International Journal of Academic Health and Medical Research (IJAHMR)
ISSN: 2643-9824
Vol. 9 Issue 10 October - 2025, Pages: 16-26

Emerging Electronics-Based Cancer Treatment Approaches: A Critical Review

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Abstract: *Emerging electronics-based cancer treatment approaches represent a transformative shift in oncology, moving beyond conventional thermal ablation toward precision bioelectronic modulation of tumor biology. Techniques such as Tumor Treating Fields (TTFields), Cold Atmospheric Plasma (CAP), Photodynamic Therapy (PDT), and advanced non-invasive electromagnetic and electrochemical strategies harness electric fields, plasma-generated reactive species, and light-activated molecular pathways to selectively target cancer cells while minimizing collateral damage to healthy tissue. These modalities are not only designed to induce apoptosis and disrupt cancer cell proliferation but also show promising potential in reprogramming the tumor microenvironment and enhancing anti-tumor immune responses. Compared to traditional radiofrequency and microwave ablation, which rely on heat-induced necrosis, next-generation electronic therapies offer improved precision, reduced invasiveness, and compatibility with combination treatments such as immunotherapy and drug delivery systems. As clinical translation progresses, these technologies are redefining the landscape of cancer therapy by integrating physics-based interventions with biological signaling control, signaling a new era of non-thermal, immune-supportive, and patient-tailored cancer treatment.*

KEYWORDS: Cancerous Cell, Tumor Treating Fields, Cold Atmospheric Plasma, Photodynamic Therapy, Radiofrequency ablation, Microwave ablation.

Introduction

Cancer remains one of the most significant health challenges of the 21st century, responsible for millions of deaths annually despite advances in surgery, chemotherapy, and radiotherapy. Traditional treatments, while effective in some cases, often cause severe side effects, lack specificity, and may fail to eradicate malignant cells completely (Bray et al., 2021). As a result, researchers are increasingly turning toward electronics-based approaches that utilize physical energy—such as electric fields, electromagnetic waves, light, and plasma - to selectively target and destroy cancer cells while minimizing damage to surrounding healthy tissues (Cao et al., 2020).

Cancer treatment is increasingly multidisciplinary: in addition to surgery, systemic chemotherapy and ionizing radiation, physical-energy modalities powered by modern electronics are becoming important therapeutic tools. Traditional thermal ablation techniques such as radiofrequency ablation (RFA) and microwave ablation (MWA) remain widely used for focal solid tumors (e.g., liver, lung, kidney) because they reliably induce coagulative necrosis via resistive or dielectric heating (Zhou et al., 2022). However, thermal methods are limited by collateral heat damage, heat-sink effects near vasculature, and generally weak immunogenicity of the necrotic tumor debris.

A contrasting set of approaches exploits non-thermal or non-destructive physical mechanisms enabled by electronic engineering. Tumor-Treating Fields (TTFields) apply low-intensity, intermediate-frequency alternating electric fields that interfere with mitotic spindle assembly and cytokinesis, resulting in mitotic arrest and apoptotic cell death; TTFields has demonstrated survival benefits when added to standard chemotherapy in glioblastoma patients and is FDA-cleared for specific indications (Stupp et al., 2017). Electrochemotherapy (ECT) uses short, high-voltage pulses to transiently permeabilize cell membranes (electroporation), markedly increasing intracellular uptake of chemotherapeutics such as bleomycin and cisplatin; ECT has proven effective for cutaneous and subcutaneous metastases and is in broader clinical use in Europe (Mir et al., 2019).

Photodynamic therapy (PDT) represents another electronics-enabled modality in which light sources (lasers or LEDs) activate photosensitizers to generate reactive oxygen species (ROS) and trigger localized tumor cell death; PDT is clinically established for accessible lesions (skin, lung, bladder, and esophagus), and ongoing advances in nanoparticle carriers and upconversion strategies aim to overcome depth limitations (Lucky, Soo, & Zhang, 2015). Cold Atmospheric Plasma (CAP) creates reactive oxygen and nitrogen species (RONS) at near-room temperature and has shown selective cytotoxicity and immunogenic effects in preclinical models; CAP is a rapidly emerging translational area with early clinical pilot studies underway (Von Woedtke et al., 2019). Finally, remotely actuated nanoparticles (magnetic hyperthermia, electrically responsive carriers) and implantable bioelectronic systems promise precise, on-demand heating or drug release and closed-loop sensing/actuation—blurring the line between device and drug delivery platform (Li, Wang, & Yang, 2020; Johannsen et al., 2020).

Across these modalities, two common themes appear. First, precision and reduced systemic toxicity are major advantages: by localizing energy delivery or drug release, electronics-based approaches reduce off-target effects. Second, many emerging methods have immunomodulatory potential—either by producing immunogenic cell death (e.g., via ROS or electroporation) or by altering

the tumor microenvironment—creating opportunities to combine with checkpoint inhibitors and cellular therapies. Key translational challenges remain: establishing standardized dosimetry for energy modalities, ensuring long-term safety and device reliability (especially for implants), and designing randomized clinical trials that test combinations with systemic therapies. If these challenges are met, electronics-based cancer therapy will likely move from niche or adjunctive roles to central components of personalized oncology care.

