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Plasma in dentistry

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Abstract

This review describes the contemporary aspects of plasma application in dentistry. Previous studies on plasma applications were classified into two categories, surface treatment and direct applications, and were reviewed, respectively according to the approach. The current review discussed modification of dental implant surface, enhancing of adhesive qualities, enhancing of polymerization, surface coating and plasma cleaning under the topics of surface treatment. Microbicidal activities, decontamination, root canal disinfection and tooth bleaching were reviewed as direct applications with other miscellaneous ones. Non-thermal atmospheric pressure plasma was of particular focus since it is gaining considerable attention due to the possibility for its use in living tissues. Future perspectives have also been discussed briefly. Although it is still not popular among dentists, plasma has shown promises in several areas of dentistry and is now opening a new era of plasma dentistry.

Keywords

Plasma; Dentistry

1. Introduction

Plasma, by far the most dominant state of matter in the universe, was identified by Sir Crooke in 1879 [1], and was first named "plasma" by Langmuir in 1929. After a long dormant phase since Simens used first plasma discharge in order to create ozone in the late 1850s, plasma research has recently evolved at a rapid pace and extended into biomedical, environmental, aerospace, agriculture and military fields [2,3].

Although biomedical application of plasma technology has become very popular in various fields today, it is not clear when it was first used in the field of dentistry. It is partly because the plasma has been nearly everywhere and has been related to nearly everything in reality, thus we do not readily recognize it. Perhaps the first application of plasma in dentistry occurred in the manufacturing process of dental instruments or the disinfection of them. Nevertheless, Eva Stoffels is believed to introduce the first investigation with the view of a possible therapeutic and thus medical question for dentistry [4,5].

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Conflict of Interest
None.

As in medicine, the dental applications of physical plasma can be mainly subdivided into two principal approaches [6]: one is the use of plasma technology for the treatment of surfaces, materials or devices to realize specific qualities for subsequent special applications including disinfection, and the other is the direct plasma application on or in the human body for therapeutic purposes; however, clear-cut classifications are sometimes impossible because of overlaps. In addition, the use of plasma for medical purposes could be divided according to its temperature and the air pressure at which it is generated.

Indeed, plasma generation can be realized at low, atmospheric and high air pressure and their temperature could be different. While thermal plasmas are natural phenomena, non-thermal plasmas are artificially made of, of which composition and temperature are adjustable. Today, non-thermal plasmas are utilized from in the appliances of daily life like energy-saving lamps, flat panel displays to for industrial purposes, such as polymer pretreatment, surface finishing, waste and air pollution management [6,7]. Non-thermal atmospheric pressure plasma (NTAPP), which is sometimes called cold atmospheric plasma (CAD) or low-temperature atmospheric pressure plasma, has the unique advantage of extending plasma treatment to living tissue. Therefore, all the studies regarding direct applications used this type of plasma even though the individual settings varied. In addition, some of the surface treatments also made use of NTAPP in the form of chairside applications. Various types of plasma devices, such as nanosecond pulsed plasma pencils [8], radio-frequency plasma needles [9], direct-current plasma brushes [10], and plasma jets [11] have been developed for non-thermal atmospheric pressure plasma generation. The common challenge for generating these plasmas is the inhibition of the glow to arc transition at one atmosphere. Different types of discharges have used different schemes to achieve this [12]. This opens up new horizons in the field of dentistry with the size of the device becoming small enough to hold by hand.

In this respect, the present review reports the current usage of plasma in dentistry basically according to the two approaches, i.e., surface treatment and direct application (Table 1). The NTAAP, which is gaining considerable attention, is discussed in great detail in each approach in this report.

2. Surface treatment

2.1. Modification of the implant surface to improve osseointegration

Restorative treatment using dental implants has become a standard procedure in contemporary dentistry [13]. Since the implant surface is the first part to interact with the host, it has been thoroughly investigated in an attempt to hasten the early host-to-implant response [14,15]. The rationale for its modification focuses upon implant interaction with biofluids, which positively alters the cascade of events leading to bone healing and intimate interaction with the surface [16]. Numerous possibilities have been suggested and evaluated for this purpose [17–19]; however, there is no consensus concerning which kinds of surface roughness and/or chemistry combination will result in optimum osseointegration [20–22].

