Transient Spark for Bacterial Cleaning of Dental Microcavities

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ABSTRACT: We present a method to disinfect microcavities such as tooth root canals. With the aim of being introduced inside of the root canal, parameters are chosen to produce reactive oxygen species that inactivate bacteria and cause little to no temperature increase within the canal. We demonstrate the device's effects on bacteria with the use of *Escherichia coli* spread on agar in a Petri dish.

KEY WORDS: plasma, atmospheric pressure, tooth, disinfection, reactive oxygen species, transient spark

I. INTRODUCTION

The application of atmospheric plasma on a biological medium started when Laroussi demonstrated its efficacy for sterilization purposes.¹ Later on, Stoffels et al.² showed that the application of low-power atmospheric plasma to living tissue was possible without its destruction from thermal energy, thus pioneering the field of plasma medicine. Since then, many different systems have been developed to generate atmospheric plasma.³ In fact, the use of atmospheric plasma has expanded so much that plasma medicine has become a vast research area. One of the most advanced topical applications is the treatment of skin wounds for cleaning and accelerating healing.^{4–6} One of the most fascinating applications has been documented by its promising results in the fight against cancer.^{7–9}

Atmospheric gas discharges can be categorized as either direct or indirect, or whether their electrical characteristics are driven by direct current, pulse power or radio frequency. Another way to categorize atmospheric plasmas is by their shape. In fact, plasmas can fill the volume between two electrodes, cover the surface of an electrode array to be brought close to the substrate¹⁰ (one of which can be a part of the body to be treated), or streamed out of the source and directed at the substrate.¹¹ The latter is termed plasma jet. Ultimately, the choice of the system depends on the application.

One field of application for atmospheric plasma jets is decontamination of the root canal of a tooth during endodontic therapy. Due to the complex shape and tiny dimensions of a root canal, of the many different sources of atmospheric plasma, treatment is *a priori* best achieved with a plasma jet operated inside of the canal.¹¹ When the root

canal is infected, a dentist devitalizes the tooth by removing the pulp from the infected canal. By doing so, eventual biofilms are also removed. Afterward, a solution of NaOCl or CHX is usually used to deactivate remaining bacteria. However, it has been shown¹² that bacteria penetrate dentinal tubules, in which they find ecological niches to survive (see Fig. 1). Due to the size of the tubules (a few micrometers in diameter), surface tension of the solution and resulting capillary forces at play make it nearly impossible to fully clean the tubules. As a consequence, in $\sim 40\%$ of cases, symptoms reappear and further treatment is necessary.^{13,14} Additionally, an adverse effect of chemical root canal disinfection is caused by the extrusion of NaOCl, which can lead to a burning sensation, nose bleeds, or severe facial pain and/or swelling or necrosis of soft and hard tissue.^{15,16}

Atmospheric plasma creates radicals that have proven to be very effective at destroying bacteria.^{17,18} Because plasma radicals are gaseous species, and due to their perdurance, they can remain active after diffusing through liquids,¹⁹ so they may endure in dentinal tubules. Thus, these radicals seem to be predisposed for root canal disinfection.²⁰

This work presents the development of a transient spark-driven plasma jet, its electrical characteristics, the relative number of radicals produced, and first qualitative results in a Petri dish using *Escherichia coli*.

FIG. 1: Scanning electron microscope image of bacteria entering dentinal tubules

II. EXPERIMENTAL SETUP

The device is comprised of a grounded, stainless steel, 1-mm outer-diameter needle, with a 400- μm -diameter copper wire introduced inside the needle and insulated apart from its two ends to allow current flow. It can be powered by a DC power source (PNC 3500-50 UMP; Heinzinger; Rosenheim, Germany) directly or by a pulse power source. In the latter case, pulses are created from a custom-made electrical circuit that converts power from a high-voltage, low-current, DC power source to short pulses of higher-current amplitude. The electronic circuit is presented schematically in Fig. 2.