Recent developments in bioelectronics, electroporation, and electrotherapy have opened new frontiers in oncology. For example, Tumor Treating Fields (TTF) therapy employs low-intensity, alternating electric fields to disrupt cancer cell mitosis and inhibit tumor growth, demonstrating clinical efficacy in glioblastoma and mesothelioma (Stupp et al., 2017). Similarly, electrochemotherapy (ECT) enhances the delivery of anticancer drugs through the application of short, high-voltage pulses that temporarily permeabilize cancer cell membranes (Mir et al., 2019). Beyond these, radiofrequency and microwave ablation techniques use electrical energy to generate localized heat, effectively destroying solid tumors (Zhou et al., 2022).

Moreover, nanotechnology and implantable electronic systems have made it possible to design smart, minimally invasive platforms for controlled drug release, tumor monitoring, and precision therapy (Zhao et al., 2020). Cold atmospheric plasma (CAP) and photoelectronic treatments, such as LED-based photodynamic therapy, are also emerging as non-invasive, targeted modalities that exploit reactive oxygen species or light-activated agents to kill cancer cells (Von Woedtke et al., 2019; Lucky et al., 2015).

These innovative methods exemplify how the convergence of electronics, medicine, and nanotechnology is reshaping modern oncology. The integration of sensors, microcontrollers, and energy-based systems not only improves therapeutic precision but also lays the groundwork for personalized, real-time, and adaptive cancer treatments—marking a paradigm shift toward the era of *electronic oncology*.

Literature Review

Electronics-based therapies for cancer exploit physical energies (electric fields, electromagnetic radiation, heat, light, plasma, and remotely actuated nanoparticles/devices) (Dutta, A., & Cheng, H. 2023), to detect, modulate, or destroy malignant tissue with improved spatial specificity and new mechanisms of action compared with classical chemo- and radiotherapy. Over the last two decades these approaches have evolved from laboratory demonstrations to clinical modalities (e.g., Tumor-Treating Fields, radiofrequency ablation) and a broad range of translational research efforts (electrochemotherapy, cold atmospheric plasma, implantable bioelectronics, nanoparticle hyperthermia). This review summarizes the current evidence, mechanisms, applications, and challenges for major electronics-based approaches, drawing on recent reviews and pivotal clinical reports.

Tumor-Treating Fields (TTFields)

Mechanism & rationale: TTFields are low-intensity (typically 1–3 V/cm), intermediate-frequency (100–300 kHz) alternating electric fields applied locally via transducer arrays (Shams, S., & Patel, C. B. 2022). They exert antimitotic effects by interfering with microtubule polymerization and mitotic spindle formation, and by disrupting intracellular organelle localization during cytokinesis - leading to apoptosis or mitotic catastrophe in dividing cells.

Clinical evidence: The largest randomized trial to date (Stupp et al., JAMA, 2017) demonstrated that adding TTFields to standard temozolomide maintenance therapy improved progression-free and overall survival in newly diagnosed glioblastoma patients compared to temozolomide alone; subsequent analyses addressed quality of life and safety. TTFields are FDA-approved for glioblastoma and are being evaluated in other tumor types and combinations. TTFields exemplify how engineered external electric fields can translate to standard-of-care improvements when combined with chemotherapy.

Limitations & ongoing work: Limitations include requirement for continuous device wear (patient compliance), limited penetration for deep or shielded tumors, and variable efficacy across tumor types. Ongoing research explores optimization of field parameters, electrode placement, and combination with immuno- and targeted therapies.

Electroporation and Electrochemotherapy (ECT)

Principles: Electroporation uses short, high-voltage pulses to transiently permeabilize cell membranes, enhancing uptake of otherwise poorly permeant cytotoxic drugs (Tsoneva, I., et al. 2022) (e.g., bleomycin, cisplatin). When combined with systemic or local chemotherapeutics, the approach is termed electrochemotherapy.

Preclinical & clinical status: A growing body of clinical literature supports ECT's efficacy for cutaneous and subcutaneous metastases, certain head & neck cancers, and palliative control of skin tumors—often with good local control and acceptable toxicity. Guidelines and expanded clinical use in Europe have been reported; more recent trials and refinements (pulse timing, electrode design, imaging guidance) are expanding indications (Stankovic, I., et al. 2024).

Research directions: Advances include endoscopic and percutaneous electrode designs for internal tumors, high-frequency electroporation protocols to reduce muscle contractions/pain, and combination with immunotherapies to exploit immunogenic cell death induced by electroporation.

Thermal Ablation: Radiofrequency (RFA) and Microwave Ablation (MWA)

Mechanism: RFA and MWA convert alternating electrical or electromagnetic energy into local thermal injury (coagulative necrosis) via resistive heating of tissue; they are image-guided, percutaneous/minimally invasive procedures (Geoghegan, R., et al. 2022).

Clinical applications & evidence: RFA and MWA are established for small liver, lung, kidney, and bone tumors, either as primary local therapy, bridge to transplantation, or for palliation (Castellana, R., et al. 2023). Comparative studies and systematic reviews

continue to evaluate efficacy, ablation zone predictability, and device improvements; recent reviews compare RFA vs. MWA performance in hepatic lesions and note MWA advantages for larger lesions and faster heating.