Among these properties, implant surface hydrophilicity or wettability has recently received considerable attention [23]. Earlier studies of the effect of plasma on titanium surfaces indicated that this treatment is capable of improving cell adhesion by changing surface roughness and wettability, which decreases after plasma exposure [24,25]. These studies used glow discharge treatment at low pressure during the manufacturing process. Recently, a chairside operating NTAPP immediately prior to implant placement was also reported [26,27], which stated that plasma treatment reduced the contact angle and supported the spread of osteoblastic cells. One of the advantages of plasma treatment is that it leaves no residues after treatment. Some changes in the physicochemical characteristics were reported, such as surface free energy, content of hydrocarbon and functional hydroxyl groups [28].

Several studies reported the plasma treatment of zirconia implants, which is increasing as an alternative to the conventional titanium implant due to its superior esthetic properties [29]. They also demostrated the increase in hydrophilicity and enhanced osseointegration in in vitro as well as in vivo experiments [28,30].

Santos et al. investigated the effect of the glow discharge treatment of titanium surfaces on plasma protein adsorption [31]. They found no difference between the untreated and glow discharge-treated titanium surface in total absorbed protein. The composition changed, but this was attributed to the protein–protein interactions and competitive/associative adsorption behavior.

2.2. Enhancing adhesive qualities

As a critical factor in improving the performance of dental composites, adhesive dentistry has greatly advanced since being first discovered by Buonocore [32]. For most dental joints, one set of adherends is usually composed of any dental substrates or previous restorations while the other set consists of restorative ones such as composite, amalgam, or ceramics [33]. Optimal adhesion could be achieved when the adhesive material is spread impulsively across the entire adherend surface. In other words, optimal wettability of the substrate is achieved with reference to that adhesive [34].

Conventional adhesive systems employed several methods to improve wettability, to elevate the surface energy and to increase the roughness through techniques involving etch-and-rinse, acid primers, Hydroxyethylmethacrylate (HEMA) primers and laser irradiation [35–38]. In the same respect, plasma treatment has been introduced as an alternative or additional procedure, especially in the bonding of ceramic restorations, which is more difficult to achieve.

Generally, the etching of feldspathic ceramic with hydrofluoric acid and coating with a silane coupling agent has been recommended as a reliable protocol [39,40]. However, because the procedure is complicated and requires toxic chemicals, other ceramic bonding techniques such as silica coating have been introduced [41,42]. As an alternative for adhesion enhancement in dental ceramic bonding, atmospheric pressure plasma treatment has been suggested [43]. It enhances adhesion by producing carboxyl groups on the ceramic surface and improves the surface hydrophilicity as a result [44].

The nonreactive surface of zirconia, sometimes described as “ceramic steel”, presents a consistent issue of poor adhesion strength to other substrates [45]. Silane treatment used for silica-based substrates is not applicable [46]. In addition, zirconia itself is known to be hydrophobic and possesses very low surface concentrations of OH groups [47]. For this more complicated bonding, several other methods have been proposed [48,49]. Plasma treatment was also tested and the results showed that a significant increase in the microtensile bond strength to zirconia surfaces was observed when non-thermal plasma was applied alone or in combination with resin. According to the XPS results, an increase of elemental O and a decrease of elemental C was detected on the zirconia surface after non-thermal plasma application [50]. Another attempt using plasma fluorination was reported, which is expected to increase hydroxylation at the surface, making it more reactive, thus allowing for covalent bonding between the zirconia surface and resin cement [51]. One report demonstrated that the high polarity was obtained on zirconia and titanium surface after NTAPP application [52].

For enamel, dentin and composite, Chen et. al. [33] reported that a super-hydrophilic surface could be easily obtained by plasma brush treatment without affecting the bulk properties regardless of the original hydrophilicity. Another study revealed that plasma treatment of the peripheral dentin surface resulted in an increase in the interfacial bonding strength, while over 100 s of prolonged treatment resulted in a decrease in the interfacial bonding strength [53]. However, no improvement in the bonding strength was observed for plasma-treated inner dentin, which probably due to the variation in dentin composition [54].

