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Cold Atmospheric Plasma; Break Through in Dentistry-A Review

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ABSTRACT

Plasma is the fourth state of matter and other states of matter are liquid, gas, and solid. There are two types of plasma: thermal and non-thermal or cold atmospheric plasma. Thermal plasma has electrons and heavy particles at the same temperature, where as non thermal atmospheric plasma or Cold Atmospheric Plasma (CAP) has electron at a hotter temperature than the heavy particles that are at room temperature. CAP is capable of bacterial inactivation and non-inflammatory tissue modification, which makes it an attractive tool for the treatment of dental caries. Due to its anti-microbial properties and its cell death properties, Cold atmospheric plasma has gained a bright future in endodontics. This review focuses on some of the recent studies related to CAP and its clinical applications in conservative dentistry and endodontics.

KEYWORDS Plasma, Thermal Plasma, Cold Atmospheric Plasma (CAP), Root Canal Disinfection, Bleaching, Composite Restoration.

INTRODUCTION

Plasma is the most common form of matter, it makes up for more than 99% of the visible universe.[1] Plasma is a collection of stripped particles. As electrons strip from atoms and molecules, these particles change state and become plasma. Plasmas are naturally energetic because stripping electrons uses constant energy. If the energy dissipates, the electrons reattach and the plasma particles again become a gas.[2] Plasmas can exist in a wide range of temperatures without changing state.[1] CAP is a specific type of plasma that is less than 104°F at the point of application.[2]

The various methods to produce CAP are Dielectric Barrier Discharge (DBD), Atmospheric Pressure Plasma Jet (APPJ), plasma needle, and plasma pencil. Different gases such as Helium, Argon, Nitrogen, Heliox (a mix of helium and oxygen), and air can be used to produce CAP. It has the ability to cause cell detachment which deactivates microorganisms. Researchers have been interested in finding uses for CAP in dentistry.[3] Plasma has been used for medical equipment sterilization, packaging in the food industry, implants, wound healing, blood coagulation, etc. The various dental applications of CAP are treatment of dental caries, sterilization, biofilm elimination, root canal disinfection, increase in bond strength at the dentin/composite interface and bleaching.[1]

HISTORY

In 1879, the British physicist Sir William Crookes discovered plasma, and the name "plasma" was coined in the year 1929 by Irving Langmuir, who was an American chemist.[4,5,6] .Plasmas were mainly used as a secondary agent to indicate biological sterilization from 1960s to 1980s.[2] Plasma science was in its infancy in the 1990s, but by 1997, multidisciplinary teams set out to understand the effects of plasmas on pathogenic and nonpathogenic microorganisms, and to develop proof of concept studies to demonstrate that plasma could be used as a decontaminant or sterilizing agent.[2]

MECHANISM OF GENERATION OF PLASMA

Plasmas can be produced by radio frequency, microwave frequencies, high voltage ac or dc, etc.[2] The main body of the device consists of a medical syringe and a needle, used for guiding the gas flow. The needle 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. As the capacitor and the resistor are connected in series, the discharge current is limited to a safety range for human. It is found that, if the resistance of R is too small or the capacitance of C is too large, a weak electric shock can be felt when the plasma is touched by human.[7]

The diameter of the syringe and the nozzle is about 6mm and 0.7mm respectively. The needle has an inner diameter of about 200μm and a length of 3cm. Working gas such as He, Ar, or their mixtures with O^2 can be used. The gas flow rate can be controlled by a mass-flow controller .[7]

When working gas such as He/O^2 (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. A finger can directly touch the plasma or even needle without any feeling of warmth or electric shock.[7]

APPLICATIONS OF COLD ATMOSPHERIC PLASMA

Sterilization

The main working principle of the plasma sterilization method is based on the generation of certain reactive species such as photons in ultraviolet (UV) wavelength and chemically reactive radicals. These reactive species helps in degradation of the bacterial DNA and destructs the capability of the microorganism's reproduction.[8]

Studies by Mccullagh C et al stated that sterilization efficacy of plasma devices is better than conventional non-thermal methods since the devices have shown to kill a higher proportion of bacteria than conventional non-thermal methods. The mechanism of plasma sterilization is mainly related to the abundance of plasma components, like reactive oxygen species, ions and electrons, and UV and electromagnetic fields. Plasma can affect both the contacted point and the area around it.[1,9,10]

E. coli is a pathogen causing focal or systemic infections, it is easily cultured as a gram-negative rod and has a significant resistance to various sterilization methods. Also spore-forming gram-positive rod B. subtilis , has a higher resistance to sterilization than gram-negative bacteria. Thus B. subtilis is currently used as a biological indicator to check sterilization efficacy. In a study done by Su-Jin Sung and et al showed that the application of cold atmospheric plasma decreased the CFUs for both E. coli and B. subtilis.[11]

Dental caries

Raymond E. J. et al studied the interactions of the plasma with dental tissue using a plasma needle (fig 1). Cleaning and disinfection of infected tissue in a dental cavity or in a root canal can be performed 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 helps in bacterial decontamination. As it operates at room temperature, it does not cause bulk destruction of the tissue. From his study he concluded that plasma treatment is potentially a novel tissue-saving technique, allowing irregular structures and narrow channels within the diseased tooth to be cleaned.[4]