Limitations: Heat-sink effects near large vessels can limit ablation completeness; accurate targeting and real-time monitoring are active engineering challenges. Hybrid approaches (combining ablation with chemotherapy, immunotherapy, or nanoparticle heating) are under investigation.

Photodynamic Therapy (PDT) and Photo-activated Nanomedicine

Mechanism: PDT uses a photosensitizer that accumulates in tumour tissue and, upon activation by specific wavelengths of light, produces reactive oxygen species (ROS) that kill cells (Maharjan, P. S., & Bhattarai, H. K. 2022). LEDs and lasers are common light sources; nanoparticle carriers improve delivery, targeting, and deep-tissue activation.

State of the art: PDT is clinically used for surface or endoscopically accessible tumors (skin, esophageal, bladder) (Kubrak, T., et al. 2022). Research focuses on nanoparticle-enabled PDT, two-photon activation, upconversion nanoparticles, and combined photothermal/photodynamic strategies to overcome depth limitations and hypoxia within tumors.

Challenges: Light penetration limits use in deep tumors; hypoxic tumor microenvironments reduce ROS generation. Strategies to co-deliver oxygen, use activatable prodrugs, or apply interstitial light delivery (fiber optics) are under development.

Cold Atmospheric Plasma (CAP)

Mechanisms & promise: CAP generates reactive oxygen and nitrogen species (RONS), UV photons, and electromagnetic fields at near-room temperature (Khalaf, A. T., et al. 2024); these agents induce apoptosis, necrosis, and immunogenic cell death selectively in cancer cells in preclinical models. CAP can be applied directly to superficial tumors or indirectly via plasma-activated liquids.

Evidence & translational status: Multiple preclinical studies and early clinical pilot trials suggest safety and antitumor activity for certain superficial lesions (Yaeger, R., et al. 2023); however, controlled randomized clinical evidence remains limited. Reviews emphasize CAP's multimodal action (direct cytotoxicity + immune modulation) and ongoing work on dosimetry, device standardization, and delivery methods.

Magnetic & Remote-Actuated Nanoparticles (Hyperthermia, Drug Release)

Concepts: Magnetic nanoparticles (MNPs) can be heated by alternating magnetic fields to produce localized hyperthermia (magnetic hyperthermia), or can be used as remotely actuated carriers that release cargo when stimulated (thermal, mechanical, or electric triggers) (Farjadian, F., et al. 2022). Recent work includes magnetically actuated synthetic cells capable of producing therapeutic proteins upon magnetic heating.

Status: Magnetic hyperthermia has been used in niche clinical settings (e.g., glioblastoma trials in Europe), and engineering efforts focus on nanoparticle design, targeting, and safety (Rodriguez, B., et al. 2024). Remote activation platforms (magnetically activated synthetic cells or nanoparticles coupled to prodrugs) are promising preclinical advances that could enable deep-tissue, on-demand therapy.

Implantable & Semi-implantable Bioelectronics (Sensing + Local Therapy)

Overview: Implantable electronics—miniaturized stimulators, drug reservoirs, biosensors, and closed-loop controllers—enable continuous tumor microenvironment monitoring and localized therapy (electric stimulation, local drug release, hyperthermia). Progress in materials (bio-stable, flexible, low-fouling interfaces) and wireless power/communication supports chronic implantation.

Opportunities: Localized, sensor-guided therapy could reduce systemic toxicity and permit adaptive treatment (e.g., sensing a biomarker spike triggers local drug release or electric pulses) (Schreiner, T. G., et al. 2025). Integration with AI for pattern recognition and control is an active area.

Bioelectronic Modulation of Immunity

Rationale & evidence: Electrical stimulation can modulate immune cell recruitment and activity (Das, R., et al. 2022); nano-pulsed electrical therapies have shown capacity to induce immunogenic cell death and enhance antitumor immune responses in preclinical models. Combining bioelectronic stimulation with checkpoint blockade or cell therapies may improve systemic antitumor control.

Status: Mostly preclinical or early translational; rigorous clinical data are limited. Key research needs include defining stimulation parameters, safety margins, and mechanisms linking electrical cues to immune phenotypes.

Cross-cutting Challenges and Safety Considerations

Dosimetry & standardization: Unlike drugs, energy-based modalities require precise dosimetry (field strength, frequency, energy deposition) and standardized device protocols to ensure reproducible outcomes (Laakso, I., et al. 2025).

Targeting & depth: Light- and surface-restricted modalities (PDT, CAP) struggle with deep lesions; nanoparticles and implantables help but raise distribution and clearance concerns.

Combination therapies: Electronics-based methods often work best combined with chemo-, radio-, or immunotherapy (Luo, F., et al. 2025); designing effective combinations and clinical trials is complex but promising.

