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REVIEW

PLASMA PROCESSES AND POLYMERS

The applications of cold atmospheric plasma in dentistry

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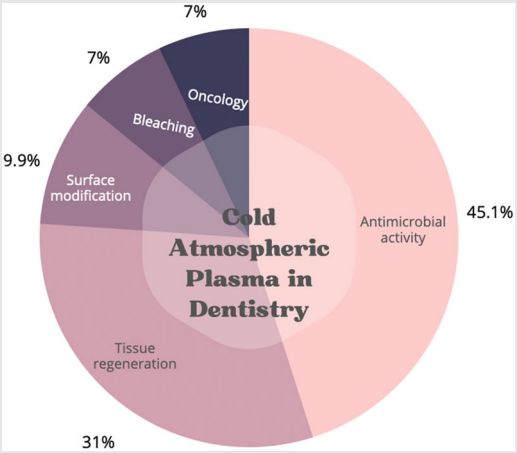
Abstract

Cold atmospheric plasma (CAP), as a noninvasive technology, has shown promise in dentistry as it might successfully treat various oral conditions. The antimicrobial capacity of CAP has been proven and it is effective in reducing the main microorganisms responsible for oral infections. Furthermore, CAP has also been explored in the field of tissue regeneration with a great response from both soft and hard tissue. The surface modification ability of CAP is another area of interest, revealing a potential improvement in the osseointegration of dental implants. Additionally, there are other areas within dentistry that have studied the use of CAP, such as surface disinfection, bleaching, and cavity preparation.



KEYWORDS

antimicrobial, biocompatibility, biomaterials, cold atmospheric plasma, dentistry

Abbreviations: AA, air abrasion; AM-CAPJ, amplitude-modulated cold atmospheric plasma jet; APGD-t, atmospheric pressure glow discharge; APPJ, atmospheric pressure plasma jet; CAP, cold atmospheric plasma; CFU, colony forming units; DBD, dielectric barrier discharge; ECM, extracellular matrix; FE-DBD, floating electrode dielectric barrier discharge; **Fim A type 2** P, gingivalis strains ATCC 33277; H_2O_2, hydrogen peroxide; hDPSCs, human dental pulp stem cells; HO_2, hydroperoxy radical; HW24D-1, *Porphyromonas gingivalis* strains; IL-1β, interleukin-1-beta; IL-6, interleukin 6; IL-8, interleukin-8; LTP, low temperature plasma; MCAP, modified cold-atmospheric pressure plasma; MD, mechanical debridement; MMP1, matrix metalloproteinase-1; NADC, nonthermal atmospheric discharge; NaOCl, sodium hypochlorite; NAP, nonthermal atmospheric plasma; NO, nitric oxide; NO, nitric oxide; NO_2, nitrogen dioxide; NTAP, nonthermal atmospheric plasma; O, atomic oxygen; O_2^-, superoxide; $O_2(^1\Delta)$, singlet delta oxygen; O_3, ozone; OH, hydroxyl; ONOOH, peroxynitrous acid; OSCC, oral squamous cell carcinoma; $O(^3P)$, atomic oxygen denoted; PDL, periodontal ligament; PDT, photodynamic therapy; PTL, plasma-treated liquid; PUI, ultrasonic irrigation; RNS, reactive nitrogen species; RONS, reactive oxygen nitrogen species; ROS, reactive oxygen species; TNF-α, tumor necrosis factor-α; VHI, human immunodeficiency virus; WHO, World Health Organization.

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1 | INTRODUCTION

Cold atmospheric plasma (CAP) technology's history dates back more than a century.[1] It was primarily concerned with the physics of electrically generated, nonthermal atmospheric pressure plasma.[2] In 1879, William Crookes carried out a pioneering experiment in which he ionized gas inside an electrical discharge tube, resulting in the emergence of plasma as a concept in science. Then, to describe a fluid that is electrified and includes ions and electrons, similar to blood plasma which carries blood cells, Irvin Langmuir introduced the term "plasma" in 1927.[3,4]

Over the past few decades, CAP has evolved as a promising technology, finding numerous applications in diverse areas, from medicine to the food industry. Personalized plasma-based therapies in dermatology, electrosurgery, dentistry, oncology, tissue regeneration, wound healing, surface modification, and decontamination have demonstrated significant potential in the medical field. Although CAP's practical application has advanced quickly, our understanding of the fundamental mechanism underlying these devices has advanced more slowly.[5,6]

In 2006, Stoffel and colleagues' research demonstrated that CAP could successfully eradicate *Streptococcus mutans*, one of the most important caries-causing bacteria. Their finding suggests the use of CAP technology for innovative dental procedures and signaled the start of CAP's use in dentistry.[7] Since then, CAP has gained more attention for its potential as a noninvasive treatment for various oral conditions such as tooth decay, periodontitis, peri-implantitis, endodontic disease, candidiasis, and oral cancer. Additionally, it has been investigated for its potential application in the preparation and treatment of cavities, composite restorations, root canal disinfection, functionalization of dental implant surfaces, disinfection, decontamination, and sterilization of dental instruments.[8–13]

CAP has emerged as a prospective dental treatment option[14] due to its noninvasive nature, lack of chemical residue, and vibration.[4,15] It is now possible to apply CAP to heat-sensitive biological materials, such as tissue, thanks to recent developments in devices that produce CAP.[16–18] However, further research is necessary to fully understand its effects and determine the ideal conditions for its safe use.[6,9,19]

Literature has pointed out that parameters such as the type of used gas, power of discharge, distance, and time of application can all affect the outcome of CAP treatment in dentistry.[20–22] In this sense, researchers are attempting to identify the ideal parameters to reach CAP's full potential in biomedicine, as CAP is still regarded as an experimental technology in dentistry.[23] Within the field of dentistry, a substantial number of articles have been published across diverse areas; however, a consensus regarding the application parameters of CAP remains elusive. Achieving standardization of these application parameters is crucial for the future utilization of CAP in clinical practice.

The objective of this manuscript is therefore to provide a comprehensive review of recently published articles on the potential uses of CAP in Dentistry, focusing on the advantages over conventional methods, the challenges, and limitations still to be addressed, and potential solutions. This review also aims to identify potential gaps in the existing research to be addressed in future studies.

This narrative review summarizes the latest advancements in CAP application in dentistry and highlights the advantages of CAP over alternative technologies that have motivated its development based on the available literature from the past 5 years on MEDLINE, JISC LIBRARY HUB DISCOVER, and SCOPUS. The review also underscores the significant potential of CAP and its successful in vitro and in vivo application (preclinical) results obtained so far in several areas of dentistry, such as disinfection and decontamination of dental materials, dental caries, periodontal disease, oncology, and material surface modifications, among others.

2 | PLASMA

2.1 | Plasma fundamentals

Along with solid, liquid, and gaseous states, plasma, or the fourth state of matter, is an ionized gas that exists in the universe.[24,25] It can be created by supplying energy to a solid to change it into a liquid, then gas, and lastly, into an entirely or partially ionized gas. Plasma is the most common state of matter making up roughly 99% of all matter. However, due to its particular properties, plasma differs from regular neutral gases.[15,26] A quasi-neutral ionized gas referred to as plasma is described as carrying a variety of reactive species, including photons, electrons, ions, free radicals, and gas atoms and molecules in the ground or excited state.[27]

2.2 | Plasma type

As there are so many different varieties of plasma, whether created naturally or artificially, it can be difficult to categorize. Despite these challenges, it is possible to classify plasmas according to their degree of ionization, which measures the ratio of the density of ions to the overall density of neutral gas molecules and ions. For plasma that is totally ionized, the degree of ionization can be one, or it can be less than one for partially ionized plasma. The thermal equilibrium, or whether the temperature or energy of the particles that make up plasma are the same, is another way to classify plasma.[26] The three main categories of plasmas are nearly thermal, thermal/equilibrium, and non-thermal/nonequilibrium. In nearly thermal plasma, the temperatures of ions and neutrals are lower compared to those of electrons. In the case of thermal/equilibrium plasma, the temperatures of ions and neutrals are identical to electrons. In nonthermal plasma, ions, and neutrals have a temperature of around 0.025 eV, while the electron temperatures are retained in the range of 1 to 10 eV. In this review, the nonthermal plasma is the main topic. Both atmospheric pressure and low pressure can produce non-thermal plasma. When gas is added to a vacuum chamber to create low-pressure plasma, it causes a longer mean free path for particles than when plasma is created at atmospheric pressure. Therefore, because the mean free path is shorter in atmospheric pressure plasma, more energy is needed to produce plasma per unit volume of gas. The name CAP (cold atmospheric pressure plasma) is another name for this particular kind of plasma.[3,28–30]

2.3 | Plasma sources

A number of plasma devices have been created over the past few years,[24] such as the plasma jet, dielectric barrier discharge (DBD), floating electrode dielectric barrier discharge (FE-DBD), atmospheric pressure glow discharge (APGD-t), plasma brush, micro hollow cathode discharge air plasma jet, microwave plasma torch, and nanosecond plasma gun.[31] However, only three plasma devices have been certified for medical use: the kINPen® MED atmospheric pressure plasma jet (INP Greifswald/neoplas tools GmbH), the PlasmaDerm® VU-2010 DBD source (CINOGY GmbH plasma technology for health; Duderstadt), and SteriPlas (Adtec Ltd.).[25] Currently, DBD and atmospheric pressure plasma jet (APPJ) are the two major types of devices used to generate CAP for medical applications (Figure 1). Indirect plasma, produced remotely, delivers plasma components to the biological target via a carrier gas (e.g., DBD). Direct plasma, on the other hand, is ignited in the gap between an isolated (dielectric) high-voltage electrode and the surface to be treated, with the biological sample or living tissue serving as the counter electrode necessary for plasma ignition (e.g., APPJ).[25,32]

3 | CAP

3.1 | Physics and chemistry of CAP

Among the various types of existing plasmas, CAP is one of those that possess singular physical and chemical properties. It is characterized by lower temperatures for ions and neutrals and higher temperatures for electrons, which enables the dissociation of molecules such as O_2 and N_2. CAP is typically generated at atmospheric pressure and is particularly effective as an antibacterial agent, producing a large number of reactive radicals, oxygen, and nitrogen species (ROS and RNS). Due to these distinctive properties, CAP treatment has found numerous biological applications, including bacterial inactivation, blood coagulation, medical equipment cleaning, and wound healing. As a result, CAP has

