Invited lecture/ Review

Use of Gaseous Plasma for Dental Applications

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Abstract:
Plasma technology is a rapidly growing field of science that permeates various branches of medicine and dental medicine. In dental medicine, cold or nonthermal gaseous plasma can be used directly in the oral cavity for the surface treatment of hard dental tissues, periodontal tissues, or oral mucosa or indirectly for treating dental materials before intraoral use or placement. Simplified atmospheric-pressure plasma devices in plasma pencils or jets have broadened the spectrum of plasma technology applications for safe plasma treatment of living tissues. Cold gaseous plasma also allows surface treatment of various heat-sensitive materials. Dental alloys, polymers, waxes, and ceramics can be decontaminated or disinfected with plasma treatment. Antimicrobial properties of cold atmospheric plasma have been demonstrated to facilitate the treatment of oral mucosa infections, dental caries, and endodontic space infections. Various dental materials can also be functionalized through plasma surface treatment to improve their biocompatibility, adhesive properties, wettability, or permeability. Promising results of cold plasma treatment have also been shown in the bleaching of teeth with external or internal staining and the enhancement of the adhesion of dental composites to dentin. Plasma may also serve as a method of dental armamentarium cleaning and sterilization. Although the use of cold gas plasma is not yet part of the standard procedures in the daily clinical practice of dentists, promising results from preclinical and clinical research are encouraging further development and exploration of this technology.

Keywords: cold gaseous plasma; atmospheric pressure plasma; plasma technology; dental medicine; surface treatment

1. Introduction

1.1. Plasma technology in dental medicine

Plasma medicine, a rapidly developing scientific discipline, is revolutionizing the medical landscape by introducing transformative treatments across diverse specialties. Although cold gas plasma is not yet a part of the standard procedures in routine dental clinical practice, promising results from preclinical and clinical research are encouraging for further development and exploration of this technology. Therefore, it is expected that the clinical use of this technology in dentistry will become increasingly widespread in the future.

1.2. Definition of gaseous plasma and cold (nonthermal) gaseous plasma

Gaseous plasma (i.e., *gas* plasma) is defined as the fourth state of matter that occurs when matter in the gaseous state is supplied with energy, leading to partial ionization of the gas (Cheruthazhekatt et al., 2010; Kim et al., 2014). This phenomenon was discovered by the British physicist Sir William Crookes in 1879, and the term "plasma" was first used to designate it by the American chemist Irving Langmuir in 1929 because of its physical properties resembling electrolytes in medicine and biology (Arora, 2013; Cheruthazhekatt et al., 2010). The term gas plasma is used more commonly to avoid confusion with blood plasma, the non-cellular component of blood.

Ionized gases constitute more than 99% of visible matter in the universe, making plasma the most common state of matter (Arora, 2013; Cheruthazhekatt et al., 2010). In everyday life, plasma can be seen in the form of several natural phenomena (flame, lightning, the solar corona, stars, aurora borealis) and is also encountered as a crucial technological foundation for many devices that have changed the way we live (e.g., mobile phones, computers, plasma screens) (Kim et al., 2014).

Ionization of the gas may be induced by supplying heat or, more commonly, by exposing the gas to an electric or electromagnetic field, leading first to the disruption of molecular bonds and subsequently to the ionization of atoms. Thus, plasma contains a roughly equal amount of electrons, positively and negatively charged ions, neutral and excited atoms and molecules, providing it electrical conductivity, in contrast to gases, which are usually electrical insulators (Cheruthazhekatt et al., 2010; Kim et al., 2014).

Plasmas can be devided to thermal and nonthermal plasmas. The thermal plasma is fully ionized or simply hot plasma, which reaches temperatures in the ranges of a tenth of thousands and up to millions of Kelvins. Such plasmas are less applicable for surface treatment processes. On the contrary, nonthermal plasmas are generated by exposing gases to non-equilibrium conditions which partially ionize them. For nonthermal plasma, electrical energy is usually used, either by directly applying a voltage to the electrode(s) or indirectly by using coils and electric current to generate strong magnetic fields to enable ionization of the gas (Laroussi et al., 2007). These types of nonequilibrium or cold gas plasma have unique applications in various scientific fields and medicine. Unlike thermal plasma, the temperature of heavy particles in cold plasma is significantly lower than the temperature of electrons, reaching values of less than 40°C (Arora, 2013). Thus, it is suitable for the surface treatment of various heat-sensitive materials and even for direct use on tissues (Wu et al., 2016).