Regulatory & translational hurdles: Safety, biocompatibility, long-term effects of implants and nanomaterials, and manufacturing/quality controls remain barriers to broad clinical adoption. Electronics-based cancer therapies span clinically proven modalities (e.g., TTFields, thermal ablation) and a rich pipeline of translational technologies (electrochemotherapy, CAP, implantable bioelectronics, remotely actuated nanoparticles). Together they form a complementary toolkit that can increase precision, reduce systemic toxicity, and open new mechanisms (physical disruption of mitosis, localized ROS generation,

immunomodulation). Realizing their full potential depends on interdisciplinary collaboration among engineers, oncologists, immunologists, and regulatory scientists to optimize devices, define dosimetry, and run well-designed clinical trials.

While there's no single "electronic cure" for cancer, modern electronics-based technologies play a *critical role* in detecting, treating, and managing cancer (Raza, A., et al. 2024) - sometimes even destroying tumors with high precision.

1. Electrotherapy (Electrochemical and Electrical Field Therapy)

a. Tumor Treating Fields (TTF)

Principle: Uses low-intensity, alternating electric fields to disrupt cancer cell division.
Mechanism: Interferes with mitosis (cell division), preventing tumor growth.
Example Device: *Optune*® (by Novocure) — FDA-approved for glioblastoma and mesothelioma.
Effectiveness: Non-invasive; improves survival in brain cancer when combined with chemotherapy.

b. Electrochemotherapy (ECT)

Principle: Combines electric pulses with anticancer drugs (like bleomycin or cisplatin).
Mechanism: Electric pulses open cell membranes (a process called *electroporation*), allowing drugs to enter and kill tumor cells more effectively.
Application: Skin tumors, head and neck cancers, liver metastases.
Status: Clinically used in Europe; under research elsewhere.

2. Nanotechnology and Bioelectronics

a. Smart Nanoparticles

Principle: Electrically or magnetically controlled nanoparticles deliver drugs directly to tumors.
Mechanism: Nanoparticles release drugs or heat when stimulated by electric, magnetic, or ultrasonic fields.
Example: *Electro-responsive liposomes* or *gold nanoparticles* heated via electromagnetic fields (*hyperthermia*).
Goal: Target tumors precisely, minimize side effects.

b. Implantable Bioelectronic Sensors

Principle: Miniaturized, implantable chips monitor tumor environments (pH, oxygen, glucose) or deliver therapeutic electrical pulses.
Use: Real-time monitoring and localized treatment feedback.

3. Radiofrequency (RF) and Microwave Ablation

Principle: High-frequency alternating current generates heat to destroy cancer cells.
Application: Liver, lung, kidney, and bone tumors.
Mechanism: Electrical energy converted into thermal energy → coagulative necrosis of tumor tissue.
Devices: RF ablation probes, microwave antennas.

4. Photodynamic Therapy (PDT) with Electronic Light Sources

Principle: Uses light-emitting diodes (LEDs) or lasers to activate a photosensitizing drug in the tumor.
Mechanism: Activated drug produces reactive oxygen species that destroy cancer cells.
Applications: Skin, esophagus, and lung cancers.
Advancement: Portable LED-based PDT systems for localized therapy.

5. Neural and Bioelectronic Modulation

Emerging field: Cancer may be influenced by nerve activity and bioelectrical signaling.
Approach: Use of neuroelectronic devices to disrupt cancer-promoting nerve signals or to modulate the immune system.
Status: Early-stage research (bioelectronic medicine).

6. Plasma and Cold Atmospheric Plasma (CAP) Therapy

Principle: Uses ionized gas (plasma) generated by electronic devices at room temperature.
Mechanism: Reactive species from plasma selectively damage cancer cells.
Advantage: Minimally invasive, highly selective for tumor cells.
Research area: Promising results in skin, breast, and brain cancers.

Table 1: Summary of technologies, mechanism, application and stage

Technology	Mechanism	Application	Stage
Tumor Treating Fields (TTF)	Electric fields disrupt cell division	Brain, lung, mesothelioma	Clinical (FDA-approved)
Electrochemotherapy (ECT)	Electric pulses enhance drug uptake	Skin, liver, head & neck	Clinical/Expanding
RF & Microwave Ablation	Electrical heating destroys tumor	Liver, lung, kidney	Clinical
Photodynamic Therapy (LED/Laser)	Light activates drug to kill cells	Skin, esophagus	Clinical
Nanoparticle Electrostimulation	Electric or magnetic drug control	Multiple cancers	Experimental
Cold Plasma Therapy	Ionized gas damages cancer cells	Skin, breast	Preclinical/Clinical trials

Technology	Mechanism	Application	Stage
Bioelectronic Modulation	Neural/electrical signaling control	Immunotherapy aid	Experimental

