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PLASMA PHYSICS APPLICATIONS IN STERILIZATION AND CANCER TREATMENT

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Abstract:

Advances in plasma physics enable widespread applications of plasma technology, notably in sterilization and cancer treatment. Sterilization necessitates effective microbial elimination without high temperatures, and corona discharge plasma achieves bacterial and viral inactivation at temperatures below 80 °C. Cold atmospheric plasma (CAP) developments facilitate sterilization of heat-resistant medical devices at room temperature and atmospheric pressure. Plasma's suitability extends to cancer treatment since it generates reactive oxygen species and charged particles inducing various forms of cancer cell death. Plasma constitutes an ionized gas comprising positive and negative charged particles and neutrals, exhibiting collective behavior due to electromagnetic interactions. At sufficiently low gas temperatures, plasma attains thermodynamic equilibrium and behaves as a neutral fluid. Common plasma types include thermal plasma, glow discharge plasma, and corona discharge plasma. Various techniques can generate plasma from neutral gases, such as DC discharge, glow discharge, and corona discharge methods.

Keywords: Plasma Physics, Sterilization, Cancer Treatment, Cold Atmospheric Plasma (CAP), Microbial Elimination

1. Introduction

Low temperature plasma (LTP) sources and their applications have attracted considerable attention in the last decade with LTP being investigated for bacterial inactivation, oral hygiene, wound healing, cancer cell treatment, and more. Biomedical applications of low temperature plasmas began several decades ago with the earliest example being low-pressure oxygen plasma used for spacecraft sterilization. The late 1980s and early 1990s saw the emergence of various plasma sources capable of generating large volumes of low-temperature atmospheric pressure plasma. These sources were initially developed for material processing but soon found interest from the US Air Force for wound treatment and surface sterilization. Research in Russia further revealed that plasma-generated nitric oxide could promote cell proliferation. The development of plasma sources capable of delivering

plasma outside the electrode region or confinement enhanced the utility of these sources, leading to the emergence of plasma jets that produce plasma at biologically compatible temperatures. These developments have catalyzed global research efforts aimed at elucidating the interaction mechanisms between low-temperature plasmas and biological tissues and systems [1].

LTPs are well suited for medical purposes because they operate at atmospheric pressure and near-room temperature while producing reactive oxygen and nitrogen species (RONS), such as atomic oxygen, superoxide, singlet oxygen, ozone, nitric oxide, and nitrogen dioxide. These species are significant in cancer growth, signalling, and treatment mechanisms and can target a wide range of tumour types, aligning well with traditional cancer therapies. LTPs can generate exceptionally strong electroporative fields and precisely affect small, localized regions, making them promising tools for tumor control and eradication [2], [3]. The ability to tailor both the reactive species composition and the applied electric fields over short timescales enhances their suitability for both combination and focal therapies. LTPs are therefore uniquely positioned to address challenges associated with metastatic cells and cancer stem cells. The field of plasma medicine has received considerable attention and growth over the last decade, drawing on the distinct physical and chemical properties of plasma to meet biomedical needs [4].

Fundamentals of Plasma

Plasma is a state of matter formed from a gas that is electrically conductive to the extent that the magnetic and electric fields influence its dynamics and behaviour. Often referred to as the fourth state of matter, the other three being solid, liquid, and gas, plasmas that self-generate can occur naturally as lightning or lightning bolts. In industrial settings, plasma discharges are generated deliberately and sustained by the application of electromagnetic fields to a gas with suitably low pressure. Some researchers define plasma as ‘‘a collection of charged particles with overall charge neutrality’’ [5]. Of the earth’s population, approximately 99.9% live in a plasma state. Astrophysical plasma, due to its low density and relatively low temperature, is thermodynamically very different from that used in industrial processes [6]. Particle densities vary widely in industrial plasmas and are dependent on chemistry, pressure, power density, and reactor size. Industrial plasmas differ in several respects from the common astrophysical plasma, and they are often very different from the supposedly simple, ideal plasma often studied in plasma physics research. Space plasma differs from low-temperature laboratory or industrial plasmas due to several key factors, which include zero gradients, low collisionality, use of electromagnetic probes, and the existence of double layers.