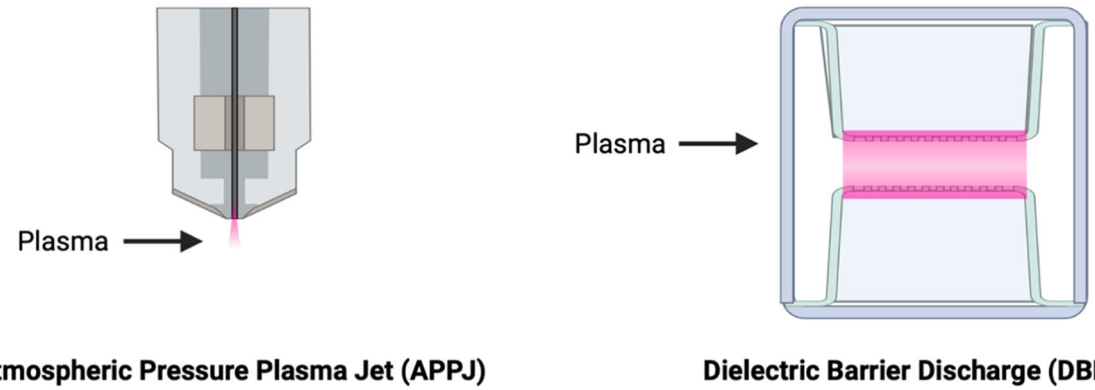

FIGURE 1 The two primary categories of devices utilized to produce cold atmospheric plasma for biomedical purposes.

become an attritive choice for many medical and scientific applications.[33,34]

3.2 | Generation method and species production

CAP is created in a laboratory environment by utilizing electrical energy between two electrodes to dissociate gas molecules. This process typically involves noble gases like helium, argon, nitrogen, heliox, and air.[35] When CAP is produced, it generates reactive species that can have both direct and indirect effects on biological samples. Some of these species react to create more stable ROS and RNS which can be active against biological targets.[6] These reactive species include nitric oxide (NO), hydrogen peroxide (H_2O_2), superoxide (O_2^-), singlet delta oxygen $O_2(^1\Delta$, singlet delta oxygen O nitric oxide (NO). Among these, OH, HO_2, $O(^3P)$, NO_2, NO, O_3, and peroxynitrous acid, ONOOH are the most abundant and important, playing crucial roles in biological interactions. The low-temperature oxidizing environment of CAP has been extensively studied to understand the chemistry induced by the presence of atomic and molecular entities with one or more unpaired electrons.[5,29,35]

3.3 | Biomedical application

As a versatile technology, CAP brings together physics, chemistry, biology, and biomedicine, making it more flexible for various applications.[36,37] For biomedical applications, plasma can be applied directly to the targets (e.g., in vitro cells, in vivo models, or human living tissues) or indirectly by transferring plasma to a specific target in situ using a plasma afterglow. The latter can be called by different names depending on the solutions treated with CAP, such as plasma-stimulated medium, plasma-treated water, or plasma-treated phosphate-buffered saline. These approaches offer an alternative way to achieve the beneficial effects of plasma without the need for direct contact.[15,38]

In different medical fields, like surface decontamination from microorganisms, CAP has demonstrated remarkable clinical or preclinical potential.[1,39] Another useful application of CAP is dermatological therapy, which can improve skin rejuvenation and promote effective wound healing. With almost no impact on healthy cells, CAP in oncology has shown potential anticancer effects against a wide range of tumor cell lines and tumor tissues in animal models. Furthermore, it seems to be effective against various types of cancer, including melanoma, cutaneous squamous carcinoma, head and neck cancer, osteosarcoma, or human fibrosarcoma, as the anticancer effect of CAP is not limited.[25,40,41]

According to current literature, ROS and RNS promote the effects of CAP on biological cells. Numerous molecules, including hydrogen peroxide, nitric oxide, superoxide anion, nitrite, and nitrate, play a crucial role in their interaction with cells or bacteria.[42] For aerobic eukaryotic organisms, which cannot survive in the absence of oxygen, the presence of unpaired electrons in reactive species can be fatal as they may interact with different cellular constituents, leading to cellular abnormalities at both functional and morphological levels. For instance, unsaturated fatty acids, an essential part of the cell membrane, can undergo peroxidation under the presence of hydroxyl radicals.[43,44] Moreover, lipids, proteins, and DNA can also be affected by hydrogen peroxide, which possesses potent oxidative properties. However, nitric oxide has a positive effect on collagen production, angiogenesis, cell proliferation, phagocytoses, and immunological deficiencies.[35] Treating cancer cells indirectly with CAP has been shown to trigger the production of singlet oxygen, which can selectively deactivate catalase that is commonly found on the surface of cancer cells but not on healthy cells. This action promotes the production of more singlet oxygen, further inhibiting catalase and enhancing the RONS-mediated apoptotic signaling pathway, resulting in the death of tumor cells.[45] However, CAP may have adverse effects on cells and tissues due to the ultraviolet radiation, strong high-frequency electromagnetic fields, ROS and RNS, ions, and molecules. The biological activity of CAP is promising, and the duration of exposure to biological tissue can be optimized to produce beneficial effects.[46]

4 | CAP IN DENTISTRY

4.1 | Antimicrobial activity

Research on oral microorganisms, particularly biofilm formation, maturation, and composition, is crucial for the development of effective dental materials. Researchers normally expose the specimens to ideal circumstances for biofilm development for a set period of time. However, before any experiments are performed, the specimen must be decontaminated or disinfected, which must not be toxic or change the surface properties. For sterilization and disinfection, high temperatures, chemicals, or ionizing radiation are frequently employed, but these techniques may cause changes at the surface of the specimen. Each approach has its benefits and drawbacks. While autoclaving can alter materials' properties at high temperatures, gamma-ray is efficient and leaves no residues, although it also may modify the properties of

materials. Despite its limited sterilization potential, UV radiation may cause material degradation as well. Chemicals are also efficient but come with a risk of biochemical changes. However, it is difficult to study oral biofilms using non-destructive methods.[15]

Microorganisms are great targets to study plasma efficiency because their susceptibility varies among different species, growth stages, and cellular envelopes.[8,19,47] Although more recent methods have been investigated, including supercritical carbon dioxide and freeze-drying, they may induce modifications in the properties of the materials being sterilized. As illustrated in Figures 2 and 3, numerous studies have investigated the effects of CAP on different types of relevant microorganisms in different areas of dentistry.[48–56] In contrast to the other technologies mentioned above, plasma has become a promising alternative, mainly due to its ability to process quickly at low temperatures without leaving behind chemical residues and without inducing alterations in material surfaces. Accordingly, recent strong evidence shows that CAP does not affect the elemental composition or surface roughness of different dental materials such as dental implants.[57] In fact, the potential modifications involve surface free energy, functional hydroxyl group formation, and hydrocarbon removal, all of which present a potential beneficial effect in host tissue interactions with implant materials.[13]

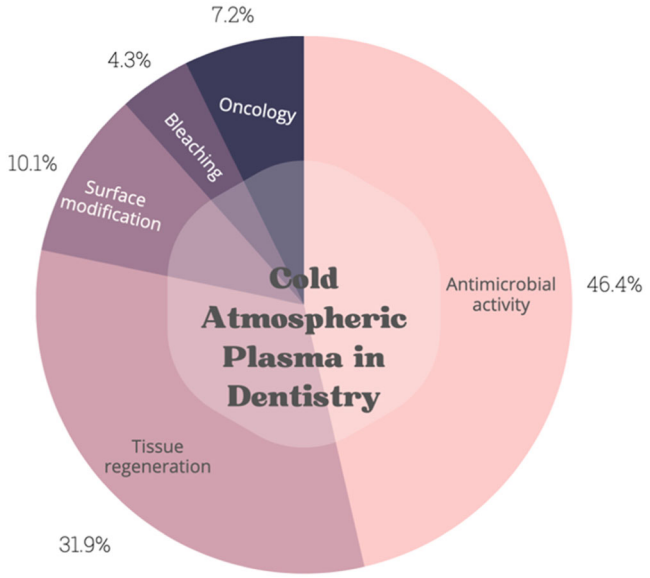

FIGURE 2 Overview of the latest 5 years of articles on cold atmospheric plasma application in dentistry.

Along with its good safety profile regarding dental material stability, CAP has shown effectiveness against a wide range of pathogens, including highly resistant bacterial spores and prions. This makes plasma technology highly valuable for sterilization, especially when other methods are ineffective.[15] Additionally, CAP demonstrated to be potentially effective against biofilms, including some mixed-species biofilms, which exhibit increased resistance to antibiotics and disinfectants, making them significant contributors to medical device-relevant associated infection.[58] CAP acts by disrupting biofilm matrices and eliminating microbial cells through diverse microbicidal mechanisms, mostly based on reactive species formation. Nonetheless, despite some current studies in this field, more investigation into oral multispecies biofilms is still needed, both in in vitro and animal models, to advance the conclusions made in the literature. Such research would be essential for confirming CAP efficacy and aiding its long-term incorporation into dental practice.

