

The bright future of dentistry with cold plasma – Review

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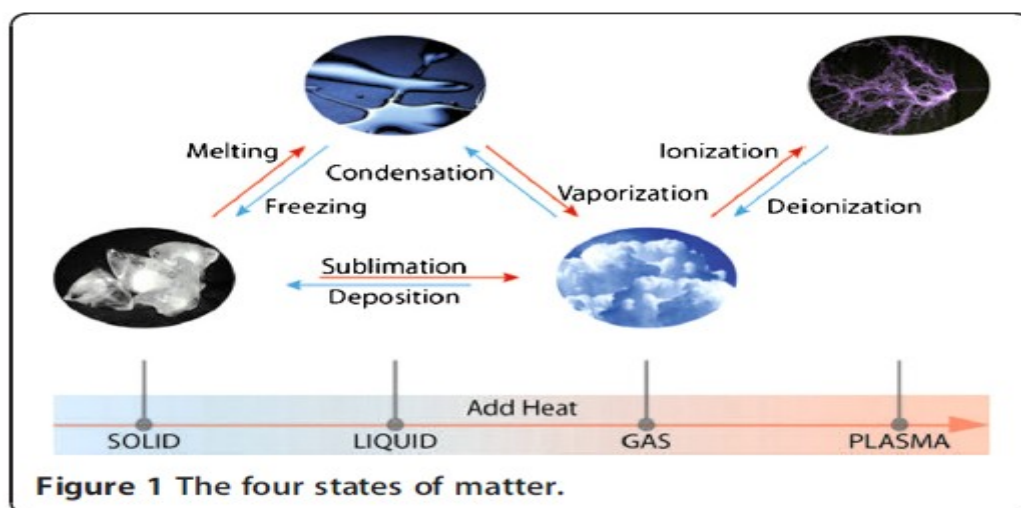
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Abstract: - Plasma is the fourth state of matter and other states of matter are liquid, gas, and solid⁴. Plasma occurs as a natural phenomenon in the universe in the form of fire, in the polar aurora borealis and in the nuclear fusion reactions of the sun and also can be created artificially which has gained importance in the fields of plasma screens or light sources¹. There are two types of plasma: thermal and non-thermal or cold atmospheric plasma. Thermal plasma has electrons and heavy particles (neutral and ions) at the same temperature. Cold Atmospheric Plasma (CAP) is said to be non-thermal because it has electron at a hotter temperature than the heavy particles that are at room temperature. . Cold Atmospheric Plasma is a specific type of plasma that is less than 104°F at the point of application⁴. So the bright future of dentistry with help of cold plasma.

Key word:- cold plasma, non thermal atmospheric plasma,

I. Introduction

The British physicist Sir William Crookes identified the fourth state of matter in 1879. It was termed “plasma” by Irving Langmuir in 1929. Plasma is a collection of stripped particles. When electrons are stripped from atoms and molecules, those particles change state and become plasma. Plasmas are naturally energetic because stripping electrons takes constant energy. If the energy dissipates, the electrons reattach and the plasma particles become a gas once again¹. Plasma, referred to as the fourth state of matter. The other states of matter are liquid, gas, and solid (Figure 1)⁴.



Physical plasma is defined as a gas in which part of the particles are present in ionized form. This is achieved by heating a gas which leads to the dissociation of the molecular bonds and subsequently ionization of the free atoms. Thus, plasma consists of positively and negatively charged ions and negatively charged electrons as well as radicals, neutral and excited atoms and molecules^{2&3}

Plasma not only occurs as a natural phenomenon as seen in the universe in the form of fire, in the polar aurora borealis and in the nuclear fusion reactions of the sun but also can be created artificially which has gained importance in the fields of plasma screens or light sources¹.

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said to be non-thermal because it has electron at a hotter temperature than the heavy particles that are at room temperature. CAP is a specific type of plasma that is less than 104°F at the point of application⁴.