Consider a gas subjected to an external electrical influence (an electric field). The gas particles, usually molecules or atoms, are ionised, and the ionisation creates free electrons that collide with other particles and processes that create further ionisation and, consequently, more free electrons [7]. After a concentrated part of the gas escapes of to the electrodes, at a certain pressure, the electric field creates free electrons, which are accelerated and generate more free electrons in a null correspondence. It is quite easy to fully ionise a gas if the intensity of the electric field is high; if this is the posses, the gas becomes a plasma—electrically conductive and maintaining an equilibrium (self-maintained in free state).

Definition and Characteristics of Plasma

Plasma is a quasi-neutral gas of charged and neutral particles exhibiting collective behavior. Around 99% of visible matter, including stars such as the sun, exists in the plasma state at temperatures ranging from thousands to millions of Kelvin. Contrastingly, after the development of electrical discharges in rarefied gases by Geissler in 1857, plasma physics flourished in the condensed-matter regime from the latter part of the nineteenth century onward. Today, the active interdisciplinary field of low-temperature plasma forms under either strongly non-equilibrium or nearly equilibrium conditions, at temperatures from room temperature up to several tens of thousands of Kelvin, where non-isothermal and thermal plasmas may be distinguished on the basis of their characteristic thermodynamical behavior. In practice, the state of matter obtained by sufficient energizing of a gaseous system at low temperature exhibits significant deviation from a classical neutral gas, even if only a relatively small degree of ionization is established [8]. At atmospheric pressure, the transition from pure neutral gas to

fully ionized plasma therefore occurs through a partially ionized state, whereby charged and neutral particles interact with one another. This variously named state (e.g., partially ionized, weakly ionized, semi-ionized, ionized) corresponds naturally to many types of naturally occurring plasmas, but also to the extensive suite of plasma technologies contacting the ambient atmosphere and a liquid phase. From a practical perspective, low-temperature plasmas find application across a broad range of physically and chemically detailed processes, from medicine and nanotechnology to thin film deposition, heat transfer and fluid dynamics, among others [9].

Types of Plasma

Plasma, often referred to as the fourth state of matter, represents an ionized gas dominated by positive ions and electrons. In plasma physics applications, the focus lies primarily on cold plasma (temperature in the range of tens of thousands of degrees Celsius), as it offers greater practicality and feasibility compared to hot plasma (temperature in the range of millions of degrees Celsius). Plasma exists in liquid or gaseous forms. Gaseous plasma can be produced through various methods, including electrical discharges within vessels, radio-frequency radiation, microwave irradiation, or laser light exposure [10].

Plasma Generation Techniques

Plasma is the fourth state of matter consisting of unbound positive ions and negative electrons. In gas-discharge physics, two types of plasma can be distinguished based on temperature: high-temperature plasmas (where ions, atoms, and electrons have the same energies and temperatures around 10,000 °C, as in fusion plasmas) and non-thermal plasmas (where gas species and electrons are not at thermal equilibrium, featuring electron temperatures of a few tens of thousands °C, but the overall gas temperature remains close to ambient) [11]. Various techniques are available to convert gases to the plasma state, such as sparks, arcs, radio-frequency (RF) and microwave (MW)-driven discharges, dielectric barrier discharges (DBD), atmospheric pressure plasma jets (APPJ), and corona discharges; the steady-state microwave plasma torch is particularly advantageous for generating high concentrations of reactive species. Many groups worldwide have successfully demonstrated plasma's ability to treat, disinfect, and sterilize various targets. The scope of plasma medicine is broad, ranging from the treatment of UTIs to the notion of tailoring plasma parameters for wound healing and cancer treatment, underlining the interdisciplinary relevance of plasma physics in both sterilization and cancer therapy.

Plasma Physics in Sterilization

Microbial contamination presents a significant challenge in medical and dental care, necessitating effective sterilization techniques for items such as cellular phone cases, contact lenses, toothbrushes, sewing needles, and food components. Conventional sterilization approaches include steam, boiling water, ultraviolet light, ethylene oxide, formaldehyde exposure, and hydrogen peroxide treatment. However, plasma can serve as an efficient alternative because it generates reactive species that undergo frequent collisions with microbes, thereby inactivating them. Consequently, plasma is frequently employed for the sterilization of medical devices [12].