A pulse generator of low voltage and low current (we use a Tektronix AGF 2021; Beaverton, OR, USA) drives an insulated gate bipolar transistor (IGBT) that controls pulse frequency and width. Current pulse values are controlled by adjusting voltage output of the DC power source (Heinzinger PNC 3500). Overall, the custom-made DC pulse power source (pulse generator + custom-made electronic circuit + DC power source) delivers current pulses of variable amplitude, frequency, and width. We monitored electri-

FIG. 2: Schematic of the custom-made pulse generator electrical circuit. Resistance R_1 , 200 Ω ; resistance R_2 , 7.3 k Ω ; R_m resistance, 1 Ω (allows measurement of total current with an oscilloscope); capacitor, 1 μF ; and IGBT with G (Gate), D (Drain or Collector), E (Emitter). The DC power supply is plugged between HV^+ (High voltage positive) and HV^- (High voltage negative).

cal behavior of the transient spark using an oscilloscope (Tektronix TDS 2012B). Here, current value during pulses was constant and set to a few tens milliamperes. We used either helium (99.996%) or nitrogen (99.999%) gas and an electronic mass flow controller (Brooks Instrument 5850E; Hatfield, PA, USA) to adjust gas flow to 1 SLM.

Because heat development during root canal treatment must be controlled, we carried out temperature measurement. For this purpose, the device was placed inside of a root canal model (Endo Trainer, Maillefer; Ballaigues, Switzerland) 2 mm above a temperature sensor (the Pt100 sensor was connected to a multimeter Keithley 2000; Solon, OH [now a Tektronix company]) mounted at the apex of the canal. We recorded temperature while varying electrical parameters of frequency, pulse width, and current. A few sets of parameters were then selected so that the root canal could be heated to a constant temperature of 40°C.

We characterized the plasma jet using optical emission spectra (OES) (Ocean Optics HR2000; Largo, FL, USA) to estimate the presence of radicals at selected parameter sets. The heads of the optical fiber and the device faced each other at 2 mm apart and were placed in a semiclosed volume to emulate the setup in a root canal. We carried out a comparison with and without confinement to estimate whether the production of oxygen radicals suffered from confinement.

For the biological investigation, the device was mounted to spurt contaminated agarose gel into a Petri dish that was contaminated with K12 *E. coli*. Treatment times varied from 30 s to 8 min.

III. RESULTS

A. Electrical Characteristics

Figure 3 shows a typical current pulse of 5 μ s and 97 mA. Brief oscillations can be observed in the first 300 ns. The shape of oscillations is independent of frequency and pulse width; peak values depend only slightly on the set voltage. Thus, current oscillation originated from electronic regulation of the IGBT.

Integrating current and applied voltage over pulse width, one can deduce the energy of a pulse, which here is in the range of a few microjoules. Multiplying pulse current and voltage with the duty cycle, one can determine the average discharge power. Those properties are used to evaluate the parameter that drives the formation of radicals.

B. Relationship between Electrical Parameters and Heat Development in a Root Canal

Figure 4 shows the plasma jet developing inside of a modeled root canal. The plasma jet heats its environment even more so when placed within a semiclosed volume such as a root canal. There, the temperature must not exceed 40°C for a prolonged time, so that protein-based dentin and surrounding vital tissues remain unaltered.²¹

FIG. 3: Typical current pulse of width 5 μs and amplitude 97 mA

Frequency and pulse width varied from 10 Hz to 50 kHz and from 1 or 2 μs to 5 μs , respectively. For each combination, we adjusted and set voltage, current, and thus power so that the temperature in the apical region of the root canal remained at 40°C. The jet was introduced inside the root canal down to 2 mm above the temperature sensor. Temperature rose upon ignition, and although the plasma jet operated within a semiclosed environment, temperature stabilized within a few seconds.