II. History

The English physicist Sir William Crookes identified plasmas in 1879, although it was an American physicist, Dr Irving Langmuir who first applied the word ‘plasma’ to ionized gas in 1929. In the late 1850s, the Siemens company used plasma discharge to generate ozone, which acted as an agent to remove contaminants and toxins from water. Nevertheless, for the next 100 years, little research was conducted exploring the relationship between plasma and biological cells. From the 1960s to 1980s, plasmas were mainly utilized as a secondary agent to indicate biological sterilization, yet diminutive cause and effect knowledge was advanced. It was not until the mid- 1990s that scientists made considerable progress in cold plasma technology. As the news of plasma science spread, visionary researchers took notice and began to explore various ways to utilize plasma’s unique properties. Plasma science was in its infancy in the 1990s, but by 1997, multidisciplinary teams set out to understand the effects that plasmas had on pathogenic and nonpathogenic microorganisms, as well as develop proof of concept studies to demonstrate that plasma could be used as a decontaminant or sterilizing agent. Since the late 1990s, plasma research has evolved at a rapid pace as technology expanded into areas, such as biomedical, environmental, aerospace, agriculture and the military^{5&6}.

Non Thermal Atmospheric Plasma

Low temperature plasma, also known as cold plasma, is used in the modification of biomaterial surfaces. It is characterised by a low degree of ionization at low or atmospheric pressure⁷⁻⁹. Low temperature plasma is created by the conversion of a compound into gas followed by ionization by applying energy in the form of heat, direct or alternating electric current, radiation or laser light. Oxygen, nitrogen, hydrogen or argon are the commonly used plasma gas sources. In material science, the possible applications of low-temperature plasmas include the modification of surface properties like electrochemical charge or amount of oxidation as well as attachment or modification of surface-bound chemical groups. Consequently, properties like hardness, resistance to chemical corrosion or physical abrasion, wettability, the water absorption capacity as well as the affinity towards specific molecules can be modulated specifically and precisely by the use of low temperature plasmas¹⁰. Non-thermal Atmospheric Plasmas are very efficient in the deactivation of bacteria. A relatively new area is the use of these plasmas in dental applications. Plasma treatment is potentially a novel tissue-saving technique, allowing irregular structures and narrow channels within the diseased tooth to be cleaned. Low-temperature plasma is a promising method for destroying microorganisms, an alternative to conventional methods which have numerous drawbacks¹¹.