As for the post surface, Costa Dantas et al. [55] showed that plasma treatment favored the wettability of the post, however, real adhesion improvement was not observed after argon plasma. Interestingly, following ethylenediamine plasma treatment, there was a significant chemical modification as indicated by the high roughness. Studies have revealed that plasma surface treatment presents with an aging effect [56], Ye et al. observed the aging effect after post-surface treatment with non-thermal plasma and reported that the improvement in bond strength disappeared when the fiber posts were exposed to air for 1 h or longer after being treated with plasma [57].

2.3. Enhancing polymerization

Plasmas also induce polymerization [58]; polymers synthesized by plasma exposure demonstrated high cross-linking and high degrees of polymerization [59]. For composite resin, plasma arc curing units are popular because of their short curing time in comparison to conventional units [60,61]. However their polymerization characteristics are reported to be less than optimal [62]. Recently, the non-thermal plasma brush was reported to be effective in the polymerization of self-etch adhesives with no negative effects of water on the degree of conversion of plasmacured samples [63].

2.4. Surface coating

Variation in surface texture or nanoscale topography features can affect the cell response for a titanium implant [25]. Plasma spraying, which used to be one of most popular coating techniques for implants, can be considered as one type of plasma treatment, but it has been reported to have problems such as delamination [64]. Several other types of thin coating techniques using plasma to enhance osseointegration, have been introduced and have shown some promise such as plasma nitriding [15,65], titanium nitride oxide coatings [66], plasma polymerized hexamethyldisiloxane [67], plasma polymerized allylamine [68], and plasma polymerized acrylic acid [69]. Films formed by plasma polymerization are generally free of pinholes, have a strong degree of adherence to a wide variety of materials, and have a greater degree of resistance to chemical and physical treatment because of their cross-linked structure [70].

The coating on the fiber post-surface was evaluated after chemical vapor deposition using glow discharge [71–73]. Yavirich et al. reported that the treatment appeared to increase the tensile-shear bond strength between the post and composite [74]. Several microcomposite and ceramic materials were coated with plasma-assisted thin film coatings and the potential for reduction of bacterial adhesion exhibited some promise [75].

2.5. Plasma cleaning

In contrast to the conventional methods of cleaning such as the use of solvents or aggressive chemicals, plasma cleaning leaves no residue, and, when optimized, typically generates only CO_2, H_2O, and N_2 as gaseous waste. Gas plasma treatment has the potential advantages of lack of toxic residue effects, reduced turnover time, and applicability for sterilization of heat- and moisture-sensitive instruments [76,77]. Its effectiveness has led to its use as a decontamination method from chemical and biological warfare agents or from spores [78,79].

Dental treatment can frequently induce cross-contamination between dental patients and dentists through instruments and materials as well as between impression materials and dental technicians [80–82]. Contaminated endodontic files exposed for a short period to low-pressure oxygen–argon plasma showed a reduction in the absolute amount of proteinaceous materials in a preliminary study, but the exact duration was not described unfortunately [83]. In one experiment using diamond burs and silicone impression materials, the colony-forming unit was significantly reduced for both *Escherichia coli* and *Bacillus subtilis* after treatment with atmospheric pressure non-thermal air plasma [84]. The role of low temperature atmospheric pressure plasma and future prospects was well discussed in McCombs' review [85].

2.6. Miscellaneous

In addition to the disinfective role of plasma cleaning on elastomeric impression materials, plasma treatment was reported to increase the surface wettability [86]. The wettability of impression materials is an important requirement for the accurate reproduction of intraoral structures, since it is directly related to the quality of die stone casts, and, therefore, the castability of prostheses [87]. The surface properties of several set elastomeric impression materials contaminated with saliva were inspected after plasma cleaning and exhibited a general increase in the critical surface tension and an improvement in the castability of all materials was also noted [88,89].

Denture stomatitis is brought about by the adhesion of *Candida albicans* to the denture surface [90]; plasma treatment was investigated based on its potential to reduce this adhesion [91,92]. The results, however, were not in agreement due to the different parameters used in the plasma treatment.