2. Atmospheric-pressure plasma appliances

Cold plasmas can be further divided into low-pressure and atmospheric-pressure plasmas. The former are generated in near-vacuum conditions via sophisticated low-pressure plasma systems that enable gas evacuation. On the contrary, atmospheric-pressure plasma is generated in less controlled conditions at atmospheric pressure and is more applicable for use in medicine (Cheruthazhekatt et al., 2010). Atmospheric pressure plasma medical devices use various noble gases or gas mixtures, usually argon, helium, or neon, as sources of gaseous plasma, with or without an added reactive gas (O_2, N_2, or air).

For gas ionization to be achieved at a pressure of 1 atm or more, high strength of the electric field is required, usually more than 30 kV/cm; hence, the distance between electrodes is often small, limiting the applicability of conventional dielectric barrier discharge

(DBD) devices for treatment of small objects that can be placed directly in the discharge field. This obstacle has been successfully surpassed by the development of devices with special nozzles (plasma pencils, plasma jets), allowing the creation of a plasma jet where radicals or charged particles reach several centimeters beyond their source, enabling safe treatment of heat-sensitive substrates (Wu et al., 2016). The gas travels through a tube, and plasma is formed in the discharge region between the inner rod-shaped electrode and the surrounding ring electrode (Wu et al., 2016).

3. Applications of plasma technology in dental medicine

Cold gaseous plasma in dental medicine can be used in two ways: directly in the oral cavity for the surface treatment of hard dental tissues, periodontal tissues, or oral mucosa, and indirectly for the treatment of dental materials before their intraoral use or placement (Li et al., 2017). Its use has been successfully tested in several areas of dental medicine.

3.1. Application as a sterilization method

Cold gaseous plasma can be utilized to sterilize surgical instruments and dental armamentariums. Effective cleaning of hard-to-reach areas of instruments (grooves and threads of endodontic instruments) and removal of protein contamination are achieved combining peroxide as a highly reactive sterilization agent and plasma, which enables full removal of degradation products. As an alternative sterilization method, it is beneficial for heat-sensitive materials that cannot be autoclaved, as it allows sterilization at room temperature (Sarkar et al., 2018). Recently, novel technological devices for simultaneous sterilization and activation of surfaces by gaseous plasma have also been developed.

3.2. Application in the field of pediatric dentistry and endodontics

Numerous *in vitro* studies have demonstrated that cold atmospheric pressure plasma has a bactericidal effect on bacteria in planktonic form and biofilms, with its effect comparable to 2% chlorhexidine. It successfully kills *E. faecalis*, a gram-positive facultatively anaerobic coccus often isolated from root canals or periapical lesions of teeth with persistent chronic apical periodontitis after unsuccessful endodontic treatment. An 8-minute treatment with He and O_2 plasma has a lytic effect on *C. albicans*, an opportunistic pathogen in the oral cavity, while a 30-second treatment also eliminates *Streptococcus mutans*, a key pathogen in carious lesions (Wu et al., 2016). Plasma can decontaminate carious cavities, an alternative to conventional mechanical removal of infected dentin with drilling or lasers. Plasma also successfully destroys bacteria on irregularly shaped carious cavities, penetrating into deeper parts of carious lesions. Simple plasma devices have been developed for safe plasma treatment of root canals by disinfecting the endodontic space (Singh et al., 2014). Atmospheric plasma successfully penetrates *in vitro* biofilms, making it suitable for disinfecting root canals, although, in some studies, it has shown less effectiveness than NaOCl (Wu et al., 2016).

3.3. Application in esthetic and restorative dentistry

In everyday clinical practice, patients increasingly express a desire for teeth whitening. Cold gaseous plasma has also been tested for this purpose. In a study by Lee et al., the tooth bleaching effect was more significant in the group with direct atmospheric pressure plasma surface treatment of stained extracted teeth than in the group with a standard 35% hydrogen peroxide gel treatment. A more pronounced change in tooth color was achieved with simultaneous plasma treatment and application of a 35% H_2O_2 bleaching gel compared to using the bleaching gel alone (Lee et al., 2009). Plasma may successfully remove both external staining via the plasma cleaning effect (removal of surface proteins) and internal staining through the plasma-induced production of hydroxyl ions. In a study by Wang et al., enamel changes after plasma treatment were comparable to changes caused by the H_2O_2 gel.