III. Mechanism Of Generation Of Cold Plasma

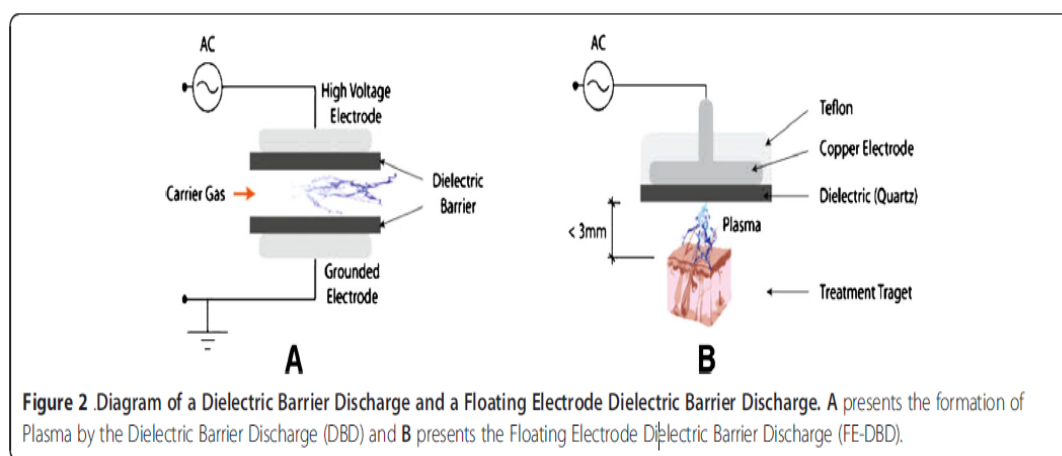
Plasmas can be produced by various means, e.g. radio frequency, microwave frequencies, high voltage ac or dc, etc. The main body of the device is made of a medical syringe and a needle. They are used for guiding the gas flow. The needle also serves as the electrode, which is connected to a high-voltage (HV) submicrosecond pulsed direct-current (dc) power supply (amplitudes of upto 10 kV, repetition rate of upto 10 kHz, and pulse width variable from 200 ns to dc) through a 60-kΩ ballast resistor R and a 50-pF capacitor C, where both the resistor and the capacitor are used for controlling the discharge current and the voltage on the needle. Because of the series-connected capacitor and the resistor, the discharge current is limited to a safety range for a human. It is found that, if the resistance of R is too small or the capacitance of C is too large, there is feeling of weak electric shock when the plasma is touched by a human [12]. The diameter of the syringe is about 6mm, and the diameter of the syringe nozzle is about 0.7mm. The needle has an inner diameter of about 200µm and a length of 3cm. Working gas such as He, Ar, or their mixtures with O₂ can be used. The gas flow rate is controlled by a mass-flow controller¹². When working gas such as He/O₂ (20%) is injected into the hollow barrel of the syringe with a flow rate of 0.4 L/min and the HV pulsed dc voltage is applied to the needle, homogeneous plasma is generated in front of the needle. finger can directly contact with the plasma or even with the needle without any feeling of warmth or electric shock. Therefore, this device is safe for the application of root-canal disinfection¹².

IV. Methods Of Production

Several different types of CAP have been developed for biomedical uses. Energy is needed to produce and maintain plasma. Thermal, electric, or light energy can be used. Usually, the discharge needed to produce CAP is induced electrically. Some methods used to produce CAP include: Dielectric Barrier Discharge (DBD), Atmospheric Pressure Plasma Jet (APPJ), Plasma Needle, and Plasma Pencil.