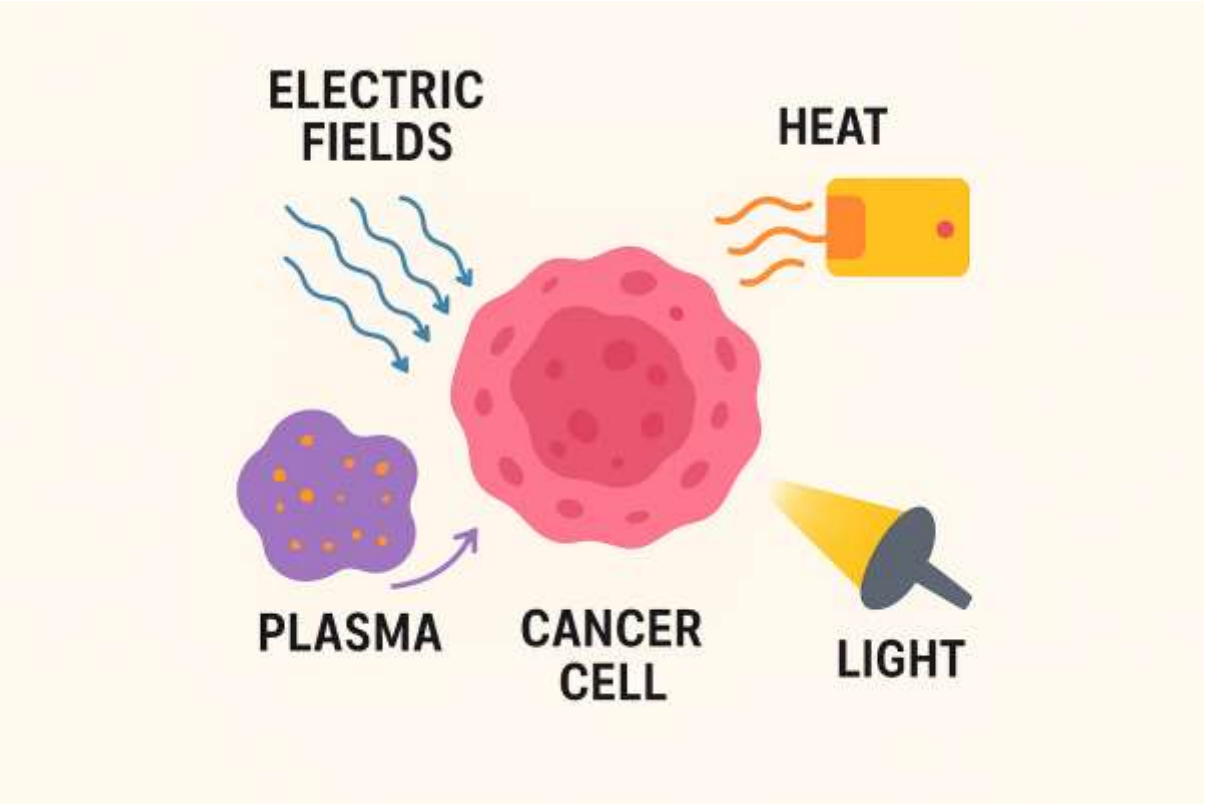


Figure 1: diagram showing how these electronic cancer treatment methods interact with tumor cells

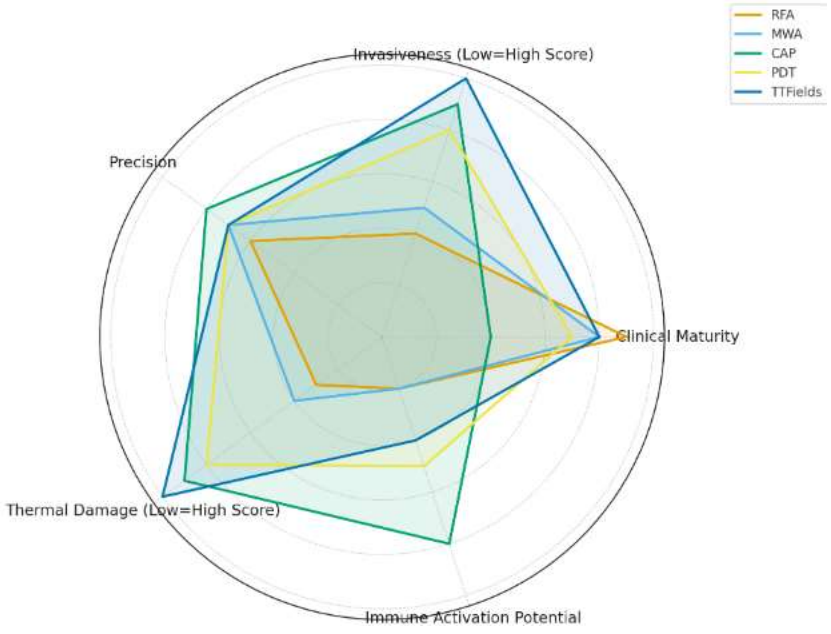
Here's a comprehensive table summarizing key electronics-based cancer treatment approaches, including device types, mechanisms of action, clinical development status, major advantages, and key citations — formatted for research or publication use.