4.1.1 | Disinfection and decontamination

Regarding disinfection and decontamination, microorganisms are divided into five categories: the most resistant (such as prions), the highly resistant (such as

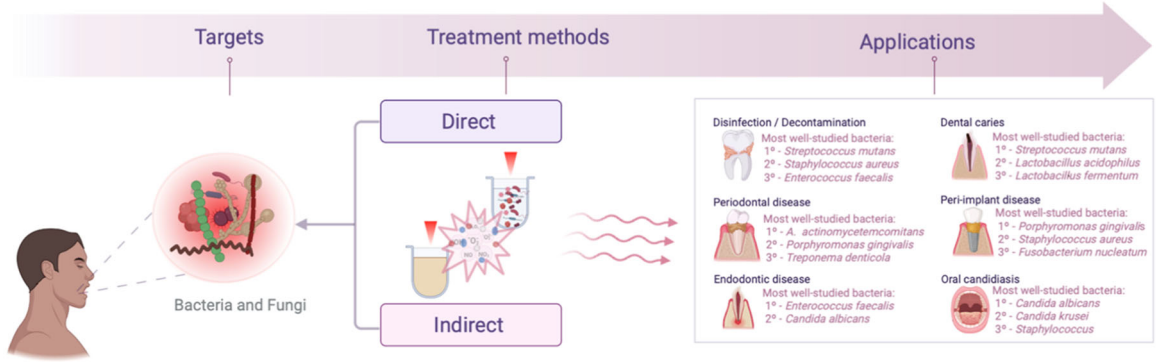

FIGURE 3 Common types of microorganisms found in dentistry that can be targeted by CAP, along with treatment methods. CAP, cold atmospheric plasma.

bacterial spores), the intermediately resistant (such as mycobacteria, fungal spores), the less resistant (such as vegetative bacteria and fungi), and the very susceptible (such as the human immunodeficiency virus—VHI). Though more target studies are needed to assess the susceptibility of microorganisms to disinfection and decontamination, the World Health Organization (WHO) claims that due to the extensive use of antibiotics, drug-resistant bacteria are now a threat to public health. Novel approaches are therefore required to combat these multidrug-resistant microorganisms. The mechanism of bactericidal activity for multidrug-resistant microorganisms and common bacteria is believed to be similar, making plasma treatment an appealing method. CAP-based disinfection and decontamination processes are nondestructive and nontoxic technologies that produce a variety of by-products, including ultraviolet radiation and radicals, which interact with biological materials and render them inactive. As stated before, even sensitive materials may potentially be able to be disinfected and decontaminated with careful adjustment of plasma discharge settings, rendering CAP an effective alternative for disinfection and decontamination of surfaces.[15,47,59] However, further research is needed to define the optimal parameters to achieve these goals.

4.1.2 | Dental caries

In the field of cariology (the diagnosis and treatment of dental caries), which is a condition brought on by microbial biofilms on the tooth surface and marked by demineralization, there is a great deal of interest in the use of CAP. Stopping the progression of caries lesions is the major objective of treatment.[60–62] Numerous in vitro research and several animal experiments are investigating the use of CAP for caries therapy. For instance, a study by Nima et al. showed that non-thermal atmospheric plasma (NTAP) 1 therapy can decrease *Streptococcus mutans* biofilms on restorative composite surfaces and suggest the use of CAP as a substitute approach for decontaminating oral surfaces before treatment.[63] Another investigation conducted by Figueira et al. revealed that low-temperature plasma (LTP) therapy can impact both single and multispecies cariogenic biofilms, indicating that LTP may be a feasible strategy for a microbial-based control of dental caries.[64] An Argon plasma jet's effectiveness was compared to that of antiseptics such as chlorhexidine digluconate and octenidine dihydrochloride by Langner et al. suggesting CAP as a viable substitute or supplement for preventing bacteria development and promoting immune defense and wound healing.[65] Despite the exciting potential of this technology as demonstrated by in vitro evidence, there are concerns regarding the accessibility of the CAP to the spongy and intricated nature of the carious lesions and dental tissues in vivo to be effective in surface decontamination for future clinical application.[4]

4.1.3 | Periodontal disease

Periodontal disease is a widespread chronic inflammatory condition that affects the supporting structures of teeth, including the gums, periodontal ligaments, and alveolar bone. An imbalance in the oral microbiota, which leads to an overgrowth of potential pathogens such as *Porphyromonas gingivalis*, *Tannerella forsythia*, and *Filifactor alocis*, is the root cause of the condition. This imbalance triggers a chain of responses that cause tissue damage, chronic inflammation, and periodontal destruction. The disorder affects millions of people worldwide leading to tooth loss, discomfort, and a poor quality of life.[66,67] Recent studies have investigated the use of CAP as a unique treatment method for periodontal disease. An investigation of the antibacterial effects of plasma therapy on *P. gingivalis* biofilms was conducted by Hong et al. They utilized NTAP treatment with pure argon gas and its mixture with 1 vol.% oxygen to evaluate the effectiveness of biofilm removal. The study found that NTAP treatment successfully eliminated *P. gingivalis* biofilms and reduced their resistance to antibiotics. Additionally, the plasma treatment increases the vulnerability of the biofilm to oxidative stresses, indicating that it might improve the host's ability to control biofilm infection. The efficiency of biofilm destruction depends on the biofilm structure and treatment times, suggesting the need for further research to optimize the treatment process.[68] The impact of non-thermal plasma therapy on zirconia surfaces contaminated with *P. gingivalis* was a subject of a different preclinical study performed by Lee et al. in 2022. The goal of the study was to determine the therapeutically beneficial time frame for plasma therapy in terms of osteoblast activity and bacterial adhesion. The researchers discovered that a 60-second application of NTAP to zirconia surfaces not only prevented the proliferation of *P. gingivalis* but also enhanced osseointegration on contaminated zirconia surfaces. Optimizing treatment methods is crucial, as exposure to NTAP longer than 60 s may promote bacterial adherence rather than have an antibacterial impact.[69] Furthermore, Lima et al. (2020) investigated the effects of CAP against mature biofilms of *P. gingivalis* (HW24D-1). The study shows that the helium CAP jet had inhibitory effects on mature biofilms of *P. gingivalis* and was not genotoxic for human oral fibroblasts or epithelial gingival cells.

The study emphasized the significance of CAP as an adjuvant therapy for periodontitis since *P. gingivalis* possesses Fim A type 2, a gene that encodes a fimbriae protein type strongly highly related to periodontal disease in chronic patients.[70] Although the results of these studies provide encouraging insights into the possibility of CAP treatment as an alternative or adjuvant therapy for periodontal disease, more studies are needed to elucidate the optimal parameters and device construction for this purpose.

4.1.4 | Peri-implant disease

For patients, partially or fully edentulous, dental implants are a common form of treatment. However, similar to natural teeth, implants are susceptible to infection and inflammation, which can result in peri-implantitis, a condition that causes bone loss. Peri-implantitis is a common ailment that affects dental implants, with an estimated incidence ranging from 28% to 56% globally, and its prevalence is increasing as dental implants are used more frequently.[60,71–73]

Peri-implantitis is an infection of the implant bed accompanied by bone tissue loss, caused by bacteria embedded in a biofilm. Currently, there are no evidence-based guidelines or protocols for the nonsurgical and surgical therapy of peri-implantitis.[74,75] The microbiota associated with peri-implantitis is dominated by well-known periodontal pathogens such as *P. gingivalis*, *T. forsythia*, and *Treponema denticola*, suggesting that similar antimicrobial strategies used in periodontal disease, such as manual or mechanical biofilm removal, may be applied.[67,76] However, the complex geometries of the implant surface and peri-implant defects create an additional challenge for successful instrumentation and decontamination. There are concerns about the effect of these instrumentation protocols on the surface characteristics of dental implants and subsequent peri-implant tissue responses.

To overcome the problem of insufficient instrumentation and the loss of hydrophilicity, a new treatment approach has been developed. It includes a new handpiece for an existing water jet device and a new CAP device with enhanced ergonomic access, both validated for surgical application. CAP is a new technology for the treatment of peri-implantitis, and preliminary data suggest that it has antimicrobial, antioxidant, and immunomodulatory effects. It also has the potential to perform biocompatible surface modifications, influencing cell adhesion, or enabling the addition of antibacterial coatings and promoting wound healing properties.[75,77]

Studies have shown that using cold plasma alone or in combination with mechanical pretreatment can effectively decontaminate surfaces under specific conditions.[9] For instance, Carreiro et al. studied the effect of LTP on *P. gingivalis* biofilm and a reconstituted human gingival epithelium. They found that LTP treatment reduced *P. gingivalis* biofilm without damaging the surrounding tissues.[23] Hui et al. compared the efficacy of different treatments, including air abrasion (AA) and CAP, in decontaminating biofilm grown on titanium implants while preserving surface topography. All treatments resulted in minimal alterations to the titanium surface.[13] Although there are limited in vivo studies published on the use of CAP for peri-implantitis, one study on beagles showed promising results with the adjunctive use of modified cold-atmospheric plasma (MCAP) and surgical mechanical debridement (MD). The combination of MCAP and MD significantly improved peri-implantitis in the study.[78]

4.1.5 | Endodontic disease

Endodontic infection, which develops in the tooth root canal system, is one of the most common oral diseases, accounting for 40%–50% of all disorders. It typically occurs when bacteria from the oral environment are introduced into the intra-radicular region through carious lesions or traumatic injuries to the tooth. Primary endodontic infections are primarily caused by polymicrobial biofilms dominated by aerobes and facultative anaerobes. *Enterococcus faecalis*, followed by *Fusobacterium* and *Propionibacterium*, are often attributed to persistent posttreatment infection in the root canal system.[79–83] Successful root canal therapy requires adequate disinfection. Not all microorganisms are sensitive to traditional therapy such as sodium hypochlorite (NaOCl), chlorhexidine, ethylenediaminetetraacetate, and citric acid. Various technologies, including passive ultrasonic irrigation (PUI), lasers, and photodynamic therapy (PDT), have been developed to improve the effectiveness of irrigation systems. However, their clinical value is still debatable.[22,84]

Recently, CAP has been researched as a possible endodontic disinfection technique. Studies have shown that CAP is an efficient way to eliminate bacterial biofilms and reduce the number of microorganisms in infected root canals.[85,86] Furthermore, CAP has been found to have no negative effects on dental pulp stem cells, making it suitable for use in endodontic procedures.[82,83,87–90]

One study compared the effectiveness of traditional disinfectants with CAP using argon combined with 1%

oxygen as a working gas on *Candida albicans* in human root canals. The study demonstrated that Plasma/O_2 treatment dramatically decreased the number of live *C. albicans* cells in extracted human teeth.[90] Another study examined the efficacy of CAP jets in removing the *E. faecalis* biofilm from the apical root canal at varying dentin depths. CAP jet and NaOCl were successful in removing *E. faecalis* biofilm, with the combination approach producing the most hopeful outcome.[90] Furthermore, a study that investigated the effects of NTAP treatment on human root dentin surfaces, on the recruitment, attachment, and growth of human dental pulp stem cells (hDPSCs), found that these surfaces supported improved hDPSCs attachment, spreading, subcellular activity, and proliferation, which may promote pulp-dentin regeneration in clinical settings.[87]

When combined with traditional disinfectants, the use of CAP in endodontic treatment can have an additive effect on the removal of bacterial biofilms and the number of bacteria in infected root canals. Additionally, CAP has shown no negative effects on dental pulp stem cells, suggesting its potential safety in endodontic procedures. These results imply that CAP might be a beneficial addition to the current endodontic treatment options for patients. However, further in vivo and clinical research are needed to confirm these findings and their translatability to clinical practice.