Plasma treatments have also been attempted to improve the adhesion of dental composites to dentin: a 30-second treatment with atmospheric argon plasma after a 15-second etching with phosphoric acid increased the bond strength (TBS) of composite resin to dentin by 64% compared to the standard adhesive protocol, with the improvement limited only to the peripheral layers of dentin and only for treatments lasting up to 100 seconds, whereas after more extended treatment (i.e., 5 min), the bond strength was lower (Ritts et al., 2010). Stasic et al. (2019) successfully increased dentin's wettability and surface free energy with plasma treatment, which did not significantly differ from the values in the control group with the conventional phosphoric acid etching. Plasma treatment may also improve dentin wetting with self-etch adhesives (Stasic et al., 2019). Treatment with cold plasma significantly improves the penetration of hydrophilic monomers of adhesive systems (HEMA) into demineralized dentin after etching (Zhang et al., 2014). Plasma-induced deposition of a thin layer of organic polymer on the enamel surface improves the bond strength between the composite and enamel, but the durability of the bond is inferior to that achieved with the standard etching protocol (Han et al., 2014).

Several studies have also attempted plasma treatment as an alternative method for polymerizing dental composites and adhesive systems to achieve greater crosslinking and more time-efficient monomer conversion (Sarkar et al., 2018).

In prosthodontics, the indirect uses of cold plasma have been researched more extensively, especially for surface modification of various dental materials: alloys, polymers, waxes, and ceramics, thereby improving their properties without affecting the chemical and physical properties of the bulk material (Cheruthazhekatt et al., 2010). Material surfaces can be activated and functionalized, thus improving their biocompatibility, adhesive properties, wettability, and permeability. Bactericidal substances (metal ions), therapeutic agents, fluorides, and extracellular matrix proteins for cell adhesion and proliferation may be attached to the material surface via plasma technology (Li et al., 2017).

In dental implantology, researchers have aimed to improve the osseointegration of dental implants or prevent bacterial colonization to prevent biological complications of implant-retained prosthodontic rehabilitation. Plasma etching and plasma spraying of titanium implants are extensively reported in the literature, providing a rough surface for improved osseointegration.

Numerous studies focus on the surface treatment of dental ceramics, especially zirconium oxide ceramic, where treatment with cold plasma increases its wettability and reduces contamination without increasing its surface roughness or changing the material's crystalline structure. Thus, improved bonding of zirconium oxide ceramic to composite cement is achieved, with the bond strength comparable to that achieved through the standard sandblasting protocol, which changes the crystal structure of ZrO_2, causes micropores in the surface, and thereby affects the material's mechanical properties. Plasma also successfully decontaminates zirconia frameworks before veneering. Surface contamination with saliva is reduced more efficiently compared to an isopropanol bath, but plasma fails to clean Fitchecker residues efficiently. Through plasma treatment, TBS of veneered porcelain to zirconia frameworks comparable to that in the group without saliva contamination was achieved (Hallmann et al., 2016; Ito et al., 2016a, 2016b; Piest et al., 2018; Valverde et al., 2013). Experimental research is also being conducted on the plasma treatment of glass ceramics before their adhesive cementation to replace the standard hydrofluoric acid etching protocol, which is technique-sensitive and hazardous (Rener-Sitar et al., 2022). Cold plasma treatment can improve the wettability and adhesive properties of the glass-ceramics (Birk et al., 2023).

3.4. Application in the fields of periodontology, oral diseases, and oral surgery

In vitro studies on the use of cold gaseous plasma on cultures of human periodontal mesenchymal stem cells have shown that plasma treatment may potentially contribute to periodontal regeneration by stimulating cell proliferation and osteogenic differentiation and inhibiting cell migration (Miletić et al., 2013). A favorable effect of plasma has been demonstrated in treating oral mucosal infections caused by *C. albicans*, such as angular cheilitis, denture stomatitis, and linear gingival erythema (Sarkar et al., 2018). Gaseous plasma has also been proven to benefit healing after surgical interventions in the oral cavity by stimulating fibroblast proliferation, extracellular matrix formation, and angiogenesis (Jha et al., 2017).

For oral tumors, plasma treatment at increased power or duration can potentially disrupt the "S" phase of tumor cell mitosis, thereby inducing their necrosis or apoptosis. The studies on the use of plasma technology in oncology have encouraging results in both *in vitro* and *in vivo* conditions, but our knowledge is still insufficient to implement this method in everyday clinical practice (Sarkar et al., 2018).

4. Conclusion

Plasma treatment shows high potential in dental applications, not only for treatment of materials but also for direct treatment of tissues and cells. Despite favorable short-term results in *in vitro* and animal studies, the long-term studies are still needed to evaluate the safety of gaseous plasma treatment for intraoral dental applications (Jablonowski et al., 2019). Concerns regarding potential carcinogenicity, particularly in individuals with pre-existing risk factors, necessitate comprehensive assessments to determine its long-term suitability as an alternative treatment option.

Conflicts of Interest: The author declares no conflict of interest.

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