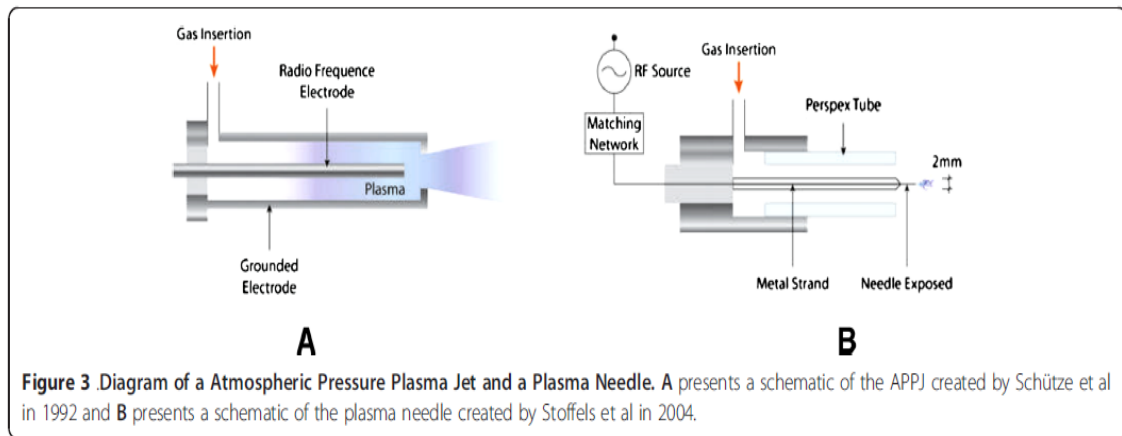
Dielectric Barrier Discharge

In 1857, Siemens was first to conduct experiments on Dielectric Barrier Discharge (DBD). DBD has many applications including: sterilization of living tissue, bacteria inactivation, angiogenesis, surface treatment, and excimer formation^{13,14}. The dielectric barrier discharge (DBD) consists of two flat metal electrodes that are covered with dielectric material. A carrier gas moves between the two electrodes and is ionized to create plasma. One electrode is a high voltage electrode and the other is a grounded electrode. High voltages are required to produce the discharge needed to create the plasma. Alternative Current (AC) high voltages generally drive DBD's with frequencies in the kHz range. The power consumption is between 10 and 100 W¹⁵. There are many variations in the configuration of the electrodes, but the concept behind them all remains the same. For example, some electrodes are cylindrical instead of flat and sometimes the dielectric material covers only one electrode instead of both. More recently, Fridman et al. developed the floating electrode DBD (FE-DBD)¹⁶. It is similar to the original DBD and consists of two electrodes: an insulated high voltage electrode and an active electrode. The difference between FE-DBD and DBD is that the second electrode is not grounded; it is active meaning that the second electrode can be human skin, a sample, and even an organ. The powered electrode needs to be close to the surface of the second electrode (< 3mm) to create the discharge. It has been used on endothelial cells, melanoma skin cancer, and blood coagulation. It has also been used in living tissue sterilization and in deactivation of *Bacillus stratosphericus* (Figure 2)¹⁷. Plasma jets using a DBD system have also been created¹⁸