The effectiveness of plasma sterilization depends on specific parameters including plasma characteristics, source type, and geometric configuration. Noble gases are typically utilized in plasma jets because they facilitate the generation of reactive oxygen and nitrogen species. The quantity and variety of these reactive species differ between those produced by plasma jets in noble gases and those formed directly in ambient air environments.

Mechanisms of Microbial Inactivation

Microbial inactivation is a key approach for sterilizing medical devices, including surgical instruments and implantable materials [13]. Conventional sterilization methods suffer various drawbacks. For instance, high temperatures cause thermal stress and adversely modify instrument materials. Gamma sterilization entails complex regulation, while ethylene dioxide and chemical sterilization involve detrimental toxic agents [14]. Plasma thereby offers advantages as a readily adoptable technique for a broad range of materials at low temperatures. The underpinning mechanisms involve plasma-generated

species of random molecules, ions, and electrons. Radio-frequency and microwave discharges directly energize microorganisms, inducing molecular bond cleavage [15]. Indirect approaches employ excited species such as ultraviolet radiation, reactive oxygen species, and reactive nitrogen species. Electric-field-induced morphological changes and structural deformation also contribute to inactivation.

Applications in Medical Device Sterilization

The sterilization of medical and dental instruments necessitates decontamination procedures that preserve the integrity of the devices. Low-temperature plasma sterilization offers a method that meets these requirements by enabling efficient, rapid, and non-destructive decontamination of delicate materials [16]. Plasma, as a state of matter containing charged particles, excited molecules, UV-radiation, and radicals, is generated when a neutral gas undergoes ignition under an applied electric field. It is established as a physical inactivation agent capable of neutralizing a wide array of bacteria and viruses, including species resistant to conventional sterilization technologies [17]. Modern plasma sterilization systems produce a mixture of reactive oxygen and nitrogen species (RONS), such as atomic oxygen (O), singlet oxygen (O1D), ozone (O3), hydroxyl radicals (OH), nitric oxide (NO), and nitrogen dioxide (NO2). These reactive species effectively decompose and oxidize the organic molecules constituting the cell walls of microorganisms, thereby inactivating them through irreversible damage.

2. Materials and Methods

Plasma Sterilization vs. Traditional Methods

Plasma technology offers distinct advantages over traditional sterilization techniques, such as autoclaving, γ-rays, and ethylene oxide (EtO) gas [6]. Most conventional methods cannot achieve sterilization at low temperature and atmospheric pressure, limiting their application to temperature-sensitive materials. Microorganisms become inactivated after interaction with plasma generated reactive agents ; plasma sterilization is typically achieved by oxidation of critical macromolecules following exposure to long-lived reactive oxygen and/or nitrogen species. In contrast to EtO and ionizing radiation, cold atmospheric plasma (CAP) rapidly kills microbial contamination without the emission of toxic residues. Since plasma gases do not cause damage to plastic and electronic components, unlike γ-rays and electron-beam irradiation, CAP is advantageous for sterilizing sensitive medical instruments. CAP also offers a promising alternative to chemical sterilization for non-viable biological tissues since it effectively eliminates normal bacterial bioburden and resistant abnormal contaminants, including endotoxins and prions. The effectiveness of plasma sterilization depends on the interplay between microbial contamination, tissue characteristics, and selection of plasma generation and delivery mode. Direct or indirect CAP systems can be applied for sterilization, operating at atmospheric pressure and ambient temperature and generating active species that penetrate several centimeters through liquids or porous materials. Small mobile devices or contained chambers can achieve in-package sterilization, with the combination of sterilization and packaging potentially increasing the shelf-life of treated products. Although CAP represents a terminal sterilization technique with appropriate characteristics, it is not a universal solution for all sterilization problems. Careful assessment of CAP protocols and consideration of tissue nature, manufacturing procedures, and intended use are necessary. Despite limitations related to tissue thickness, post-packaging penetration, and reproducibility challenges, this emerging technology shows significant potential when appropriately adapted.