4.1.6 | Oral candidiasis

In the oral cavity of healthy people, the fungus *C. albicans* is frequently present. However, under some circumstances, like when the immune system is compromised, *C. albicans* can cause infections, known as oral candidiasis, which can be irritating and painful. Antifungal drugs are typically used to treat fungal infections, including candidiasis. However, this course of therapy has the potential to cause adverse effects and the formation of drug-resistant strains. As a result, there is a demand for complementary therapies for oral candidiasis.[91,92]

The potential of CAP as a cutting-edge treatment strategy for microbial decontamination has attracted increasing interest in recent years. It has been demonstrated that CAP works well against several strains of *C. albicans*. Previous research has shown that CAP can improve the results of traditional antifungal drugs.[93,94]

Borges et al. carried out a comprehensive in vitro investigation employing an amplitude-modulated CAP jet device operating with helium (AM-CAPJ) to examine their efficacy against *C. albicans* biofilms. The findings have shown that after 5 min of AM-CAPJ exposure, the viability of *C. albicans* biofilms dramatically decreased while maintaining a high level of vitality in Vero cell lines. The study also discovered that when comparing the AM-CAPJ group to the nontreated and nystatin-treated groups, histological analysis demonstrated a considerably decreased incidence of inflammatory changes.[92,95]

The potential of CAP as a novel therapeutic approach for oral candidiasis has shown promising results in preclinical studies that need to be confirmed by clinical research.

4.2 | Tissue regeneration

The complex process of regenerating both hard and soft tissues necessary for oral wound healing is aided by a number of growth factors and cytokines, including interleukin-1 (IL-1β), IL-6, IL-8, and tumor necrosis factor-α. These molecules control the synthesis of MMP1, which in turn influences how the soft and hard tissues rebuild. The periodontal ligament (PDL), which contains collagen fibers and PDL fibroblast that control the creation and remodeling of the extracellular matrix (ECM), is essential for oral adaptation. The three stages of wound healing—inflammatory, proliferation, and remodeling—are each regulated by a different set of growth factors and cytokines. Pathogens in periodontal pockets can be removed surgically or nonsurgically to promote periodontal healing. Enamel matrix derivatives or laser treatments to increase attachment levels can stimulate tissue regeneration.[96,97]

The use of CAP has emerged as a potential method to accelerate wound healing processes. CAP consists of reactive oxygen and nitrogen species, ions, radicals, electric fields, and electromagnetic radiation, and has shown stimulating effects on cell proliferation and migration in vitro, as well as a strong antimicrobial effect. While the specific effects of CAP on eukaryotic cells are largely unknown, studies have shown that the complex mixture of reactive species, including H_2O_2, O_3, O_2*, NO, NO_2, N_2*, and OH, within the physiologic range of the body during natural tissue repair processes allows for a higher cell turn-over rate.[4] Moreover, CAP can upregulate certain genes and increase cell migration and viability in human periodontal cells, keratinocytes, and fibroblasts, and enhance cell adhesion onto pretreated surfaces. Cold plasmas can support wound healing by accelerating cell proliferation, promoting increased oxygen saturation, and triggering and mimicking immune processes.[60,98]

Studies have looked at how well CAP accelerates the healing of oral wounds.[16,97–100] In a recent study, Eggers et al. looked at the effect of CAP on the ability of human osteoblasts to differentiate into osteogenic tissue, with particular emphasis on how well it promotes oral wound healing. The outcomes showed that CAP had a modest

impact on the capacity of human osteoblasts to differentiate. However, the length of the therapy and the distance between the CAP device and cells had a negative impact on their viability. CAP demonstrated favorable benefits on osteogenic differentiation ability into osteoblasts, despite the detrimental effects on cell viability. It's Interesting to note that, in comparison to a single treatment, multiple CAP applications not only reduced proliferation but also significantly increased the mRNA expression of RANK and RANK. Temporal delays in gene expression were detected, but these delays were regarded as insignificant in the therapeutic environment.[16] It is crucial to assess the effects of CAP on animal models before assessing its impacts on humans. In this regard, the effect of CAP treatment on the oral mucosa of mice was investigated using histological tissue analysis in a study by Jablonowski et al. The outcomes showed that the mucosa changed from red to white in the treated area, 1 day after CAP treatment. Histologically, fibrin deposits were found, as well as superficial homogeneity of the underlying stroma, localized ulceration, and necrosis. These changes were also followed by a minor inflammatory response, indicated by the presence of neutrophil granulocytes, lymphocytes, and a few plasma cells. Eosinophilic granulocytes were rarely found. Overall, the CAP therapy was well tolerated in the short-term study.[101]

To compare the effects of CAP on cementoblasts and its capacity to promote mineralization and cell proliferation to enamel matrix derivates (EMD), Eggers et al. conducted a study in 2021. The study showed that CAP has a stimulating effect on cell processes related to regeneration and cementoblasts' capacity for mineralization. The expression of specific mineralization-related genes in cementoblasts after CAP treatment was examined by the researchers to characterize the hard tissue. The findings indicated that CAP treatment increased alkaline phosphatase (ALP) expression and activation levels, suggesting that CAP has the potential to enhance mineralization and tooth regeneration. Regarding osteopontin and periostin, both genes were found to be upregulated, indicating the regenerative efficacy of CAP at the molecular level. DMPI was induced by CAP-mediated mineralization and COL1A1 and showed upregulation at both the mRNA and protein levels. RUNX2 was also found upregulated, confirming the physiological activation of cementoblasts. Other important markers such as BGLAP and OSX, were also found significantly upregulated. Overall, the researchers demonstrate that CAP increases cementoblasts regeneration-related features, including increasing mineralization, the expression of relevant genes to mineralization, and cell proliferation.[98]

CAP has the potential to regenerate both hard and soft tissues; however, there is currently no agreement among researchers as to the optimal parameters for various test types. It is challenging to compare the outcomes of different research because of the variety in parameter values, such as the length and time of plasma application. Future research must develop standardized procedures that can be regularly used in in vitro and animal investigations to overcome this problem. A better knowledge of the best use of CAP and safety in tissue regeneration will be attained by defining precise and consistent parameters that allow for more relevant comparisons between researchers. In the end, this will make it easier for CAP research to be applied in clinical settings, enabling its efficient and secure use in human treatment. Figures 2 and 4 summarize the most frequent applications and types of cells used in recent research on tissue regeneration in dentistry.[57,98,102–109]

4.3 | Oncology

Oral squamous cell carcinoma (OSCC) is a common type of head and neck cancer[110] and the second most common cause of mortality globally.[43] Current

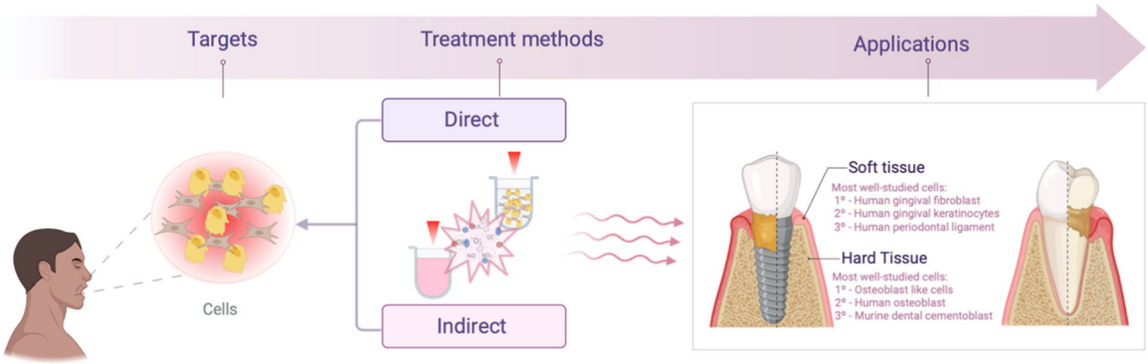

FIGURE 4 Types of cells used to test the potential regeneration capacity of cold atmospheric plasma (CAP), along with typical treatment methods.

treatments for OSCC, such as surgery, radiation therapy, and chemotherapy, can have severe adverse effects due to the need for large and frequent dosages to achieve therapeutic impact. Research is focused on discovering alternative therapies that can be combined with already-effective treatments to improve results for OSCC patients.[17,39,110]

Several modalities of cell death, including apoptosis, necrosis, necroptosis, autophagy, and pyroptosis, can be therapeutically targeted for the treatment of cancer cells.[111] CAP treatment raises intracellular ROS, which can impact various elements in the signaling of tumor cell death. By targeting proteins or kinases involved in cell death signaling, apoptosis, and death can be effectively induced in cancer cells.[31,38,112–115]

CAP may selectively eliminate cancer cells while normal cells are left unharmed. Healthy cells can repair the damage caused by oxidative stress, whereas cancer cells undergo cell death in response to oxidative stress. The synergies effects of H_2O_2 and nitrites can be used to determine the dosage of CAP that can kill cancer cells in a dose-dependent manner through growth arrest, apoptosis, and necrosis.[11]

In 2022, Afrasiabi et al. examined the specific toxicity of CAP on OSCC cells and mitochondria, as well as any potential synergistic effects of cisplatin. They discovered that CAP especially targets cancerous mitochondria, leading to increased ROS levels, collapse of the membrane potential, and swelling of the mitochondria. The subsequent release of proapoptotic protein cytochrome c and the activation of caspase 3 was linked to mitochondrial swelling. When CAP and cisplatin were combined, all toxicity indicators were significantly increased, indicating that CAP may be a suitable therapeutic complement for treating OSCC.[116] A study conducted in 2021 by Evert et al. examined the long-term risk of repeated application of CAP on mouse oral mucosa. The results revealed no carcinogenesis and good treatment tolerance. Unlike the injection of carcinogens, CAP exposure did not promote the growth of invasive lesions of squamous cell carcinoma (SCC). The inflammatory profiles linked to each treatment plan were identified by molecular analysis. Despite the fact that CAP did not exhibit consistent changes in gene expression across several carcinogens' regimes, one gene, IL33, which is linked to oral lichen planus, showed a consistent rise in both CAP and non-CAP treatments. With CAP treatment, SPP1 and HIF1A were found upregulated while SMAD3, linked to oral lichen planus and SCC, was frequently downregulated. CAP therapy enhanced CXCL10 levels among the carcinogen regimens, which is important for both the SCC response and fostering antitumor immunity. CAP shows distinctive inflammatory profiles, gene expression alterations, and potential antitumor immunity-promoting.[117]