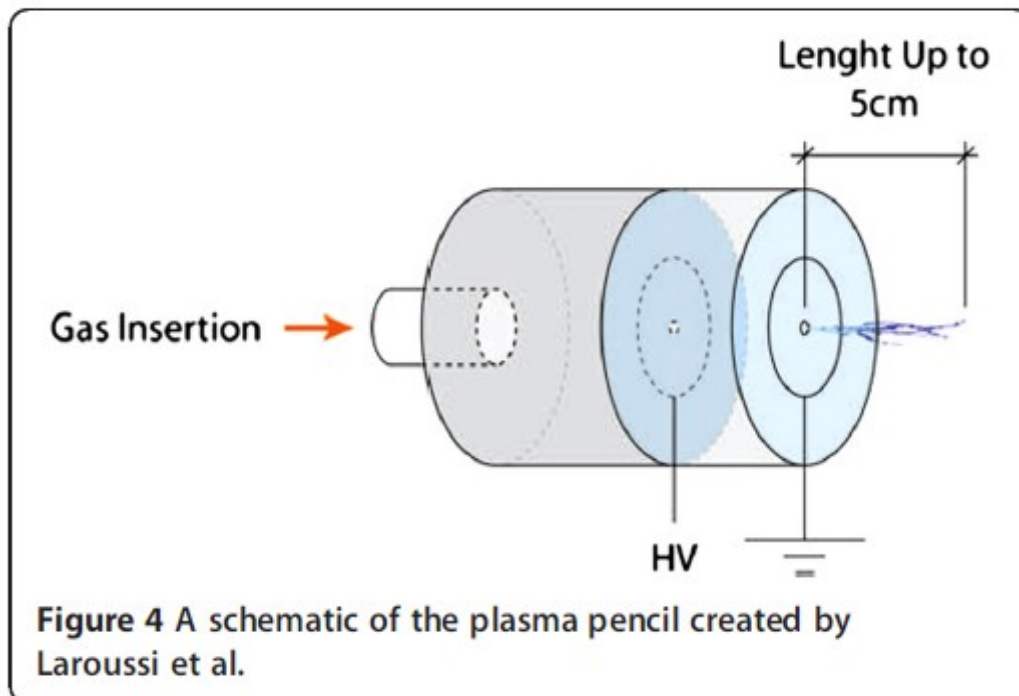
Plasma Jet-Radio Frequency Plasma Jets

One type of plasma jet, which is employed for bacterial sterilization, is the Atmospheric Pressure Plasma Jet (APPJ)¹⁹. The APPJ consists of two coaxial electrodes between which a feed gas (mixtures of helium, oxygen, and other gases) flows at a high rate. The outer electrode is grounded while Radio Frequency (RF) power (50-100W) at 13.56 MHz is applied to the central electrode that creates a discharge. The reactive species produced exits the nozzle at high velocity and arrives to the area that is to be treated. APPJ has been used for the inactivation of several micro-organisms²⁰⁻²³. Koinuma et al. developed the earliest RF cold plasma jet in 1992²⁴. The cathode is a needle electrode made of tungsten or stainless steel with a 1 mm diameter connected to a RF source (13.56 MHz). The needle electrode lies within a quartz tube whereas the anode electrode is grounded. Depending on the application, helium or argon was mixed with various gases. This group published several papers describing its variants and applications of the plasma jet^{25,26}. In 2002, Stoffels et al. created a miniature atmospheric plasma jet that they called plasma needle²⁷ and created a new version in 2004²⁸. In the former version, the needle was enclosed in a box and as a result, the samples had to be placed inside of the box to be treated. In the new version, the plasma needle consists of a 0.3 mm metal strand diameter with a sharpened tip inside of a Perspex tube. The length of the entire needle is 8 cm and 1.5 cm remains uncovered by the Perspex tube. The gas used most frequently is Helium due to its high thermal conductivity. The gas is then mixed with air at the needle tip where a micro discharge is created. Gases other than Helium are also used²⁹. The diameter of the plasma glow generated is 2 mm. Microplasma is created when RF power at 13.05 MHz ranging between 10 mW and several watts is applied to the needle. Its small size enables it to be used to treat small areas where accuracy is required like in dentistry^{30,31}. It has also been used to deactivate *E. Coli* (Figure 3)³².



Pulsed Direct Current-Driven Plasma Jets

Laroussi et al. developed a miniature jet that they called plasma pencil³³. It consists of a dielectric cylindrical tube of 2.5 cm in diameter where two disk electrodes of the same diameter as the tube are inserted. The two electrodes are separated by a gap (the distance can vary from 0.3 to 1 cm) and consist of a thin copper ring attached to a dielectric disk. To create the plasma, sub-microsecond high voltage pulses are applied between the two electrodes while a gas is injected through the holes of the electrodes. When the discharge is created, a plasma plume is launched through the hole of the outer electrode into the air. Because the plasma plume (up to 5cm in length) remains at low temperature (290K), it can be touched safely. The electrical power is supplied to the electrodes by a high voltage pulse generator. The high voltage is supplied to the pulse generator by a DC voltage supply with variable output. The plasma pencil has been used in the treatment of E. coli, Leukemia cells, and P. Gingivalis³⁴. Forster et al., Zhang et al., and Wash et al. developed a plasma jet using a DBD configuration (Figure 4)^{35,36}.



Applications Of Cold Atmospheric Plasma In Dentistry

Sterilization by eradication of bacteria. The sterilization efficacy of plasma devices is influenced by gas composition, driving frequency, and bacterial strain, but plasma devices have shown to kill a higher proportion of bacteria than do conventional non-thermal methods such as UV sterilization^{37,38}. The mechanism of plasma sterilization is related to the abundance of plasma components, like reactive oxygen species, ions and electrons,