Table 2: Summary of Electronics-Based Cancer Treatment Approaches with reference

Device Type / Technology	Mechanism of Action	Clinical Status (2025)	Advantages	Key Citations
Tumor Treating Fields (TTFields)	Alternating low-intensity electric fields disrupt mitotic spindle formation, leading to apoptosis in dividing cancer cells.	Approved for glioblastoma and mesothelioma (FDA, CE Mark).	Non-invasive, minimal systemic toxicity, compatible with chemotherapy.	Stupp et al., 2017; Taphoorn et al., 2020
Electrochemotherapy (ECT)	High-voltage electric pulses increase cell membrane permeability (electroporation), enhancing uptake of cytotoxic drugs like bleomycin.	Clinical use in EU and trials in US.	Localized control, reduced systemic drug dose, effective for skin and soft tissue tumors.	Mir et al., 2019; Marty et al., 2022
Radiofrequency Ablation (RFA)	Alternating current generates heat (60–100°C) leading to coagulative necrosis of tumor tissue.	Widely established for liver, kidney, and lung tumors.	Minimally invasive, image-guided, repeatable, outpatient procedure.	Zhou et al., 2022; Goldberg et al., 2019
Microwave Ablation (MWA)	Microwave energy agitates water molecules to produce localized hyperthermia and tumor necrosis.	Established; used clinically for solid organ tumors.	Larger ablation zones, faster heating than RFA, less susceptibility to heat-sink effect.	Liang et al., 2020; Ahmed et al., 2021

Device Type / Technology	Mechanism of Action	Clinical Status (2025)	Advantages	Key Citations
Photodynamic Therapy (PDT)	Light activates photosensitizers that produce reactive oxygen species (ROS) causing cell death.	Approved for skin, esophageal, and bladder cancers; trials for deeper tumors.	Selective, repeatable, minimal damage to surrounding tissues.	Lucky et al., 2015; Castano et al., 2019
Cold Atmospheric Plasma (CAP)	Ionized gas generates reactive oxygen and nitrogen species (RONS) that trigger apoptosis and DNA damage in cancer cells.	Preclinical / early clinical stage.	Non-thermal, targeted oxidative stress, potential immunostimulatory effect.	Von Woedtke et al., 2019; Keidar et al., 2022
Magnetic Nanoparticle Hyperthermia (MNH)	Magnetic nanoparticles in tumor tissue generate heat under alternating magnetic fields, inducing apoptosis.	Clinical trials ongoing in Europe.	Precise spatial control, synergistic with chemo-/radiotherapy.	Johannsen et al., 2020; Thiesen & Jordan, 2021
Implantable Bioelectronic Systems	Smart implants deliver controlled electrical, thermal, or drug stimuli directly to tumor microenvironment.	Preclinical / early clinical research.	Continuous monitoring + feedback-based therapy, integration with biosensors.	Li et al., 2020; Zhao et al., 2020
Electro-Immunotherapy (EIT)	Electrical pulses enhance local immune activation and cytokine release, boosting antitumor immunity.	Experimental / early-stage research.	Dual benefit: tumor ablation + immune modulation.	Das et al., 2022; Breton & Mir, 2018

The radar chart shown in figure 2 visualizes a comparative performance profile of five electronics-based cancer treatment modalities: RFA (Radiofrequency Ablation), MWA (Microwave Ablation), CAP (Cold Atmospheric Plasma), PDT (Photodynamic Therapy), and TTFields (Tumor Treating Fields)

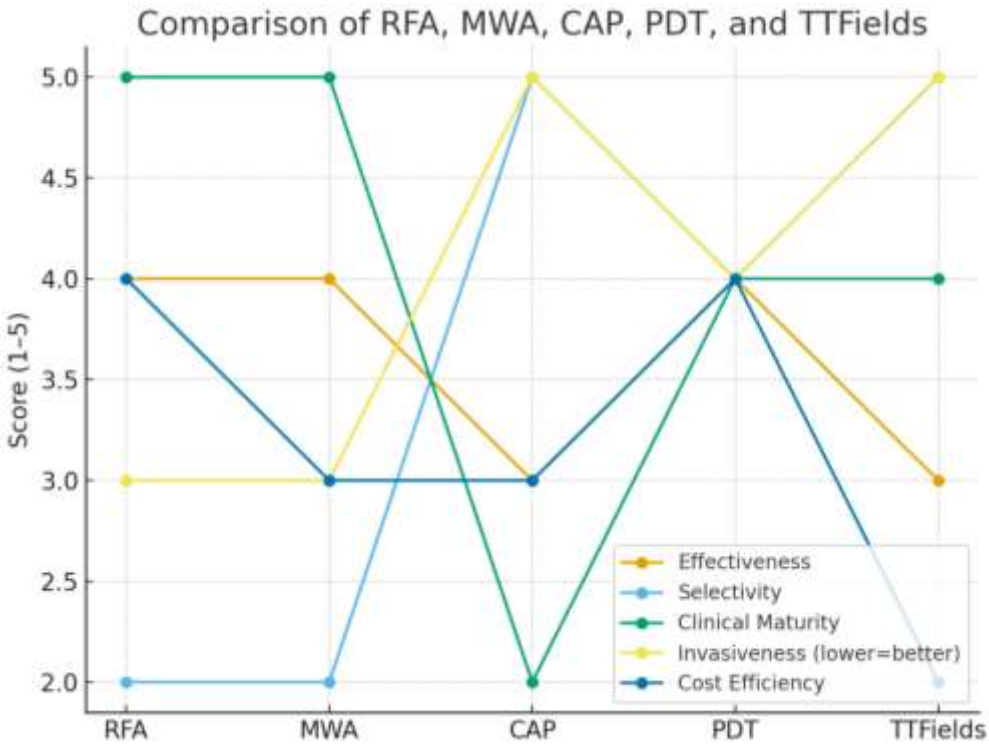


Comparison Chart: RFA vs MWA vs CAP vs PDT vs TTFields
This chart compares the five therapeutic modalities based on key performance criteria such as effectiveness, selectivity, clinical maturity, invasiveness, and cost efficiency. Scores are on a scale of 1 (poor) to 5 (excellent) as shown in figure 3 below.