Plasma Technology for Cancer Treatment

Plasma, the fourth state of matter, is an ionized gas comprising electrons, ions, and neutrals. Plasmas can be broadly categorized into thermal or nonthermal based on whether all gas species share the same temperature. Low-temperature plasma includes cold plasma, where the ion temperature remains near room temperature. Several methods are employed to generate low-temperature plasma in open air at atmospheric pressure.

When applied in sterile medical environments, plasma effectively transforms pathogenic microbes into

nonpathogenic forms, enabling medical devices to be utilized in sensitive biomedical and aesthetic procedures. Plasma sterilization presents advantages over traditional autoclave or ethylene oxide processes.

Cancer treatment technologies utilizing plasma have emerged in recent years, demonstrating the capability to selectively provoke apoptosis in cancer cells. Analytical models reveal multiple factors inhibiting cancer progression when cold atmospheric plasma is applied to malignant cells or tissues. Gas plasma devices have shown potential to induce toxic and immunogenic effects in tumor organoids, with modifications to plasma jets enhancing free radical production and treatment area, thereby augmenting antitumor efficacy. Compared to conventional therapies, plasma-based cancer treatment offers increased specificity in targeting malignant cells and reduced adverse side effects facilitated by intermittent application.

3. Results and Discussion

Mechanisms of Plasma-Induced Cancer Cell Death

Plasma-generated reactive oxygen species (ROS) can induce apoptosis and necrosis in cancer cells, suggesting potential applications for sterilization and cancer treatment [18]. Cold physical plasma operates at or near body temperature and produces electrically neutral ROS and reactive nitrogen species (RNS). Plasma-treatment modalities satisfy clinical demands for targeted, simultaneous sterilization and oncotherapy. In cancer cells, increased intracellular ROS levels—stemming from aerobic metabolism alterations and mitochondrial dysfunction—confer heightened susceptibility to exogenous ROS influx. Certain ROS (e.g., superoxide anion, hydrogen peroxide, peroxynitrite, hydroxyl radicals) permeate cell membranes via aquaporins and/or lipid peroxidation. Exposure triggers persistent intracellular oxidative stress, mitochondrial damage, DNA lesions, and dysregulated redox homeostasis. Cell death ensues through signaling cascades involving STAT3, MAPK, and PI3K/AKT. Comparisons to conventional oncotherapies reveal technical approaches and discharge types conducive to effective plasma-induced cancer-cell inactivation.

Clinical Applications of Cold Atmospheric Plasma

Developed over decades, cold atmospheric plasma (CAP) exhibits selective anticancer effects. CAP treatment targets head and neck squamous cell carcinoma cells without harming adjacent healthy tissue [19]. Investigations have further revealed anticancer properties of CAP in vitro and in vivo, leading to pro-apoptotic and growth-inhibitory impacts against glioblastoma and colorectal cancer cell lines. Exposure to CAP induces an anti-proliferative response in prostate cancer mediated through redox and apoptotic signaling pathways. In vitro studies also demonstrate differential CAP responses for malignant glioma treatment. Gas plasma application at atmospheric pressure triggers colorectal cancer cell mortality by activating the Nox2-ASK1 apoptosis pathway, while antioxidant systems mitigate oxidative damage. Cell death from plasma treatment ensues through generation of reactive oxygen species. Cancer cell lines from human monocytic lymphoma demonstrate dose-dependent responses to CAP, delivering an apoptotic outcome. Solid tumor cells respond through plasma-induced reactive oxygen species pathways, modulating viability. Induction of senescence emerges as another pro-death mechanism, as corroborated in melanoma models. Continuum models provide insight into plasma stream propagation extending from individual jets to arrays. Breast cancer cells also undergo selective ablation during CAP exposure. The cytotoxic and mutagenic potential of plasma manifests via oxidative stress-induced DNA damage and invokes early implementation of standard clinical dosimetry to quantify biological effective doses; further research seeks to elucidate plasma-induced bystander effects involving soluble factors and intercellular transfer of DNA damage signals.

