological biomarkers of a microwave brain stimulation device". In: *Sensors* 21.5 (2021), p. 1896.

[3] Bernhard Gruber et al. "RF coils: A practical guide for nonphysicists". In: *Journal of magnetic resonance imaging* 48.3 (2018), pp. 590–604.

[4] MM Paulides et al. "Recent technological advancements in radiofrequency-andmicrowave-mediated hyperthermia for enhancing drug delivery". In: *Advanced drug delivery reviews* 163 (2020), pp. 3–18.

[5] Kelvin Hong and Christos Georgiades. "Radiofrequency ablation: mechanism of action and devices". In: *Journal of Vascular and Interventional Radiology* 21.8 (2010), S179–S186.

[6] Peter Wust, Ulrike Stein, and Pirus Ghadjar. "Non-thermal membrane effects of electromagnetic fields and therapeutic applications in oncology". In: *International Journal of Hyperthermia* 38.1 (2021), pp. 715–731.

[7] Omid Yaghmazadeh et al. "Neuronal activity under transcranial radio-frequency stimulation in metal-free rodent brains in-vivo". In: *Communications engineering* 1.1 (2022), p. 15.

[8] Peter Wust et al. "Radiofrequency electromagnetic fields cause non-temperature-induced physical and biological effects in cancer cells". In: *Cancers* 14.21 (2022), p. 5349.

[9] David O Carpenter. "The microwave syndrome or electro-hypersensitivity: historical background". In: *Reviews on environmental health* 30.4 (2015), pp. 217–222.

[10] M Nilsson and L Hardell. "Development of the microwave syndrome in two men shortly after installation of 5G on the roof above their office". In: *Ann Clin Case Rep. 2023; 8* 2378 (2023).

[11] Declan A Doyle et al. "The structure of the potassium channel: molecular basis of K+ conduction and selectivity". In: *science* 280.5360 (1998), pp. 69–77.

[12] HS Kim et al. "Radio-frequency response of single pores and artificial ion channels". In: *New Journal of Physics* 13.9 (2011), p. 093033.

[13] Andrew Wood and Ken Karipidis. "Radiofrequency fields and calcium movements into and out of cells". In: *Radiation Research* 195.1 (2021), pp. 101–113.

[14] Ken Karipidis et al. "5G mobile networks and health—a state-of-the-science review of the research into low-level RF fields above 6 GHz". In: *Journal of Exposure Science & Environmental Epidemiology* 31.4 (2021), pp. 585–605.

[15] John T Butters, Xavier A Figueroa, and Bennett Michael Butters. "Non-thermal radio frequency stimulation of tubulin polymerization in vitro: a potential therapy for cancer treatment". In: *Open Journal of Biophysics* 4.4 (2014), pp. 147–168.

[16] Vijay Harid et al. "A method for non-destructive microwave focusing for deep brain and tissue stimulation". In: *Plos one* 18.2 (2023), e0278765.

[17] Arthur A Pilla. "Nonthermal electromagnetic fields: from first messenger to therapeutic applications". In: *Electromagnetic biology and medicine* 32.2 (2013), pp. 123–136.

[18] Xiao-Wei Xiang et al. "Glioblastoma behavior study under different frequency electromagnetic field". In: *iScience* 26.12 (2023), p. 108575. ISSN: 2589-0042. DOI: https://doi.org/10.1016/j.isci.2023.108575. URL: https://www.sciencedirect.com/science/article/pii/S2589004223026524.

[19] Yael Stein and Iris G Udasin. "Electromagnetic hypersensitivity (EHS, microwave syndrome)–Review of mechanisms". In: *Environmental research* 186 (2020), p. 109445.

[20] Mobina Zibandepour et al. "Preliminary Guidelines for Electrode Positioning in Noninvasive Deep Brain Stimulation via Temporally Interfering Electric Fields". In: *2023 11th RSI International Conference on Robotics and Mechatronics (ICRoM)*. IEEE. 2023, pp. 739–744.