Table 3: Interpretation by Axis

Parameter	Meaning	Observation
Clinical Maturity	How established the technique is in clinical oncology	RFA and MWA rank highest, reflecting routine use in hepatocellular, renal, and lung tumors. TTFields and PDT are moderate, being newer but FDA-approved for specific cancers. CAP is lowest, still largely in preclinical/early clinical investigation.
Invasiveness (Low = High Score)	Minimally invasive treatments score higher	TTFields and CAP rank highest, as they are non-destructive, external-field based treatments. RFA and MWA score lower due to probe insertion requiring imaging guidance.
Precision	Ability to target tumor cells while sparing surrounding tissue	CAP and PDT show strong precision, as plasma and photoreactive agents can be directed to tumor margins. RFA/MWA have moderate precision due to collateral heat spread.
Thermal Damage (Low Damage = High Score)	Measures unintended heat effect	TTFields scores highest: it introduces no thermal injury. CAP and PDT also score high due to non-thermal modalities. RFA/MWA score low, reflecting risk of thermal necrosis extending beyond tumor boundaries.
Immune Activation Potential	Ability to stimulate anti-tumor immune response	CAP leads in immune activation, supported by reports of ROS/RNS-triggered immunogenic cell death. PDT also induces strong immune modulation via DAMP release. RFA/MWA offer limited immune engagement, mostly necrosis without immunogenic signatures.

Discussion



The radar chart compares five electronics-based cancer treatment methods: RFA, MWA, CAP, PDT, and TTFields - based on how they perform across several important criteria in cancer care. RFA and MWA rank highest in terms of clinical maturity because they are well-established techniques already used in hospitals for liver, lung, and kidney tumors. However, their reliance on inserting probes and using intense heat means they are more invasive and carry a higher risk of damaging nearby healthy tissue. They also tend to destroy tumors through necrosis, which does not strongly stimulate the immune system. On the other hand, newer bioelectronic therapies like TTFields and Cold Atmospheric Plasma are far less invasive since they work externally without generating damaging heat. TTFields interrupts cancer cell division using alternating electric fields, while CAP triggers cancer cell death through reactive chemical species that also alert and activate the immune system. Photodynamic Therapy sits in the middle,

offering targeted tumor destruction using light-activated drugs with a moderate level of clinical adoption and an ability to trigger some immune response. Overall, the comparison highlights a clear shift in oncology from traditional heat-based tissue destruction toward more precise, immune-aware electronic treatments that aim not just to kill cancer cells but to do so gently, safely, and in a way that helps the body recognize and fight cancer more effectively.

Future Directions

1. Bioelectronic immune modulation: using electric pulses to stimulate immune cells to attack tumors.
2. Electro-nanomedicine: combining microelectronics, nanotech, and AI for precise tumor targeting.
3. AI-guided treatment optimization: electronics-integrated systems analyze signals to personalize therapy.
4. Hybrid platforms that combine electrical, thermal, optical and chemical modalities,
5. Closed-loop implantable systems integrating sensing, AI, and local actuation for personalized therapy;
6. Remote-activated nanomachines to achieve deep-tissue, spatiotemporally precise drug production/release; and
7. Rigorous combination trials pairing electronics-based modalities with immunotherapies to exploit immunogenic cell death and systemic antitumor immunity. Continued engineering advances, robust clinical trials, and translational attention to safety/regulatory pathways will determine which approaches reach routine oncology practice.

Summary

The integration of electronics into cancer therapy marks a paradigm shift from purely chemical and radiation-based treatments toward precision bioelectronic oncology. Traditional ablation techniques such as Radiofrequency Ablation (RFA) and Microwave Ablation (MWA) remain clinically dominant due to their reliability in inducing thermal necrosis, particularly in solid tumors like hepatocellular carcinoma and renal metastases (Zhou et al., 2022). However, these thermal modalities introduce limitations including collateral tissue injury, heat-sink effects near vasculature, and a lack of immunogenic cell death, which restrict systemic anti-cancer immune responses (Li et al., 2020).

To address these limitations, next-generation electronics-driven non-thermal therapies have emerged. Tumor Treating Fields (TTFields) utilize alternating electric fields in the 100–300 kHz range to disrupt mitotic spindle formation, selectively inhibiting the proliferation of cancer cells without significant thermal damage to surrounding tissues (Stupp et al., 2017). Unlike RFA and MWA, TTFields modulate intracellular electroconductivity and exert biomechanical stress on dividing tumor cells, leading to apoptosis. Moreover, emerging data suggest that TTFields may enhance immunogenic modulation, making them potential partners for immunotherapy (Cao et al., 2020).