As a polymerization technique of glass fiber to improve mechanics, plasma was investigated and showed some promise in increasing the flexural strength of the denture base resin [93]. In contrast, the adhesion between the cobalt–chromium alloy and self-curing acrylic resin was not improved by plasma treatment in removable partial denture cases [94]. Tungsten inert gas welding, one form of plasma arc, is reported to produce better results than brazing or laser welding [95].

3. Direct plasma application

3.1. Microbicidal activities

The antibacterial effects of cold plasma have been shown for a variety of micro-organisms in numerous studies [8,96–102]. However, some studies have shown that bacterial DNA is not completely destroyed by cold plasma [103,104]. Methods for the decontamination and conditioning of intraoral surfaces are of great interest in the field of dentistry. Cold plasmas are of particular interest, as heat damage to dental pulp must be prevented [105]. The removal of carious dentin has been suggested as an alternative to conventional drilling [4,5]. The in vitro disinfection of *Streptococcus mutans* grown on agar plates [106] has been demonstrated. The substantial reduction of oral microorganisms adherent to dentin slices was also reported with the use of plasma [105]. The sterilization effect was suggested to be due to reactive oxygen species [107].

In the real oral environment, micro-organisms exist in the form of a biofilm and not in a planktonic state. The established and matured oral biofilm is a three-dimensionally-structured community of many microbial species [108] and is relevant to the development of caries and periodontal disease [109]. For example, dental plaque, a biofilm on the tooth surface, consists of complex communities of oral bacteria with hundreds of species present [110]. Furthermore, biofilms are also present on artificial surfaces in the oral cavity such as dentures or implants [111]. Therefore, there was a shift in research model from planktonic to biofilm, and the effects of non-thermal plasma were evaluated on biofilm models. Several studies exhibited imperfect, but highly promising results [112,113].

3.2. Decontamination

Research has succeeded in improving the biological acceptance and osseointegration of dental implants. However, its long-term success is still challenging because of peri-implant diseases caused by the formation of biofilms [114]. The decontamination of implant surfaces represents a basic procedure in the management of peri-implant diseases [115], but remains a challenge.

Several studies have been published dealing with the decontamination efficacy of mechanical, chemical, and physical methods [116–118]. All techniques have advantages and disadvantages, and no single technique produced a convincing solution to the problem [119]. Biofilms play a major role in the pathogenesis of various oral diseases, especially peri-implant mucositis. In recent studies, the use of NTAPP has been suggested for the removal of biofilms in general [120], and for the treatment of both peri-implant mucositis and peri-implantitis in particular [121–123].

The mechanisms are not clearly elucidated but can be hypothesized generally as two: One is the generation of reactive species such as oxygen, nitrogen or nitrogen oxide radicals [124,125] and the other is the etching effect of the plasma on biofilms during the chemical process of oxidation [120]. Although physical degradation by burning was also suggested, it is not thought to be relevant because the NTAPP has the temperature below 401 C [126].

3.3. Root canal disinfection in endodontic treatment

Root canal disinfection can be considered as a special type of decontamination. However, it is separately mentioned as a single topic in this review because of its importance in the endodontic procedures for successful outcome and difficult nature of eradicating the root canal micro-organisms due to its biological and geometrical characteristics. The tooth root canal system has complicated structures, such as isthmuses, ramifications, deltas, irregularities, and in particular dentinal tubules [127]. It has been reported that bacteria can enter dentinal tubules as deep as 500–1000 μm [128].

A variety of methods have been performed such as mechanic cleaning, irrigation, laser irradiation, ultrasound and application of hypochlorite and other antibacterial compounds [129–133]. However, eliminating the residual micro-organisms especially within the biofilm is still a challenging task and clinical investigations showed that there are around 10% of treatment failures when conventional disinfections were performed [134,135].

Since persistent endodontic infections are frequently caused by *Enterococcus faecalis* [136,137], numerous in vitro experiments have been reported on this issue using this micro-organism [138–143]. They have shown quite promising results after using NTAPP alone or with conventional approaches pointing out that the NTAPP as a gas phase has a capability of reaching deep into the complex canal. Therefore, there is a unique advantage of direct contact with bacteria when using NTAPP, which is compulsory but impossible with conventional methods. The effective inactivation of *E. faecalis* has been attributed to several mechanisms, such as excited species, charged particles, and ultraviolet radiations. Among these, several studies suggested that the reactive oxygen species plays the most crucial roles in both bacterial inactivation [144,145] and biological effects in intercelluar matrices [146].