The short-lived chemical species in gas phase produced by the plasma needle can interact on a tooth's surface, and they can dissolve into a liquid. Unlike liquid rinses with bactericidal ingredients that linger in the mouth after treatment, the plasma needle produces bactericidal agents locally, which can reach the inside of the cavity and fissure spaces[12]

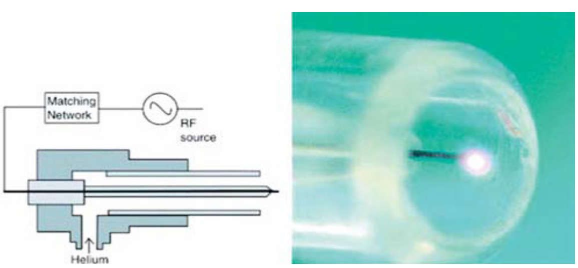

Fig 1. Schematic drawing of the plasma needle set-up (left) and plasma generated by the plasma needle (right)[4]

Root canal disinfection.

Lu et al in his study used a plasma-jet device, which could generate plasma inside the root canal (fig 2). The plasma could be directed manually by a user into root canal for disinfection without causing any painful sensation. When Helium/Oxygen(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. Experiment results showed that it can efficiently destruct enterococcus faecalis, one of the main bacterium causing root-canal failure.[4,12]

Yinglong et al performed an invitro study to evaluate cold plasma treatment in disinfecting 3- week root canal enterococcus faecalis biofilm. In this study teeth with three weeks "e" faecalis biofilm were treated with cold atmospheric plasma with various treatment times and compared with those treated with calcium hydroxide, 2% chlorhexidine gel, and $Ca(OH)^2$ /chlorhexidine for a week. Antimicrobial efficacy was assessed by colony forming unit method. The results showed all groups acquired a CFU reduction compared with control group, but only the plasma group (exposure time for 12 minutes)was able to kill E. faecalis biofilm completely.[13]

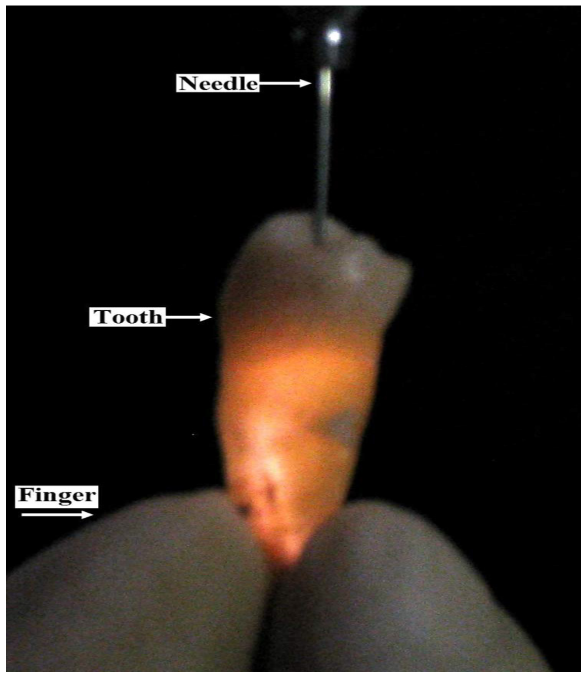

Fig 2: Photograph of the plasma generated inside the root canal of teeth[7]

Composite restoration.

Studies has shown that plasma treatment increases bonding strength at the dentin/ composite interface by about 60 percent. This interface-bonding enhances composite performance, durability, and longevity.[12]

The modern day, clinical practice relies on mechanical bonding rather than chemical bonding. The culprit that foils mechanical methods is a protein layer, known as "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 for causing premature failure of the composite restoration. It contributes to inadequate bonding that can leave, unprotected collagen exposed at the dentin- adhesive interface, allowing bacterial enzymes to enter and further degrade the interface and the tissue.[2]

Dr. Kong and his colleagues studied the plasma treatment effects on dental composite restoration for improved interface properties and their experimental results concluded that plasma brush, fig 3(The apparatus applies small amounts of electricity to a nontoxic gas through a "narrow slit chamber" to generate plasma with a brush-like shape)[6] 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 porosity.[12]

It is mentioned that the majority of non thermal atmospheric plasma devices reported in dental studies have been based on oxygen- containing feeding gases, such as ambient air, O_2, H_2O_2 and H_2O. A few studies included vaporized triethyleneglycol dimethacrylate, a relatively hydrophobic monomer (compared with hydroxyethylmethacrylate [HEMA]) in the feeding gas, and verified triethyleneglycol dimethacrylate deposition on dental ceramic surfaces. In addition, adjustment of feeding gas to a fluoride-containing compound such as SF_6 resulted in plasma affording hydrophobic properties to surfaces. So far, such hydrophobic rendering of tooth surfaces has not been reported yet, but it has the intriguing potential to address the overhydrophilicity of current dental adhesives by compatibilizing tooth surface with more hydrophobic bonding systems. It may enhance the penetration of hydrophobic components (e.g.,bisphenol A and glycidyl methacrylate [BisGMA]) into dentin, resulting in stronger bonding and better sealing.[14]