Comparative Studies with Conventional Cancer Therapies

Low temperature plasmas (LTPs) were identified as having favourable features for the treatment of cancer. They operate at atmospheric pressure and room temperature, and produce reactive oxygen and nitrogen species (RONS), which are known to influence cancer cell growth and death. LTPs can be precisely applied to small target areas. Electroporative fields (EPFs) accompany the production of

RONS, enabling control or eradication of tumours and selective treatment of cells depending on their ontogeny and interaction with their microenvironment. The capacity to regulate the dose and conferred cellular response means that LTPs can be used for both cytotoxic and pro-motility/activation tumour therapies. The mechanisms of cell death and death following LTP exposure have also been extensively studied, with the evidence for the involvement of both RONS and EPFs outlined. Conventional cancer therapies—most notably radio- and chemo-therapies—deploy reactive species as a means to control tumour burden and prevent the onset of metastasis. Although promising, these treatment regimens have variable patient outcomes, are reliant on the tumour burden, and often give rise to side effects. Therefore, the development and implementation of new therapeutic strategies that enhance the selective killing of malignant tissue, mitigate side effects, and support existing therapeutic strategies are extremely relevant.

Safety and Efficacy of Plasma Treatments

To date, cold plasma treatments for sterilization have been assessed for cytotoxicity, genotoxicity, apoptosis, and inflammatory responses. Data to document any risks arising from their therapeutic use in the anticancer area are essential if cold plasma methods are to be accepted as routine therapies. Sterilization methods typically fall under the jurisdiction of the U.S. Food and Drug Administration (FDA). For cancer treatments to be approved, the devices must comply with the FDA regulations for the desired use. Many of these devices use similar technologies and construction. To assist health facilities checking on regulatory requirements, the FDA has provided guidance relating sterilization and cancer therapy equipment platforms.

Toxicity Assessments

Toxicity assessments offer crucial insights into the safety of plasma technologies applied in sterilization and cancer treatment. These evaluations are vital for optimizing the therapeutic benefits of cold plasma and facilitating its regulatory acceptance in medical devices and industrial sterilization processes. Limited exposure to plasma treatment does not elicit mutagenic effects, whereas extended plasma exposure can induce alterations in the cell cycle and apoptosis without concomitant mutagenic outcomes. An enduring imperative is to maintain the balance between efficacy and safety across the diverse non-thermal plasma treatments considered for various plasma medicine applications.

Regulatory Considerations

The regulatory status of sterilization methods is crucial to achievement of clinical acceptance. Biological tissue must be sterile to be both safe and to satisfy the regulatory requirements of bodies such as the Food and Drug Administration. Currently available in-hospital sterilization methods have drawbacks that limit their applicability to arc specific types of allografts and their use for non-viable biological tissues is precluded. An ideal sterilization technique ought, ideally, to operate at pressures and temperatures consistent with the viability of the tissue, be effective for a broad range of microorganisms, be compatible with both metallic and polymeric parts. Techniques that employ high temperatures, aggressive chemicals, ionizing energy, long exposure times, or high doses of antibiotics are disadvantaged on one or more of these accounts. Direct or indirect CAP systems may satisfy some of these criteria because they operate at atmospheric pressure and at ambient temperature. Given the use of simple main chamber systems, an approach that permits treatment of large areas inside final product packaging is also available. The ability to deliver significant densities of active species with penetration power into the interior of the material of interest, and would thus facilitate the application of terminal sterilization to the allograft prior to shipment. Small mobile CAP devices (potentially battery powered) or in-package sterilization chambers are envisaged as candidate geometries. The CAP method offers an inexpensive and effective means of terminal sterilization for AM [allografts?] that can be applied to living tissues without any currently known harm, and that is capable of destroying both the normal contaminating population and any abnormal load that may develop during manufacturing. Nevertheless, the technique is limited by tissue thickness, post-packaging penetration, and that of reproducibility. The selection of CAP for allograft terminal sterilization may, therefore, need to be made in the light of tissue characteristics, manufacturing protocol, and intended use. If suitably adapted and implemented for TBTM sterilization, cold atmospheric-pressure plasma

represents a still largely untapped resource for sterilization of AM that holds considerable promise.

