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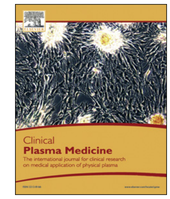

Invited paper

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.

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].

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,

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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.

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