FIG. 4: N₂ plasma jet in a root canal model

Figure 5(A) displays the voltage–current profile of helium discharge for various combinations of frequency and pulse width. The figure indicates that discharge resistance decreases as current increases. This is expected because discharge resistance depends on ionization rate, which in turn dictates the current developing through the discharge. Figure 5(B) displays voltage against duty cycle, varying here from 5% down to 0.001%, when power is set so that heat development remains constant in the root canal. It shows—as expected—that as duty cycle increases, power must be reduced to hold temperature constant. Hence, average pulse power is the key parameter driving heat development caused by the plasma jet. Figure 5 suggests that, at a given frequency, the longer the pulse, the hotter the plasma jet; hence, to remain at a chosen temperature, voltage must be reduced as pulse width increases. Similarly, for a given pulse width and temperature, voltage must reduce as frequency increases. The same correlations apply to nitrogen discharges. However, because helium heat capacity is much higher than that

FIG. 5: Voltage versus current (A) and voltage versus duty cycle (B) for various frequency/pulse width combinations with the current adjusted, so that the temperature in the root canal remains constant (40°C). Results are obtained with helium.

of nitrogen, the voltage applied to keep the temperature constant must be reduced for nitrogen discharge compared to helium.

C. OES

OES were recorded for the pulse-powered plasma jet. Frequency, pulse width and current value were set so that the apical region of the modeled tooth remained at a temperature of 40°C. Typical spectra are shown in Fig. 6. OES measurement results show that although discharge is from pure helium and operated within a confined volume, oxygen radicals (OH at 309 nm) are produced. In the case of nitrogen, an OH peak was not observed in either case.

FIG. 6: Typical spectral results using optical emission spectroscopy of He (A) and N₂ (B) plasma jets. Frequency and pulse width are 15 kHz and 5 μ s, respectively, for both, but voltage differs (helium, 870 V; nitrogen, 570 V) so that temperature remains the same.

Figure 7 depicts the influence of current on helium and OH peaks. When current increased, both peaks increased proportionally. The ratio of light intensity emitted from helium ions to that of OH radicals is approximately constant ($\sim 1\%$) for all parameter variations. Because oxygen is not added to the gas, oxygen radicals are not created directly by the discharge; rather, they are produced from the interactions of helium ions with the surrounding air. The figure also shows that a minimum amount of current is required to produce a measurable amount of OH peaks. Because for the same temperature, a higher voltage—hence a higher current—can be applied using helium, the helium plasma jet has a higher radical formation to temperature than does the nitrogen plasma jet.

D. Biological Tests

The bactericidal efficacy of the plasma jet was tested in *E. coli*, which was cultured in a nutritious solution for 24 h before being spread on an *E. coli* and coliforms (ECC) agar plate. The colorless agar turns blue when the Gram-negative bacteria grow on the agar. Figure 8 shows a typical uncolored bacteria-free area on the agar as a result of plasma jet treatment. No effect was observed when only the gases were applied to the agar plate, that is, when the plasma was turned off. We observed that the diameter of the bacteria-free area increased with treatment time.

IV. CONCLUSIONS

For biological applications, atmospheric pressure discharge usually requires the presence of oxygen radicals. Atmospheric pressure discharges using pure gases such as he-

FIG. 7: Intensity of helium and oxygen radical as a function of discharge current for a given set of discharge parameters (1 kHz; 5 μ s)

FIG. 8: K12 *E. coli* contaminated on ECC agar in a Petri dish. The helium plasma jet is positioned 2 mm above. Discharge conditions: 100 Hz, 5 μ s, and 100 mA for 30 s.

lium and nitrogen produce no such species *per se*. However, the produced ions carry enough energy to trigger formation of oxygen radicals when interacting with surrounding air. This explains why the plasma jet kills bacteria on an open surface such a Petri dish, as shown in this work. Because the formation of radicals occurs in a semiclosed space, the same effect can be expected when the device is introduced in a root canal. This remains to be shown and is the topic of ongoing study, along with quantifying bacterial destruction and testing on additional bacteria. In this initial work, we found that a transient spark-driven plasma jet produced a sufficient disinfection effect.

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