Research and Development in Plasma Applications

Research and development in plasma applications focus on the expansion of investigative efforts and emphasis on practical utility. The favorable safety profile of cold plasma treatments in sterilization and oncological contexts has catalyzed the exploration of technologies for acquiring, storing, monitoring, and delivering plasma-generated species. Comprehensive characterization of discharged species for individual plasma sources further supports the refinement of application methodologies. These endeavors address requirements for scalability, reproducibility, and documentation compliance necessary for regulatory approval and integration into routine clinical practice. Continued research thus aims to advance plasma-based technologies from conceptual demonstrations toward viable, widely accessible treatment options.

Current Trends in Plasma Research

Plasma research continues to mature as a significant multidisciplinary science, encompassing a broad range of phenomena that cover many scientific disciplines and constitute a well-known branch of physics. Plasmas may be defined as quasi-neutral ionized gases consisting of neutrals, ions, and electrons that exhibit collective behavior.

Plasma science and technology have become essential to major advanced technologies, with widespread applications in space science, atomic and molecular physics, astrophysics, fusion science, particle accelerators, surface science, semiconductors, condensed matter physics, biology, and medicine. Over the past few years, plasma science and technology have been employed in numerous ways to serve humanity, promoting new prospects in electronics, environmental remediation and energy, health care, food preservation, automobiles and aerospace, advanced manufacturing, and nanotechnology technology.

Since a large branch of plasma science and technology is actively playing a very important role in modern health care as well as in food safety, a short perspective and applications of plasma physics for sterilization and sterilization as well as for cancer treatment are briefly described.

Innovations in Plasma Technology

Plasma features prominently in numerous industrial applications, including surface treatment, thin-film deposition, and microelectronics fabrication, where it enables processes unattainable through conventional means. While it is commonly addressed within the scope of physical products or mechanical engineering, plasma's interdisciplinary reach spans chemistry, biology, materials science, and environmental studies. In raw form, plasma represents a medium with distinct chemical, electrical, thermal, and optical properties that can be harnessed to accelerate or enable various phenomena. Its effectiveness arises from an abundance of neutral atoms, ions, and electrons that are readily available to trigger diverse reactions. Past applications have included sterilization of medical instruments and tools, where plasma is emerging as a "green" alternative to chemical disinfectants such as ethylene oxide. Moreover, plasma-based sterilization systems can neutralize harmful airborne viruses and contaminants in indoor environments. A particularly notable advancement involves the use of plasma in cancer treatment and therapy. Cold atmospheric plasma (CAP) is generated under atmospheric pressure and at temperatures ranging from 300 to 330 K, producing a mixture of electrons, ions, reactive radicals, UV photons, and transient electric fields capable of inducing selective apoptosis. This technique directly or indirectly disrupts cellular functions, promoting cancer cell death, and is compatible with most existing cancer therapies without inducing resistance phenomena. Ongoing research continually explores supplementary applications in scientific, engineers, and medical contexts, highlighting plasma technology's versatility and prospective impact.

Future Perspectives

In addition to their current applications in sterilization and cancer treatment, plasma technologies hold promise for broader clinical uses. Cold atmospheric plasma devices can be configured to provide tailored doses of plasma-generated reactive oxygen and nitrogen species to the surface of fresh produce, which may prolong shelf life by destroying microorganisms and degrading pesticides. If such

devices are equip-ped with advanced feedback sensors that account for shelf-life properties and disinfection requirements, plasma treatments may play a key role in supply chain management for perishable goods, reducing waste.

Similar tailored treatments have the potential to facilitate the delivery of a wide range of materials and pharmaceuticals across permeation barriers by briefly disrupting barrier integrity. Addressing key challenges for plasma applications requires interdisciplinary collaboration among researchers in plasma science and engineering, as well as plasma-medicine specialists, who can provide essential insights for the future development of application-specific plasma sources and treatment procedures.