and UV and electromagnetic fields³⁹. Also, plasma can affect not only the contacted point but also the area around it. Recently, plasma sterilization has been used to treat dental diseases⁴⁰. The risk of prior transmission through surgical instruments is of both current public and professional concern. The use of plasma decontamination of surgical instruments is limited. Whittaker et al. has indicated that the use of gas plasma cleaning may be extremely beneficial in reducing the absolute amount of proteinaceous materials that may be transferred between patients when endodontic files are reused⁴¹. Yang Hong Li et al. stated that plasma sterilization, with the advantage of low temperature, fastness, thoroughness, safety, overcomes the deficiency of the traditional sterilization technology, and may become a novel method for killing microbe⁴². Autoclaves and UV sterilizers are presently used to sterilize dental instruments. To develop a dental sterilizer which can sterilize most materials, such as metals, rubbers, and plastics, the sterilization effect of an atmospheric pressure non-thermal air plasma device was evaluated by Su-Jin Sung et al. It was proved that the atmospheric pressure nonthermal air plasma device was effective in killing both *Escherichia coli* and *Bacillus subtilis*, and was more effective in killing *Escherichia coli* than the UV sterilizer⁴³.

Plasma In Dental Cavities

Plasma can treat and sterilize irregular surfaces; making them suitable for decontaminating dental cavities without drilling. Although, plasma itself is superficial, the active plasma species it produces can easily reach inside of the cavity. This approach was pioneered by Eva Stoffels, who suggested the use of plasma needles in the dental cavity on the basis of the ability of plasma to kill *Escherichia coli*⁴⁴. Goree et al., provided substantial evidence that non thermal atmospheric plasmas killed *Streptococcus mutans*, a gram-positive cariogenic bacterium⁴⁵. Sladek et al., studied the interactions of the plasma with dental tissue using a plasma needle⁴⁴. It is an efficient source of various radicals, which are capable of bacterial decontamination; but, it operates at room temperature and thus, does not cause bulk destruction of the tissue. Raymond EJ et al., studied the interactions of the plasma with dental tissue using a plasma needle. Cleaning and sterilization of infected tissue in a dental cavity or in a root canal can be accomplished using mechanical or laser techniques. However, with both approaches, heating and destruction of healthy tissue can occur. A plasma needle is an efficient source of various radicals, which are capable of bacterial decontamination; however, it operates at room temperature and thus, does not cause bulk destruction of the tissue. From his research he concluded that plasma treatment is potentially a novel tissue-saving technique, allowing irregular structures and narrow channels within the diseased tooth to be cleaned¹¹.

Intraoral Diseases

Oral candidiasis includes Candida-associated denture stomatitis, angular stomatitis, median rhomboid glossitis, and linear gingival erythema. Koban et al. and Yamazaki et al. reported the high efficiency of *Candida albicans* sterilization using various plasmas. Their result indicates the possibility that stomatitis caused by *Candida albicans* can be cured by plasma jets^{46,47}.

Root Canal Sterilisation

Lu et al., used a reliable and user-friendly plasma-jet device, which could generate plasma inside the root canal. The plasma could be touched by bare hands and directed manually by a user to place it into root canal for disinfection without causing any painful sensation. When He/O₂(20%) is used as working gas, the rotational and vibrational temperatures of the plasma are about 300 K and 2700 K, respectively. The peak discharge current is about 10 mA. Preliminary inactivation experiment results showed that it can efficiently kill *Enterococcus faecalis*, one of the main types of bacterium causing failure of root-canal treatment in several minutes⁴⁸. Pan et al., investigated the feasibility of using a cold plasma treatment of a root canal infected with *Enterococcus faecalis* biofilms in-vitro. It was concluded that the cold plasma had a high efficiency in disinfecting the *Enterococcus faecalis* biofilms invitro dental root canal treatment.

Use of Plasma in Composite Restorations

Preliminary data has also shown that plasma treatment increases bonding strength at the dentin/composite interface by roughly 60%, and with that interface-bonding enhancement to significantly improve composite performance, durability, and longevity. Current clinical practice relies on mechanical bonding when it should rely on chemical bonding. The culprit that foils mechanical methods is a protein layer, the so-called “smear layer,” which is primarily composed of type I collagen that develops at the dentin/adhesive junction. To create a porous surface that the adhesive can infiltrate, current preparation techniques etch and demineralise dentin. Interactions between demineralised dentin and adhesive gives rise to the smear layer, which actually inhibits adhesive diffusion throughout the prepared dentin surface. This protein layer may be responsible, in part, for causing premature failure of the composite restoration. It contributes to inadequate bonding that can leave exposed, unprotected collagen at the dentin- adhesive interface, allowing bacterial enzymes to enter and