The aforementioned findings and the current literature indicated that CAP is effective in treating SCC and OSCC. However, additional studies for in vitro and animal models are needed to fully understand how SCC and OSCC react to CAP therapy. Standardizing CAP application parameters such as treatment time, intensity, and distance is essential to enable improved consistency between experiments. Figure 2 provides a summary of recent studies on PAC treatment in oncology, as well as other relevant studies.[118]

4.4 | Bleaching

Tooth discoloration is a common problem that can negatively affect people's physical appearance. As a result, tooth whitening procedures, like bleaching, have grown in popularity recently as a conservative treatment for discolored teeth.[119] However, typical tooth whitening techniques could have downsides like tooth sensitivity, gingival irritation, and inconsistent outcomes. The acidic nature of bleaching agents has the potential to have negative effects on enamel surfaces, compromising their microhardness, structure, and morphology.[120–122] Researchers have looked into other tooth-whitening procedures, such as the use of CAP, to overcome these problems. Several trials have investigated the effectiveness of CAP in tooth whitening, with encouraging outcomes. CAP has been shown to whiten teeth more effectively than traditional techniques while still protecting oral tissues.[123]

For instance, in 2020, Choi et al. studied the effects of nonthermal plasma and a neutral pH bleaching gel on dental hard tissues and found successful results when treatment times were minimized.[124] The use of nonthermal atmospheric discharge on tooth bleaching in vitro was explored in a different study by Kusanagi et al. and they discovered a bleaching effect without the use of peroxides or water.[125] In a 2018 study, Nam et al. examined the surface properties of enamel following bleaching in conjunction with plasma treatment. The findings showed that bleaching with 15% carbamide peroxide (CP) alone could change the characteristic of the bleached surface, making it more favorable for *Streptococcus mutans* binding. However, when bleaching and plasma were used together, *S. mutans* adherence was reduced. These results imply that the application of plasma did not alter the surface properties, as confirmed by the SEM and safranin staining data. Furthermore, bleached enamel treated with 15% CP alone showed a significant increase in *S. mutans* colony significantly,

suggesting that teeth whitening with only 15% CP may have an impact on the surface morphology and structure of the bleached enamel.[120]

To evaluate the histological alterations in oral tissues following NAPP therapy, Nam et al. undertook a study in 2021 to guarantee the safety and efficacy of NAPP for tooth whitening. Given that human immune system genes are similar to those of rabbits, using them as an animal model increased study applicability. These results strongly suggest that oral tissues are not harmed when NAPP and 15% CP are used together for tooth whitening. NAPP effectively converts harmful HP into nontoxic OH without producing excessive heat, ensuring the safety and efficacy of NAPP on tooth-whitening procedures.[123] It is important to note that the assessment of tissue safety was only conducted during a brief period of time, and additional long-term research is required to fully understand the effects of CAP on oral tissues (Figure 2).[4,7,120-122]

4.5 | Surface modification in implants and other dental materials

Dental implants are a common option for replacing missing teeth, however, infections connected to implants, such as peri-implantitis, can cause implant failure and jeopardize the overall outcome of implant therapy. Researchers have concentrated on creating infection-resistant biomaterials to prevent the formation of bacterial biofilm on implant surfaces, which is essential. Although effective, conventional methods can harm the treated substrate, requiring the deployment of new strategies. CAP shows promise in replacing traditional approaches by preventing the formation of bacterial biofilm and promoting tissue regeneration.[69,120,126,127] The limitations of the vacuum system are overcome by CAP and cause physical and chemical changes in biological materials without causing harm to healthy tissues.[7,9]

Surface modification employing CAP is a frequently researched method in interface biotechnology to improve the performance of surgical implants. The clinical efficacy of implants is significantly influenced by the topography, chemistry, and bioactivity of implant material. CAP has been found to increase implant bioactivity by enhancing surface chemistry, such as by raising hydrophilicity. CAP treatment is practical for surface alterations like coating or patterning, as well as for improving hydrophilicity or surface roughness.[128] This improves the initial interaction between cells and the surface and increases wettability, playing a critical role in restoring the surface and enabling re-osseointegration of damaged dental implants.[6,57] Numerous investigations have focused on the usefulness of CAP in altering implant surface and preventing or treating implant-related infections.

The effects of CAP on titanium and zirconia dental implant discs were examined in a 2022 study by Wagner et al. The study found out that CAP treatment did not considerably change biomaterials elemental composition. However, it did promote cell viability and proliferation on the titanium surfaces, particularly when applied for 60 to 120 s. This suggests that CAP may have the potential to promote healing around dental implants.[57] Sevilla et al. conducted a study on plasma surface treatments in CAD-CAM ceramics. The treatments resulted in lower roughness values compared to the control group, and the contact angle was reduced with etching plasma treatment. Smoother surface textures can decrease the likelihood of defects or fractures in restorations. The effects of plasma treatments on the ceramics were similar, even with different exposure times for oxygen and argon plasma.[129] These studies highlighted the potential of CAP for modifying dental materials' surface properties, making it a promising approach for managing peri-implantitis.[57,130] CAP treatment on dental implant materials like titanium (Ti) and zirconium (Zr) has shown positive outcomes in terms of its effectiveness against microorganisms. It inhibits bacterial activity, particularly in Gram-negative bacteria, without compromising bone formation. With extended treatment times, CAP becomes more effective at reducing bacterial presence.[131] The antibacterial and antibiofilm characteristics of CAP on dentin were examined in a study by Jungbaeur et al.[67] Time-dependent CAP efficacy was discovered with a 60-s application yielding the best outcomes. While the 30-second treatment decreased the number of bacteria in the planktonic sample for each species, the 12-species biofilm was not significantly affected. However, on dentin and titanium surfaces, a 120-second treatment considerably decreased bacterial populations.[67] A study conducted in 2022 by Florke et al.[49] examined the efficacy of CAP, photodynamic therapy (PDT), and chemical decontamination using 35% phosphoric acid gel (PAG) for cleaning titanium implant surfaces. The study found that the best treatment involved applying CAP to the implants for 3 min at 5 W output. The colony-forming unit (CFU) count was considerably lower after CAP therapy as compared to positive control. These results show that CAP is more effective than other methods at reducing bacterial contamination on titanium implants. Additionally, the study showed that although plasma treatment could inactivate the biofilm, full eradication required the use of extra air-water spray.

Notably, no surface modification was seen after plasma treatment.[49]

These studies have shown how effective CAP may be as a solution that combines antimicrobial benefits with enhanced tissue repair. With CAP, microorganisms can be successfully removed from difficult places, such as inaccessible pockets and implant surfaces with rough or moderately rough textures. Additionally, it can stimulate wound healing immediately after implant insertion and encourage the re-osseointegration process in infected dental implants. However, it is crucial to recognize that complex multispecies biofilms, such as those present in the oral cavity, have a high resistance to CAP therapy. This suggests the necessity for additional therapeutic approaches or changes to the CAP parameters to improve its effectiveness in such circumstances. Future developments in CAP approaches and technology could help solve the problems brought on by multispecies biofilms, increasing the overall efficiency of CAP treatment against them. CAP has demonstrated encouraging results in the modification of implant surfaces and in the prevention or treatment of implant-related infection, but additional study is required to draw firm conclusions. As shown in Figure 2, CAP may be a viable substitute technique for cleaning and repairing dental implants. This strategy might create new opportunities for improving the stability and effectiveness of dental implants in the long term.[57,71,130–133]

5 | CONCLUSION

Based on the available literature, which consists of in vitro and preclinical studies, CAP seems to provide a promising alternative approach to traditional methods for treating and preventing oral conditions. CAP has the potential to offer a noninvasive and effective treatment option, especially for patients who cannot undergo traditional treatment procedures or have contraindications to certain treatments. However, to develop a CAP-based tool for potential clinical use in the diverse applications of dentistry, additional preclinical and clinical research is necessary. It is crucial to gain a deeper understanding of the mechanisms of action and effects of CAP in oral tissues and to define the optimal parameters for its various applications in dentistry. Future research should specifically address the optimal parameters and protocols of CAP-based therapies regarding the safety profile, especially when applied on healthy tissues, as well as the antimicrobial and antibiofilm properties, in particular against complex, multi-species biofilms.

AUTHOR CONTRIBUTIONS

Neusa Silva, **Joana Marques**, and **Mariana B. da Cruz**: participated in conceptualization. **Neusa Silva**: investigation, writing—original draft. **Henrique Luís**, **Susana Sério**, and **António Mata**: project management. **Neusa Silva**, **Joana Marques**, **Mariana B. da Cruz**, **Henrique Luís**, **Susana Sério**, and **António Mata**: investigation, writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Research data are not shared.

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REFERENCES

[1] M. Domonkos, P. Tichá, J. Trejbal, P. Demo, *Appl. Sci.* **2021**, *11*, 4809. https://doi.org/10.3390/app11114809
[2] H. D. Stryczewska, O. Boiko, *Appl. Sci.* **2022**, *12*, 4405. https://doi.org/10.3390/app12094405
[3] D. Braný, D. Dvorská, E. Halašová, H. Škovierová, *Int. J. Mol. Sci.* **2020**, *21*, 2932. https://doi.org/10.3390/ijms21082932
[4] S. Lata, S. Chakravorty, T. Mitra, P. K. Pradhan, S. Mohanty, P. Patel, E. Jha, P. K. Panda, S. K. Verma, M. Suar, *Mater. Today Bio* **2022**, *13*, 100200. https://doi.org/10.1016/j.mtbio.2021.100200
[5] R. Peverall, G. A. D. Ritchie, *Plasma Sources Sci. Technol.* **2019**, *28*, 073002. https://doi.org/10.1088/1361-6595/ab2956
[6] W. L. Hui, V. Perrotti, F. Iaculli, A. Piattelli, A. Quaranta, *Nanomaterials* **2020**, *10*, 1505.
[7] M. Gherardi, R. Tonini, V. Colombo, *Trends Biotechnol.* **2018**, *36*, 583.
[8] G. Jungbauer, D. Moser, S. Müller, W. Pfister, A. Sculean, S. Eick, *Antibiotics* **2021**, *10*, 211.
[9] L. Garcia, L. Rojas, G. Gonzales, D. Alvitez-Temoche, R. Mendonza, F. Mayta-Tovalino, *J. Int. Oral Health* **2021**, *13*, 326.
[10] M. E. Bergmann, T. Wieland, V. Straub, F. Engesser, E. Buerkin, M. J. Altenburger, G. A. Urban, L. Ledernez, *Plasma Med.* **2022**, *12*, 13.
[11] C. M. Lee, Y. I. Jeong, M. S. Kook, B. H. Kim, *Int. J. Mol. Sci.* **2020**, *21*, 7646.