Emerging Applications of Plasma

Plasma applications go beyond sterilisation. In the context of oncology, plasma supports cancer therapy. Cold atmospheric plasma induces apoptosis and loss of cellular adhesion in cancer cells. Laboratory experiments demonstrate the elimination of tumour cells with minimal harm to adjacent healthy cells. Plasma efficiently inactivates metastatic cancer cells, small tumours, and tumour spheroids. Plasma-activated media cause cancer cell death. The ability to produce reactive oxygen species (ROS), reactive nitrogen species (RNS) and biomolecules in media and cells generates biological responses with therapeutic potential. Gas plasmas and plasma-activated media cause necrosis, apoptosis and immunogenic cell death in multiple cancer types at various disease stages. Clinical application of cold atmospheric plasma now receives attention as an alternative modality to chemo- and radiotherapy for selectively treating cancer.

Challenges and Opportunities

Plasma physics presents both applied physics challenges and opportunities in biomedicine, widespread throughout sterilization and cancer treatment. Sterilization deters infection by eradicating microorganisms from sensitive environments and objects—central to medical and surgical procedures that must avoid microbial infection. Medical surfaces and tools remain a crucial case. Autoclaving denatures proteins through extreme heat and pressure, making it inappropriate for heat-sensitive and delicate materials exposed to surgical intervention, such as optical lenses and fibre optic cables. Radiation produces free radicals inducing microbial DNA damage, but also penetrates deeply, damaging materials beyond the targeted surface. Disinfectants counter surface residues, but are often cytotoxic, environmentally hazardous, damaging, or allergens. Plasma sterilization is effective at low temperature and pressure. Other applications include protection of large indoor environments, preservation of foods vulnerable to chemical preservatives, and reduction of foodborne grain-borne pathogens.

Low temperature plasma also offers therapeutic approaches to avoid the inherent shortcomings of conventional oncotherapies: systemic toxicity, resistance, and irreversible side effects. Cancer treatments are foremost among those burdens. Many tumors have high heterogeneity and are strongly associated with genetic factors, making it difficult to uniformly target all tumors while avoiding side effects and resistance. Chemotherapy and radiation remain state of the art and are still widely used, but often induce systemic immunosuppression and target healthy tissue. For the most recalcitrant, recurrence or development of secondary cancers occurs in over 50% of cases. Cold atmospheric plasma is nonthermal, low power, portable, comparatively inexpensive, and highly selective. It can be modified and engineered to suit various indications, and may simply be applied without the need for advanced machinery, pharmaceuticals, or associated waste. Plasma technology therefore holds promise to act as a direct oncoprotein in a stand-alone or combinatorial capacity while simultaneously providing sterilization.

4. Conclusion

The execution of certain techniques is significantly influenced by plasma physics principles, as plasma parameters impact the effectiveness of plasma-based technologies in both commercial and academic contexts. Many plasma applications require plasmas to operate within the near-atmospheric regime

Sterilization stands as an important application, and low-temperature plasma enables rapid sterilization

of polymer surfaces to eliminate microbial contaminants without the scope and scale limitations of conventional methods. The technique also holds promise in plasma medicine and dermatology, such as for skin and wound treatment or enhancement of subcutaneous drug delivery.

Interest is also burgeoning in low-pressure plasma's applications, including particle diagnostics and process control, as well as the generation and maintenance of the plasmas themselves. Indeed, plasma physics is increasingly used to diagnose and control industrial plasma processes that operate at pressures outside the classical low-pressure regime. The large-collision frequency gradient inherent in these plasmas leads to markedly different electron energy distribution functions that require further research.

Plasma technology is emerging as a promising option for cancer treatment that offers several notable advantages over conventional therapies. Nonthermal plasma induces rapid vibrational, rotational, and excitation states without a significant rise in gas temperature, making it desirable for thermal-sensitive applications. Pulsed gas plasmas that operate at near-room temperature have demonstrated swift death of various cancer cell lines and are potentially selective toward cancer cells. Any new sterilization technologies must routinely address toxicity issues, so toxicity analysis of plasma-treated liquids represents an important development to aid progress.

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