further degrade the interface and the tissue¹¹. Kong et al., investigated the plasma treatment effects on dental composite restoration for improved interface properties and their results showed that atmospheric cold plasma brush (ACPB) treatment can modify the dentin surface and thus increase the dentin/adhesive interfacial bonding. The solution is to introduce bonds that depend on surface chemistry rather than surface porosity⁴⁹.

Plasma In Tooth Bleaching

A non thermal, atmospheric pressure, helium plasma jet device was developed to enhance the tooth bleaching effect of hydrogen peroxide (H_2O_2). Combining plasma and improved the bleaching efficacy by a factor of 3 compared with using H_2O_2 alone. Tooth surface proteins were noticeably removed by plasma treatment. When a piece of tooth was added to a solution of H_2O_2 as a catalyst, production of OH after plasma treatment was 1.9 times greater than when using H_2O_2 alone. It is suggested that the improvement in tooth bleaching induced by plasma is due to the removal of tooth surface proteins and to increased OH production⁵⁰. Nam et al., used a plasma jet on 40 extracted human molar teeth with intact crowns. The 40 teeth were randomly divided into four groups (n=10) and were treated with Carbamide peroxide + CAP, Carbamide peroxide + Plasma Arc Lamp (PAC), Carbamide peroxide + diode laser, or Carbamide Peroxide alone (control). They observed CAP was the most effective at bleaching teeth. Moreover, they observed that CAP does not damage the tooth due to its low temperature⁵¹. Claiborne D et al., used a plasma plume on extracted human teeth. They observed a statistically significant increase in the whitening of the teeth after exposure to CAP + 36% hydrogen peroxide gel, compared with 36% hydrogen peroxide only, in the 10 and 20 min groups. The temperature in both treatment groups remained under 80°F throughout the study, which is below the thermal threat for vital tooth bleaching⁵². In a study by Jamali and Evans results revealed that prolonged plasma treatment (without bleaching) removed some blue-stain, but the effect was small⁵³. On the contrary, the combination of plasma treatment and bleaching removed most of the blue-stains. It was concluded that vacuum plasma pre-treatment and bleaching showed promise as a way of removing blue-stain.

Post and Core

Yavrich et al., studied the effects of plasma treatment on the shear bond strength between fiber reinforced composite posts and resin composite for core build-up and concluded that plasma treatment appeared to increase the tensile-shear bond strength between post and composite¹¹.

MERITS

Enables the dentist to perform procedures without shots and pain¹¹. Reduces or avoids the use of routinely practiced painful and destructive drilling [12]. Noiseless, painless cavity preparations would be a huge advance¹¹.

SAFE TO USE

The flame is cool to touch without any feeling of warmth or touch¹². It operates at room temperature and does not cause bulk destruction of the tissue, being superior to lasers¹¹.

LIMITATIONS

The technique is highly sensitive⁵⁴. It does not work well in cases where amalgam restoration is present in the oral cavity⁵⁴. Cost of the equipment, marketing, maintenance and availability are also some of the issues at present⁵⁵. Plasma needle technology has a long way to go and shall prove its applicability in the days to come⁵⁴.

V. CONCLUSION

Based on the above evidence, we can say that CAP has a bright future in dentistry due to its anti-microbial properties and its cell death properties on cells. Studies of CAP showed promising results in tooth bleaching, deactivation of biofilms in teeth, instrument sterilization, and in composite restoration. Nevertheless, progress needs to be made concerning the ideal width and depth of the plume of plasma to enable the treatment to reach lower in teeth. However, more studies need to be performed regarding the mechanism of action.

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