[12] W. L. Hui, D. Ipe, V. Perrotti, A. Piattelli, Z. Fang, K. Ostrikov, A. Quaranta, *Dent. Mater.* **2021**, *37*, 359.
[13] W. L. Hui, V. Perrotti, A. Piattelli, K. Ostrikov, Z. Fang, A. Quaranta, *Clin Oral Investig.* **2021**, *25*, 6633. https://doi.org/10.1007/s00784-021-03949-x
[14] O. Bunz, P. Kalz, C. I. Benz, E. A. Naumova, W. H. Arnold, A. Piwowarczyk, *Dent. J.* **2021**, *9*, 59. https://doi.org/10.3390/dj9060059
[15] A. Sakudo, Y. Yagyu, T. Onodera, *Int. J. Mol. Sci.* **2019**, *20*, 5216. https://doi.org/10.3390/ijms20205216
[16] B. Eggers, A. M. Wagenheim, S. Jung, J. Kleinheinz, M. Nokhbehsaim, F. J. Kramer, S. Sielker, *Int. J. Mol. Sci.* **2022**, *23*, 2503. https://doi.org/10.3390/ijms23052503
[17] V. Perrotti, V. C. A. Caponio, L. lo Muzio, E. H. Choi, M. C. Di Marcantonio, M. Mazzone, N. K. Kaushik, G. Mincione, *Int. J. Mol. Sci.* **2022**, *23*, 10238. https://doi.org/10.3390/ijms231810238
[18] A. Stancampiano, D. Forgione, E. Simoncelli, R. Laurita, R. Tonini, M. Gherardi, V. Colombo, *J. Adhes. Dent.* **2019**, *21*, 229.
[19] I. Niedźwiedź, A. Waśko, J. Pawłat , M. Polak-Berecks, *Pol. J. Microbiol.* **2019**, *68*, 153.
[20] Y. Yang, M. Zheng, Y.-N. Jia, J. Li, H. P. Li, J. G. Tan, *Mater. Sci. Eng. C* **2021**, *120*, 111633. https://doi.org/10.1016/j.msec.2020.111633
[21] M. Shahmohammadi Beni, W. Han, K. N. Yu, *Appl. Sci.* **2019**, *9*, 2119. https://doi.org/10.3390/app9102119
[22] H. Ballout, M. Hertel, J. Doehring, E. Kostka, S. Hartwig, S. Paris, S. Preissner, *J. Biophotonics* **2018**, *11*, e201700186. https://doi.org/10.1002/jbio.201700186
[23] A. F. P. Carreiro, J. A. Delben, S. Guedes, E. J. D. Silveira, M. N. Janal, C. E. Vergani, S. Pushalkar, S. Duarte, *J. Periodontol.* **2019**, *90*, 507.
[24] L. Gan, J. Jiang, J. W. Duan, X. J. Z. Wu, S. Zhang, X. R. Duan, J. Q. Song, H. X. Chen, *J. Biophotonics* **2021**, *14*, 902. https://doi.org/10.1002/jbio.202000415
[25] T. Bernhardt, M. L. Semmler, M. Schäfer, S. Bekeschus, S. Emmert, L. Boeckmann, *Oxid. Med. Cell. Longevity* **2019**, *2019*, 1. https://doi.org/10.1155/2019/3873928
[26] F. L. Tabares, I. Junkar, *Molecules* **2021**, *26*, 1903. https://doi.org/10.3390/molecules26071903
[27] B. Kopuk, R. Gunes, I. Palabiyik, *Food Chem.* **2022**, *382*, 132356. https://doi.org/10.1016/j.foodchem.2022.132356
[28] K. Chaudhary, A. M. Imam, S. Z. H. Rizvi et al., *Kinetic theory*. InTech, Greece, **2018**. https://doi.org/10.5772/intechopen.70843
[29] N. Kaushik, N. Kaushik, N. Linh, B. Ghimire, A. Pengkit, J. Sornsakdanuphap, S. J. Lee, E. Choi, *Nanomaterials* **2019**, *9*, 98. https://doi.org/10.3390/nano9010098
[30] M. Zhianmanesh, A. Gilmour, M. M. M. Bilek, B. Akhavan, *Appl. Phys. Rev.* **2023**, *10*, 021301. https://doi.org/10.1063/5.0130829
[31] F. Faramarzi, P. Zafari, M. Alimohammadi, M. Moonesi, A. Rafiei, S. Bekeschus, *Oxid. Med. Cell. Longevity* **2021**, *2021*, 1. https://doi.org/10.1155/2021/9916796
[32] J. Šimončicová, S. Kryštofová, V. Medvecká, K. Ďurišová, B. Kaliňáková, *Appl. Microbiol. Biotechnol.* **2019**, *103*, 5117.
[33] S. M. al Qaseer, M. K. Khalaf, S. I. Salih Optimal Power of Atmospheric Pressure Plasma Jet with a Simple DBD Configuration for Biological Application. In: *J. Phys. Conf. Series* IOP Publishing Ltd. **2021**. https://doi.org/10.1088/1742-6596/1999/1/012058.
[34] A. S. Katsigiannis, D. L. Bayliss, J. L. Walsh, *Compr. Rev. Food Sci. Food Saf.* **2022**, *21*, 1086.
[35] M. Laroussi, *Plasma* **2018**, *1*, 47.
[36] D. Yan, A. Malyavko, Q. Wang, K. Ostrikov, J. H. Sherman, M. Keidar, *Biomedicines* **2021**, *9*, 1259. https://doi.org/10.3390/biomedicines9091259
[37] F. Tan, Y. Fang, L. Zhu, M. Al-Rubeai, *Stem Cell Res. Ther.* **2020**, *11*, 368. https://doi.org/10.1186/s13287-020-01886-2
[38] A. Dubuc, P. Monsarrat, F. Virard, N. Merbahi, J. P. Sarrette, S. Laurencin-Dalicieux, S. Cousty, *Ther. Adv. Med. Oncol.* **2018**, *10*, 175883591878647. https://doi.org/10.1177/1758835918786475
[39] D. Braný, D. Dvorská, J. Strnádel, T. Matáková, E. Halašová, H. Škovierová, *Int. J. Mol. Sci.* **2021**, *22*, 12252. https://doi.org/10.3390/ijms222212252
[40] P. Zubor, Y. Wang, A. Liskova, M. Samec, L. Koklesova, Z. Dankova, A. Dørum, K. Kajo, D. Dvorska, V. Lucansky, B. Malicherova, I. Kasubova, J. Bujnak, M. Mlyncek, C. A. Dussan, P. Kubatka, D. Büsselberg, O. Golubnitschaja, *Int. J. Mol. Sci.* **2020**, *21*, 7988.
[41] B. F. Gilmore, P. B. Flynn, S. O'Brien, N. Hickok, T. Freeman, P. Bourke, *Trends Biotechnol.* **2018**, *36*, 627.
[42] E. H. Choi, N. K. Kaushik, Y. J. Hong, J. S. Lim, J. S. Choi, I. Han, *J. Korean Phys. Soc.* **2022**, *80*, 817.
[43] Y. A. Salaheldin, S. S. M. Mahmoud, E. E. Ngowi, V. A. Gbordzor, T. Li, D. D. Wu, X. Y. Ji, *Oxid. Med. Cell. Longevity* **2021**, *2021*, 1. https://doi.org/10.1155/2021/5522054
[44] P. Bhartiya, N. Kaushik, L. N. Nguyen, S. Bekeschus, K. Masur, K. D. Weltmann, N. K. Kaushik, E. H. Choi, *Int. J. Mol. Sci.* **2022**, *23*, 3120. https://doi.org/10.3390/ijms23063120
[45] T. Min, X. Xie, K. Ren, T. Sun, H. Wang, C. Dang, H. Zhang, *Front. Med.* **2022**, *9*, 884887. https://doi.org/10.3389/fmed.2022.884887
[46] A. G. Volkov, J. S. Hairston, G. Taengwa, J. Roberts, L. Liburd, D. Patel, *Molecules* **2022**, *27*, 7051. https://doi.org/10.3390/molecules27207051
[47] E. A. Naumova, A. S. Engel, H. T. Kranz, M. Schneider, J. Tietze, T. Dittmar, M. Fiebrandt, K. Stapelmann, A. Piwowarczyk, W. H. Arnold, *Coatings* **2019**, *9*, 99. https://doi.org/10.3390/COATINGS9020099
[48] I. Chattopadhyay, W. Lu, R. Manikam, M. B. Malarvili, R. R. Ambati, R. Gundamaraju, *Biotechnol. Genet. Eng. Rev.* **2022**, *39*, 85. https://doi.org/10.1080/02648725.2022.2102877
[49] C. Flörke, J. Janning, C. Hinrichs, E. Behrens, K. R. Liedtke, S. Sen, D. Christofzik, J. Wiltfang, A. Gülses, *Int. J. Implant Dent.* **2022**, *8*, 12. https://doi.org/10.1186/s40729-022-00411-9
[50] Y. Jiao, F. R. Tay, L. Niu, J. Chen, *Int. J. Oral Sci.* **2019**, *11*, 28. https://doi.org/10.1038/s41368-019-0062-1
[51] Y. M. Kim, H. Y. Lee, H. J. Lee, J. B. Kim, S. Kim, J. Y. Joo, G. C. Kim, *J. Dent. Res.* **2018**, *97*, 179.
[52] K. Kniha, S. C. Möhlhenrich, A. Bock, N. Ayoub, A. Modabber, F. Hölzle, G. Conrads, E. Goloborodko, *Br. J. Oral; Maxillofac. Surg.* **2020**, *58*, 329.