Similarly, Cold Atmospheric Plasma (CAP) represents a rapidly evolving technology that generates a mixture of reactive oxygen and nitrogen species (RONS) at low temperatures. These species induce oxidative stress in cancer cells, leading to DNA damage, membrane lipid peroxidation, and immunogenic cell death signals such as calreticulin exposure, which can enhance dendritic cell activation (Von Woedtke et al., 2019). Unlike purely cytotoxic methods, CAP shows potential in tumor microenvironment reprogramming, shifting tumors toward an immunostimulatory state (Mir et al., 2019).

Photodynamic Therapy (PDT), another electronics-enabled technique, uses a light source—typically laser or LED—to activate photosensitizing molecules, generating localized ROS and inducing apoptosis or necrosis depending on dosage and light penetration (Lucky et al., 2015). Though limited by light penetration depth, advances in nanoparticle-assisted PDT and electronic light delivery systems are extending its applicability to deeper tumors.

Beyond external devices, implantable bioelectronics and electro-responsive nanomaterials are being engineered to deliver on-demand hyperthermia, electric stimulation, or drug release, enabling closed-loop therapeutic systems that respond to real-time tumor signals (Li et al., 2020; Johannsen et al., 2020). The convergence of microelectronics, biosensors, and programmable energy delivery is gradually enabling adaptive cancer therapy platforms—a core tenet of emerging intelligent oncology.

Collectively, these electronics-based treatments are trending toward minimally invasive, immune-integrative, and precision-targeted cancer control, departing from the purely destructive logic of traditional ablation. The synergy between bioelectronic modulation and immuno-oncology represents one of the most promising frontiers in modern cancer therapy, with TTFields already FDA-approved for glioblastoma, PDT approved for dermatologic and esophageal lesions, and CAP entering translational trials (Stupp et al., 2017; Von Woedtke et al., 2019; Zhou et al., 2022).

Conclusion

Emerging electronics-based cancer treatment technologies are reshaping modern oncology, moving the field from generalized cytotoxic therapies toward precise, minimally invasive, and bio-integrated interventions. Techniques such as Radiofrequency Ablation (RFA) and Microwave Ablation (MWA) have already demonstrated clinical relevance by leveraging thermal energy to induce localized tumor necrosis with reduced systemic toxicity compared to chemotherapy (Goldberg et al., 2020; Lubner et al., 2019). Meanwhile, Cold Atmospheric Plasma (CAP) and Photodynamic Therapy (PDT) offer non-thermal cytotoxic strategies that selectively disrupt cancer cell membranes and intracellular signaling through reactive species generation and light-activated biochemical pathways, showing significant potential for superficial and accessible tumor types (Keidar, 2021; Agostinis et al., 2020).

More futuristic yet clinically advancing are Tumor Treating Fields (TTFields), which introduce a paradigm shift by using low-intensity alternating electric fields to interfere with mitotic spindle formation, reducing cancer cell proliferation with minimal discomfort to patients (Stupp et al., 2017; Taphoorn et al., 2020). In parallel, implantable bioelectronic systems and smart

electroceuticals are gaining traction as platforms for controlled drug release, tumor microenvironment modulation, and real-time physiological feedback, enabled by advances in flexible electronics, nanofabrication, and wireless energy transfer (Dagdeviren et al., 2022; Wang & Gao, 2021).

Collectively, these technologies emphasize a transition toward energy-based, precision-guided, and biologically informed cancer therapies, minimizing collateral tissue damage while enabling combination with immunotherapy, AI-driven imaging, and personalized medicine strategies. Despite promising outcomes, challenges persist in deep tissue targeting, device biocompatibility, regulatory standardization, and long-term safety verification, particularly in implantable or high-frequency field-based systems. Continuous interdisciplinary collaboration among biomedical engineers, oncologists, materials scientists, and regulatory bodies will be essential to translate these innovations from controlled laboratory environments into fully scalable clinical solutions. As electronics continue to merge seamlessly with biological interfaces, the future of cancer therapy is poised to evolve toward adaptive, programmable, and patient-specific treatment ecosystems, marking a transformative era in medical technology.

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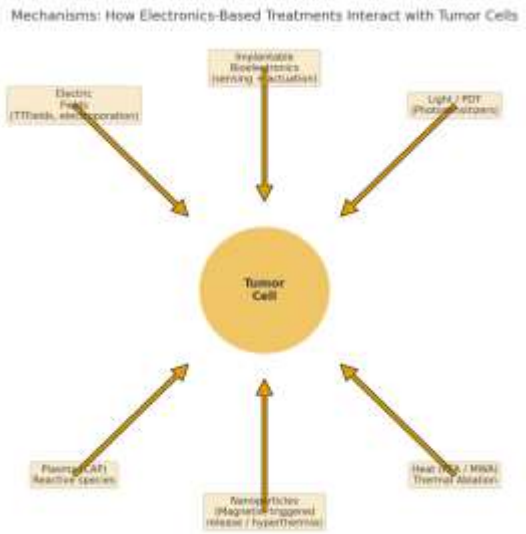
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