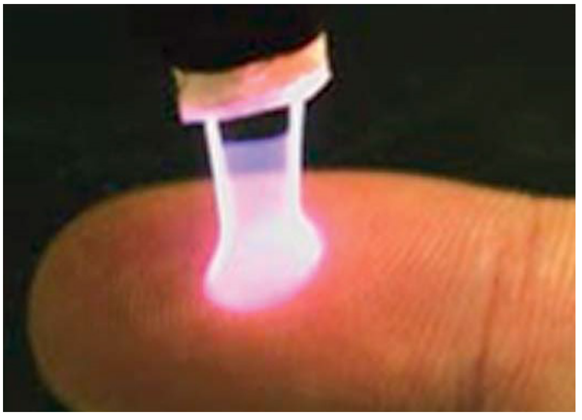

Fig 3: plasma brush.[4]

Tooth whitening.
Lee et al. showed that cold atmospheric plasma in place of light sources bleached teeth(fig 4) by increasing the OH radicals generation and surface protein removal. Furthermore, Lee et al. also showed that in combination with hydrogen peroxide, this plasma removed stains from extracted teeth stained by either coffee or wine . The tooth bleaching method using an atmospheric pressure jet shows reasonable promise of becoming practical in the future. Tooth whitening can also be achieved using a DC plasma jet and hydrogen peroxide.[1]

Plasma along with H_2O_2 showed high bleaching efficacy than H_20_2 alone.[15] The non- thermal atmospheric pressure plasma tooth bleaching device provides a high bleaching effect with a low concentration of Hydrogen Peroxide. It could replace conventional light sources that have limitations, such as questionable bleaching efficacy and high temperatures.[16]

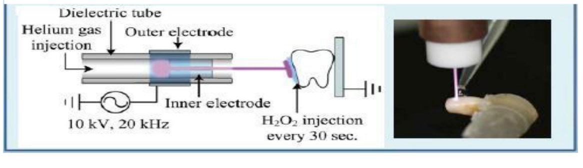

Fig 4:Schematic representation of a plasma apparatus for enhanced tooth bleaching.[15]

Biofilms
Koban I et al studies showed treatment of single and multispecies dental biofilms on titanium discs with non-thermal atmospheric pressure plasma was more efficient than CHX application in vitro.[17]

List of Various uses of CAP in dentistry in general[3]

Deactivation of biofilms	Tooth bleaching	Instrument sterilization	Composite restoration
S. mutans	Hydrogen Peroxide + CAP enhanced the tooth Bleaching	Removal of biofilms on microstructures titanium	CAP treatment increases dentin/ adhesive interfacial Bonding
B. cereus and G. Stearothermophilus	CAP + saline		
L. acidophilus and S. mutans	Carbamide Peroxide + CAP	Dental instruments	CAP treatment improves the tensile-shear bond strength between post and composite
P. Gingivalis	Plasmplume + 36%"H^2O^2 gel on extracted teeth	Ti discs inoculated with biofilms	
S. mutans			
Root canal disinfection			
E. coli, L. casei, S. mutans and C. albicans on agar and dentine plates			
E. faecalis in the root canal			
Ex-vivo biofilms on root canals of extracted teeth			

Table .1

DISCUSSION
Plasma is a gaseous medium which penetrates into irregular cavities and fissures. When compared to laser beams, which propagate linearly, plasma has many useful advantages in its application to oral tissues. Moreover, plasma has the strong advantage that it destroys only pathogens in bacterial plaque on oral tissues, without harming the normal tissue.[1]

Non-thermal atmospheric pressure plasma equipment was used to kill E. faecalis biofilm incubated for 3 weeks. No cultured bacteria were recovered from the agar plate after 12 minutes of treatment, which indicates that the E. faecalis biofilm was destroyed completely.[13] Plasma is painless in patients, as it does not induce thermal damage. Since, oral diseases are caused by different pathogens; research must be conducted as to whether non thermal atmospheric plasmas can also kill various other oral pathogens at the same time. Considering all the properties of plasmas, such as its sterilizing effect, blood coagulation, wound healing, and tooth bleaching, the application of plasma to oral tissues is potentially a fascinating novel technique in dental care. Based on known physical and biological properties of plasma, it is worthwhile to speculate that a number of dental applications are possible, but fundamental principles of how plasma influences cells and effect time needs further investigation.[1]

LIMITATIONS
The technique is highly sensitive. It does not work well in cases where amalgam restoration is present in the oral cavity. Cost of the equipment, marketing, maintenance and availability are also some of the issues at present. Plasma

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needle technology has a long way to go and shall prove its applicability in the days to come.[18]

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.2 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.2 Although plasma technology isn't an end-all to all the techniques we perform, it could well become a valuable tool.4

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