[53] L. D. P. Leite, M. A. C. Oliveira, M. R. C. Vegian, A. G. Sampaio, T. M. C. Nishime, K. G. Kostov, C. Y. Koga-Ito, *Molecules* **2021**, *26*, 5815. https://doi.org/10.3390/molecules26195815

[54] S. Schramm, K. A. Hiller, S. Cantzler, H. Weilemann, M. Cantzler, J. L. Zimmermann, F. Cieplik, T. Maisch, *Front. Microbiol.* **2020**, *11*, 576500. https://doi.org/10.3389/fmicb.2020.576500

[55] X. Wang, L. Pang, S. Yang, L. Zou, Y. Zhang, T. Zhao, *Biochem. Biophys. Res. Commun.* **2021**, *576*, 53.

[56] M. E. Zarif, A. Yehia, B. Biță, V. Sătulu, S. Vizireanu, G. Dinescu, A. M. Holban, F. Marinescu, E. Andronescu, A. M. Grumezescu, A. C. Bîrcă, A. T. Farcașiu, *Int. J. Mol. Sci.* **2021**, *22*, 13103. https://doi.org/10.3390/ijms222313103

[57] G. Wagner, B. Eggers, D. Duddeck, F. J. Kramer, C. Bourauel, S. Jepsen, J. Deschner, M. Nokhbehsaim, *Clin. Oral. Investig.* **2022**, *26*, 2949.

[58] Y. Rao, W. Shang, Y. Yang, R. Zhou, X. Rao, *Front. Microbiol.* **2020**, *11*, 1000. https://doi.org/10.3389/fmicb.2020.01000

[59] M. Fiebrandt, J. W. Lackmann, K. Stapelmann, *Plasma Processes Polym.* **2018**, *15*, 1800139. https://doi.org/10.1002/ppap.201800139

[60] H.-R. Metelmann, von T. Woedtke, K.-D. Weltmann, *Cold physical plasma for medical application*, Springer, Cham, 2019. https://doi.org/10.1007/978-3-319-67627-2

[61] M. Aumir Beg, M. Raihan, A. Santram Bansode, S. Nisar Kakroo, *Int. Arch. BioMed. Clin. Res.* **2018**, *04*, 99. https://doi.org/10.21276/iabcr.2018.4.2.29

[62] M. Hertel, J. Schwill-Engelhardt, T. Gerling, K.-D. Weltmann, S. M. Imiolczyk, S. Hartwig, S. Preissner, *Plasma Med.* **2018**, *8*, 73.

[63] G. Nima, E. Harth-Chu, R. D. Hiers, V. G. A. Pecorari, D. W. Dyer, S. S. Khajotia, M. Giannini, F. L. E. Florez, *Sci. Rep.* **2021**, *11*, 23800. https://doi.org/10.1038/s41598-021-03192-0

[64] L. W. Figueira, B. H. D. Panariello, C. Y. Koga-Ito, S. Duarte, *Appl. Sci.* **2021**, *11*, 570.

[65] I. Langner, A. Kramer, R. Matthes, F. Rebert, C. Kohler, I. Koban, N. O. Hübner, T. Kohlmann, M. Patrzyk, *Plasma Processes Polym.* **2019**, *16*, 1800162. https://doi.org/10.1002/ppap.201800162

[66] I. Fragkioudakis, M. P. Riggio, D. A. Apatzidou, *J. Med. Microbiol.* **2021**, *70*, 001247. https://doi.org/10.1099/JMM.0.001247

[67] G. Jungbauer, L. Favaro, S. Müller, A. Sculean, S. Eick, *Antibiotics* **2022**, *11*, 752. https://doi.org/10.3390/antibiotics11060752

[68] Q. Hong, H. Sun, M. Chen, S. Zhang, Q. Yu, *PLoS One* **2022**, *17*, e0274523. https://doi.org/10.1371/journal.pone.0274523

[69] S. K. Lee, M. K. Ji, Y. J. Jo, C. Park, H. Cho, H. P. Lim, *Materials* **2022**, *15*, 5348. https://doi.org/10.3390/ma15155348

[70] de G. Morais Gouvêa Lima, C. F. L. Carta, A. C. Borges, T. M. C. Nishime, C. A. V. da Silva, M. V. Caliari, M. P. A. Mayer, K. G. Kostov, C. Y. Koga-Ito, *Appl. Sci.* **2022**, *12*, 7247. https://doi.org/10.3390/app12147247

[71] Y. Yang, J. Guo, X. Zhou, Z. Liu, C. Wang, K. Wang, J. Zhang, Z. Wang, *Dent. Mater. J.* **2018**, *37*, 157.

[72] M. Ulu, T. Pekbagriyanik, F. Ibis, S. Enhos, U. Ercan, *Niger. J. Clin. Pract.* **2018**, *21*, 758.

[73] R. di Gianfilippo, B. Sirinirund, M. V. Rodriguez, Z. Chen, H. L. Wang, *Appl. Sci.* **2020**, *10*, 9084.

[74] Y. Yang, M. Zheng, Y. Yang, J. Li, Y. F. Su, H. P. Li, J. G. Tan, *Clin. Oral. Investig.* **2020**, *24*, 1465.

[75] R. Matthes, L. Jablonowski, V. Pitchika, B. Holtfreter, C. Eberhard, L. Seifert, T. Gerling, L. Vilardell Scholten, R. Schlüter, T. Kocher, *BMC Oral Health* **2022**, *22*, 157. https://doi.org/10.1186/s12903-022-02195-1

[76] G. A. Kotsakis, D. G. Olmedo, *Periodontol. 2000.* **2021**, *86*, 231.

[77] X. Shi, S. Liu, R. Jiang, J. Chen, S. Jin, D. Mei, R. Zhou, Z. Fang, P. J. Cullen, *Results Phys.* **2022**, *36*, 105405. https://doi.org/10.1016/j.rinp.2022.105405

[78] X. Zhou, D. Wu, D. Liang, W. Zhang, Q. Shi, Y. Cao, *Oral Dis.* **2022**, *28*, 495.

[79] I. Prada, P. Mico-Munoz, T. Giner-Lluesma, P. Mico-Martinez, N. Collado-Castellano, A. Manzano-Saiz, *Med. Oral Patol. Oral y Cirugia Bucal* **2019**, *24*, e364.

[80] M. KS, S. Mathew, *J. Otolaryngol. ENT Res.* **2018**, *10*, 417. https://doi.org/10.15406/joentr.2018.10.00394

[81] A. C. Borges, K. G. Kostov, R. S. Pessoa, G. M. A. de Abreu, G. M. G. Lima, L. W. Figueira, C. Y. Koga-Ito, *Appl. Sci.* **2021**, *11*, 1975.

[82] K. Jhajharia, *Int. J. Appl. Dent. Sci.* **2019**, *5*, 227.

[83] J. F. Siqueira, I. N. Rôças, *Int. Endod. J.* **2022**, *55*, 512.

[84] A. Kerlikowski, R. Matthes, C. Pink, H. Steffen, R. Schlüter, B. Holtfreter, K. D. Weltmann, T. Woedtke, T. Kocher, L. Jablonowski, *J. Biophotonics* **2020**, *13*, e202000221. https://doi.org/10.1002/jbio.202000221

[85] A. Sarkar, *IOSR J. Dent. Med. Sci.* **2018**, *17*, 15.

[86] V. Arora, V. Nikhil, N. K. Suri, P. Arora, *Dentistry* **2013**, *04*, 2161. https://doi.org/10.4172/2161-1122.1000189

[87] Y. J. Yoo, M. J. Kang, H. Perinpanayagam, J. C. Park, S. H. Baek, K. Y. Kum, *Appl. Sci.* **2021**, *11*, 6836. https://doi.org/10.3390/app11156836

[88] S. Fatemeh, P. Mousavi, A. Ganjovi et al., *Plasma Med.* **2021**, *11*, 41. https://www.dl.begellhouse.com/journals/5a5b4a3d419387fb,734a683b298a445e,35022c69610e6b0f.html

[89] M. Okuno, S. Aoki, S. Kawai, R. Imataki, Y. Abe, K. Harada, K. Arita, *Appl. Sci.* **2021**, *11*, 10119. https://doi.org/10.3390/app112110119

[90] K. Saleewong, P. Wanachantararak, P. Louwakul, *IOP Conference Series: Materials Science and Engineering*, Institute of Physics Publishing, Bangkok, Tailândia, **2019**. https://doi.org/10.1088/1757-899X/526/1/012027

[91] P. Wanachantararak, P. Suanpoot, M. Nisoa, *Walailak J. Sci. Technol.* **2019**, *16*, 401. http://wjst.wu.ac.th

[92] A. C. Borges, G. M. G. Lima, T. M. C. Nishime, A. V. L. Gontijo, K. G. Kostov, C. Y. Koga-Ito, *PLoS One* **2018**, *13*, e0199832. https://doi.org/10.1371/journal.pone.0199832

[93] O. Handorf, T. Weihe, S. Bekeschus, A. C. Graf, U. Schnabel, K. Riedel, J. Ehlbeck, *Appl. Environ. Microbiol.* **2018**, *84*, e01163-18. https://journals.asm.org/journal/aem