3.4. Tooth bleaching

Tooth bleaching has become a popular esthetic service in dentistry. Hydrogen peroxide (H_2O_2) is a widely used bleaching material that is effective and safe [147]. In-office bleaching systems usually use a 30–44% H_2O_2 bleaching gel and a high-intensity light source [148,149]. The light source may enhance bleaching by heating the H_2O_2 and consequently accelerating bleaching, but this mechanism has yet to be confirmed. The application of light may [150] or may not [151] significantly improve the efficacy of the bleaching system. Plasma treatment was suggested to be complementary to the conventional method because it provides effective bleaching without thermal damage [152,153].

3.5. Miscellaneous

Koban et al. reported an interesting direct application of NTAPP, which reduced the contact angle of untreated dentin surface and caused a superior spreading of osteoblasts on the dentin. These results may be utilized to optimize periodontal regeneration in the future [154]. According to Miletic et al. [155], the interaction of NTAPP with the human periodontal ligament mesenchymal stem cells demonstrated that NTAPP inhibited the migration of the cells and induced some detatchment, without affecting their viability. In addition, the plasma significantly attenuated the cells' proliferation, but promoted their osteogenic differentiation. The issue as to how deep the plasma penetrate can into a biofilm was addressed by several researchersv [156,157]. Among them, Pei et al. [157] showed that 25.5 um thick *E. faecalis* biofilm layer was penetrated by NTAPP, which is the deepest up to now. The simultaneous use of plasma and disinfecting agents showed an increased treatment efficacy on dental biofilms in vitro [158].

4. Discussion and conclusions

The study of plasma integrates various fields of science, such as physics, chemistry, biology, and engineering, and has recently involved medicine and dentistry in its research efforts. However, dentists do not realize well even though they use plasma in daily practice, such as electrosurgical applications for tissue removal, cauterization, and plasma spraying of titanium implants.

Numerous research papers have been published providing evidences of efficacy when using plasma technology in the field of dentistry. The application of plasma in dentistry showed several unique advantages over conventional approaches, and the introduction of NTAPP is attracting a lot of attention [159]. Because of its low temperature under atmospheric condition, it can be used directly onto or in the human tissues. Many of oral diseases such as dental caries and periodontitis are infectious ones, and the bactericidal effect of plasma could replace conventional surgical removal or usage of antibiotics. It does not induce resistance problems, nor has toxic residues. In addition, it can overcome some anatomic complexity in endodontic treatment. Aside from these, several biological applications are now of interest, such as enhancing hydrphilicity of the surface, effects on human cells and tooth bleaching. Even, plasma drug delivery in the dental tissue was envisaged as a new possibility in the future [160].

Currently, clear conclusions are not yet drawn and the effects of NTAPP have on human and nonhuman cells require further exploration [McComb]. Moreover, the studies have applied non-standardized protocols which were different in nearly all cases; thus, it is hard to compare and interpret the results. There may be this confusion because it is now the beginning era of the novel field of plasma dentistry. Nonetheless, the advancement of technologies that parallel plasma dentistry will surely overcome this confusion in the near future. At the same time, there is a strong need for more in vivo studies and eventually the clinical studies in order for the plasma treatment to be used and accepted widely. The user-friendly interface and compact size of equipment would gain more popularity although manufacturers recently provide hand-held devices proper for the clinic not laboratory.

Further understanding of the cellular and molecular mechanisms involved could also give researchers and clinicians insight into future applications.

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Table 1

Classification of plasma used in dentistry[a].

Surface treatments	Direct applications
Modification of the implant surface	Microbicidal activities
Enhancing adhesive qualities	Decontamination
Surface coating	Root canal disinfection
Plasma cleaning	Tooth bleaching
Miscellaneous	Miscellaneous

[a]Some usages are hard to separate into other classification due to overlaps.