[94] F. Ebrahimi-Shaghaghi, Z. Noormohammadi, S. M. Atyabi, M. Razzaghi-Abyaneh, *Arch. Biochem. Biophys.* **2021**, *700*, 108772. https://doi.org/10.1016/j.abb.2021.108772
[95] M. Veerana, N. Yu, W. Ketya, G. Park, *J. Fungi* **2022**, *8*, 102. https://doi.org/10.3390/jof8020102
[96] B. Kleineidam, M. Nokhbehsaim, J. Deschner, G. Wahl, *Clin. Oral. Investig.* **2019**, *23*, 1941.
[97] B. Eggers, J. Marciniak, S. Memmert, G. Wagner, J. Deschner, F. J. Kramer, M. Nokhbehsaim, *Head. Face. Med.* **2021**, *17*, 37. https://doi.org/10.1186/s13005-021-00287-x
[98] B. Eggers, J. Marciniak, J. Deschner, M. B. Stope, A. Mustea, F. J. Kramer, M. Nokhbehsaim, *Int. J. Mol. Sci.* **2021**, *22*, 5280. https://doi.org/10.3390/ijms22105280
[99] B. Eggers, M. B. Stope, J. Marciniak, A. Mustea, J. Deschner, M. Nokhbehsaim, F. J. Kramer, *Cells* **2022**, *11*, 2740. https://doi.org/10.3390/cells11172740
[100] B. Eggers, J. Marciniak, S. Memmert, F. J. Kramer, J. Deschner, M. Nokhbehsaim, *Odontology.* **2020**, *108*, 607.
[101] L. Jablonowski, T. Kocher, A. Schindler, K. Müller, F. Dombrowski, von T. Woedtke, T. Arnold, A. Lehmann, S. Rupf, M. Evert, K. Evert, *PLoS One* **2019**, *14*, e0215099. https://doi.org/10.1371/journal.pone.0215099
[102] G. Daeschlein, R. Rutkowski, S. Lutze, S. von Podewils, C. Sicher, T. Wild, H. R. Metelmann, T. von Woedkte, M. Jünger, *Biomed. Eng./Biomedizinische Technik* **2018**, *63*, 603.
[103] S. Hafner, M. Ehrenfeld, A. C. Neumann, A. Wieser, *J. Cranio-Maxillofac. Surg.* **2018**, *46*, 2197.
[104] D. Küçük, L. Savran, U. K. Ercan, Z. B. Yarali, O. Karaman, A. Kantarci, M. Sağlam, S. Köseoğlu, *Clin. Oral. Investig.* **2020**, *24*, 3133.
[105] G. M. G. Lima, A. C. Borges, T. M. C. Nishime, G. F. Santana-Melo, K. G. Kostov, M. P. A. Mayer, C. Y. Koga-Ito, *Molecules* **2021**, *26*, 5590. https://doi.org/10.3390/molecules26185590
[106] Z. Liu, X. Du, L. Xu, Q. Shi, X. Tang, Y. Cao, K. Song, *Oral Dis.* **2023**, *24*, 5790. https://doi.org/10.1111/odi.14547
[107] R. Matthes, L. Jablonowski, B. Holtfreter, T. Gerling, T. von Woedtke, T. Kocher, *Int. J. Oral Maxillofac. Implants* **2019**, *34*, 809.
[108] F. Tan, X. Rui, X. Xiang, Z. Yu, Mohamed Al-Rubean, *FASEB J*, *16*, 401.
[109] M. Zheng, L. Zhan, Z. Liu, H. P. Li, J. G. Tan, *Beijing Da Xue Xue Bao Yi Xue Ban* **2019**, *51*, 315.
[110] L. Ramireddy, C. Ho Lai, B. S. Low, C. Li, J. H. Hsieh, J. W. Lee, H. Y. Wu, *Plasma Med.* **2018**, *8*, 411.
[111] L. Galluzzi, I. Vitale, S. A. Aaronson, J. M. Abrams, D. Adam, P. Agostinis, E. S. Alnemri, L. Altucci, I. Amelio, D. W. Andrews, M. Annicchiarico-Petruzzelli, A. V. Antonov, E. Arama, E. H. Baehrecke, N. A. Barlev, N. G. Bazan, F. Bernassola, M. J. M. Bertrand, K. Bianchi, M. V. Blagosklonny, K. Blomgren, C. Borner, P. Boya, C. Brenner, M. Campanella, E. Candi, D. Carmona-Gutierrez, F. Cecconi, F. K. M. Chan, N. S. Chandel, E. H. Cheng, J. E. Chipuk, J. A. Cidlowski, A. Ciechanover, G. M. Cohen, M. Conrad, J. R. Cubillos-Ruiz, P. E. Czabotar, V. D'Angiolella, T. M. Dawson, V. L. Dawson, V. De Laurenzi, R. De Maria, K. M. Debatin, R. J. DeBerardinis, M. Deshmukh, N. Di Daniele, F. Di Virgilio, V. M. Dixit, S. J. Dixon, C. S. Duckett, B. D. Dynlacht, W. S. El-Deiry, J. W. Elrod, G. M. Fimia, S. Fulda, A. J. García-Sáez, A. D. Garg, C. Garrido, E. Gavathiotis, P. Golstein, E. Gottlieb, D. R. Green, L. A. Greene, H. Gronemeyer, A. Gross, G. Hajnoczky, J. M. Hardwick, I. S. Harris, M. O. Hengartner, C. Hetz, H. Ichijo, M. Jäättelä, B. Joseph, P. J. Jost, P. P. Juin, W. J. Kaiser, M. Karin, T. Kaufmann, O. Kepp, A. Kimchi, R. N. Kitsis, D. J. Klionsky, R. A. Knight, S. Kumar, S. W. Lee, J. J. Lemasters, B. Levine, A. Linkermann, S. A. Lipton, R. A. Lockshin, C. López-Otín, S. W. Lowe, T. Luedde, E. Lugli, M. MacFarlane, F. Madeo, M. Malewicz, W. Malorni, G. Manic, J. C. Marine, S. J. Martin, J. C. Martinou, J. P. Medema, P. Mehlen, P. Meier, S. Melino, E. A. Miao, J. D. Molkentin, U. M. Moll, C. Muñoz-Pinedo, S. Nagata, G. Nuñez, A. Oberst, M. Oren, M. Overholtzer, M. Pagano, T. Panaretakis, M. Pasparakis, J. M. Penninger, D. M. Pereira, S. Pervaiz, M. E. Peter, M. Piacentini, P. Pinton, J. H. M. Prehn, H. Puthalakath, G. A. Rabinovich, M. Rehm, R. Rizzuto, C. M. P. Rodrigues, D. C. Rubinsztein, T. Rudel, K. M. Ryan, E. Sayan, L. Scorrano, F. Shao, Y. Shi, J. Silke, H. U. Simon, A. Sistigu, B. R. Stockwell, A. Strasser, G. Szabadkai, S. W. G. Tait, D. Tang, N. Tavernarakis, A. Thorburn, Y. Tsujimoto, B. Turk, T. Vanden Berghe, P. Vandenabeele, M. G. Vander Heiden, A. Villunger, H. W. Virgin, K. H. Vousden, D. Vucic, E. F. Wagner, H. Walczak, D. Wallach, Y. Wang, J. A. Wells, W. Wood, J. Yuan, Z. Zakeri, B. Zhivotovsky, L. Zitvogel, G. Melino, G. Kroemer, *Cell Death Differ.* **2018**, *25*, 486.
[112] X. Dai, K. Bazaka, E. Thompson, K. Ostrikov, *Cancers* **2020**, *12*, 3360.
[113] S. Pereira, P. A. Ribeiro, S. Sério Optimization of a cold atmospheric plasma treatment to selectively affect the viability of skin cancer cells. In: *PHOTOPTICS 2020 - Proceedings of the 8th International Conference on Photonics, Optics and Laser Technology, Vallettta, Malta*. SciTePress, **2020**, 201.
[114] S. Prreira, S. Sério, P. Ribeiro, Study of the efffects of cold atmospheric plasmas on skin cancer cells. Costa da Caparica, Universidade Nova de Lisboa, Portugal.
[115] G. Bauer, D. Sersenová, D. B. Graves, Z. Machala, *Sci. Rep.* **2019**, *9*, 14210. https://doi.org/10.1038/s41598-019-50291-0
[116] M. Afrasiabi, G. Tahmasebi, E. Eslami, E. Seyedi, J. Pourahmad, *Iranian J. Pharm. Res.* **2022**, *21*, e124106. https://doi.org/10.5812/ijpr-124106
[117] K. Evert, T. Kocher, A. Schindler, M. Müller, K. Müller, C. Pink, B. Holtfreter, A. Schmidt, F. Dombrowski, A. Schubert, von T. Woedtke, S. Rupf, D. F. Calvisi, S. Bekeschus, L. Jablonowski, *Sci. Rep.* **2021**, *11*, 20672. https://doi.org/10.1038/s41598-021-99924-3
[118] D. Murillo, C. Huergo, B. Gallego, R. Rodríguez, J. Tornín, *Biomedicines*, **2023**, *11*, 208.
[119] A. Kikly, S. Jaâfoura, S. Sahtout, *J. Esthet. Restor. Dent.* **2019**, *31*, 441.
[120] S. H. Nam, S. M. Ok, G. C. Kim, *Int. Endod. J.* **2018**, *51*, 479.
[121] X. Yang, K. Sun, W. Zhu, Y. Li, J. Pan, *BMC Oral Health* **2022**, *22*, 535. https://doi.org/10.1186/s12903-022-02601-8
[122] B. Pavelić, M. Z. Švarc, S. Šegović, I. Bago, *Quintessence Int.* **2020**, *51*, 364.

[123] S. H. Nam, B. B. R. Choi, G. C. Kim, *Int. J. Environ. Res. Public. Health* **2021**, *18*, 4714. https://doi.org/10.3390/ijerph18094714
[124] J. O. Choi, M. S. Han, S. H. Nam, G. C. Kim, *J. Magn.* **2020**, *25*, 620.
[125] A. Kusanagi, M. Otsuki, J. Tagami, *Asian Pac. J. Dent.* **2018**, *18*, 7.
[126] J. Kamionka, R. Matthes, B. Holtfreter, C. Pink, R. Schlüter, T. von Woedtke, T. Kocher, L. Jablonowski, *Clin. Oral. Investig.* **2022**, *26*, 3179.
[127] B. H. D. Panariello, D. P. Mody, G. J. Eckert, L. Witek, P. G. Coelho, S. Duarte, *BioMed Res. Int.* **2022**, *2022*, 1.
[128] S. Duarte, B. H. D. Panariello, *Arch. Biochem. Biophys.* **2020**, *693*, 108560. https://doi.org/10.1016/j.abb.2020.108560
[129] P. Sevilla, C. Lopez-Suarez, J. Pelaez, C. Tobar, V. Rodriguez-Alonso, M. J. Suarez, *Appl. Sci.* **2020**, *10*, 8856.
[130] H. Naujokat, S. Harder, L. Y. Schulz, J. Wiltfang, C. Flörke, Y. Açil, *J. Cranio-Maxillofac. Surg.* **2019**, *47*, 484.
[131] F. Tan, Y. Fang, L. Zhu, M. Al-Rubeai, *Crit. Rev. Biotechnol.* **2021**, *41*, 425.
[132] O. Karaman, S. Kelebek, E. A. Demirci, F. İbiş, M. Ulu, U. K. Ercan, *Med.* **2018**, *15*, 13.
[133] X. Qi, X. M. Zhu, X. Liu, J. LI, L. X. Zhao, H. P. Li, J. Tan, *Dent. Mater. J.* **2022**, *41*, 101.

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