An RC Plasma Device for Sterilization of Root Canal of Teeth

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Abstract—The application of cold plasma in sterilization of a root canal of a tooth has recently attracted great attention. In this paper, a reliable and user-friendly plasma-jet device, which can generate plasma inside the root canal, is reported. The plasma can be touched by bare hands and can be 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 show that it can efficiently kill Enterococcus faecalis, one of the main types of bacterium causing failure of root-canal treatment in several minutes.

Index Terms—Atmospheric-pressure plasma, biomedical application, nonequilibrium plasma, plasma jet, root canal, sterilization.

I. INTRODUCTION

BECAUSE of the enhanced plasma chemistry, atmospheric-pressure nonequilibrium plasmas (APNPs) have been widely studied for several emerging applications such as surface and materials processing [1]–[3], biological and chemical decontamination of media [4]–[10], light source [11], [12], absorption and reflection of electromagnetic radiation [13], [14], and synthesis of nanomaterial [15]. Among the novel applications, the biomedical applications of APNPs, such as sterilization, are attracting significant attentions [16]–[22]. For the biomedical applications, plasma-jet devices, which generate plasmas in open space (surrounding air) rather than in confined discharge gaps only, have lots of advantages over the traditional dielectric-barrier-discharge devices. For example, it can be used for root-canal disinfection, which cannot be realized by the traditional plasma device. This is one reason that atmospheric-pressure plasma-jet devices have recently been attracting significant attentions [23]–[30].

II. EXPERIMENTAL SETUP

The schematic of the experimental setup is shown in Fig. 1. 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) submicrowe pulsed direct-current (dc) power supply (amplitudes of up to 10 kV, repetition rate of up to 10 kHz, and pulsewidth variable from 200 ns to dc) through a 60-Ohm ballast resistor $R$ and a 50-pF capacitor $C$, where both the resistor and

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the capacitor are used for controlling the discharge current and the voltage on the needle. We will refer this device as Model RC-1 in the future. 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.

The diameter of the syringe is about 6 mm, and the diameter of the syringe nozzle is about 0.7 mm. The needle has an inner diameter of about 200 $\mu$m and a length of 3 cm. Working gas such as He, Ar, or their mixtures with O$_2$ can be used. The gas flow rate is controlled by a mass-flow controller.

The applied voltages are measured by a P6015 Tektronix HV probe and currents by CT1 Tektronix current probe. The voltage and current waveforms are recorded by a Tektronix DPO7104 wideband digital oscilloscope. The optical emission spectra are measured by a half-meter spectrometer (Princeton Instruments Acton SpectraHub 2500i). The resolution of the spectrum is about 0.4 nm.

III. EXPERIMENT RESULTS

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, a homogeneous plasma is generated in front of the needle as shown in Fig. 2. It is interesting to point out that a 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 disinfection.

The current and voltage waveforms of the discharge are shown in Fig. 4, where $V_a$ is the applied voltage, $I_{tot}$ is the total current (with gas flow: plasma on), and $I_{no}$ is the displacement current (without gas flow: plasma off). It should be mentioned that the voltage waveform remains the same whether the plasma is on or off. This figure clearly shows that the actual discharge current, i.e., the difference between $I_{tot}$ and $I_{no}$, has a peak value of about 10 mA. The displacement current waveform behaves as that of a typical resistor–capacitor (RC) charge and discharge circuit. The voltage on the needle $V_{needle}$ has a peak of about 6 kV. According to the current and voltage waveforms of the discharge, the power deposited into the plasma can be estimated to be less than 0.1 W for applied voltage of 8 kV, pulsedwidth of 500 ns, and pulse frequency of 10 kHz.

When the device is used for root-canal treatment, the gas temperature, which is close to the molecular rotational temperature, needs to be at or close to room temperature. To determine the rotational temperatures of the plasma, the emission spectra of nitrogen second positive system are used. By comparing the simulated spectra of the $^3\Pi_u - ^3\Pi_g (\Delta v = -2)$ band transition of nitrogen with the experimental recorded spectra, the rotational and vibrational temperatures of the nitrogen can be obtained when best fit is achieved [45]. To make comparison, all spectra (experimental and calculated) are normalized to the intensity of the (0–2) band head. First, the rotational temperature is determined with the (0–2) band. Then, vibrational temperature is obtained when best fit is achieved between the simulated and experimental spectra. Fig. 5 shows the simulated
Fig. 3. Photograph of the plasma generated inside the root canal of a tooth. The tooth is held by human fingers. The operation conditions are the same as that of Fig. 2.

Fig. 4. Current and voltage waveforms of the discharge. Applied voltage: $V_a$; voltage on the needle: $V_{\text{needle}}$; total current: $I_{\text{tot}}$ (plasma on); and displacement current: $I_{\text{no}}$ (plasma off). The operation conditions are the same as that of Fig. 2.

and experimental spectra of the plasma. It clearly shows that the simulated spectra at $T_{\text{rot}} = 300$ K and $T_{\text{vib}} = 2700$ K give good fit to the experimental spectra. Such $T_{\text{vib}}$ should be considered only as indicating the nonequilibrium characteristic of the plasma since $T_{\text{vib}}$ is only determined by the three vibrational bands. The gas temperature measured by this method has an error of about ±10 K. However, we are convinced that the gas temperature is at room temperature. It can actually be easily verified by touching the plasma with a finger. The finger does not feel warm at all. However, this optical emission spectra method allows us to determine the vibrational temperature of the plasma at the same time, which cannot be determined by other simple way.

Moreover, to identify the various reactive species generated by the plasma plume, we also measured the emission spectra of the plasma from 280 to 800 nm. For all the recorded spectra, the applied voltage (amplitude of 8 kV, frequency of 10 kHz, and pulsed width of 500 ns), the total gas flow rate of 0.4 L/min (He/O$_2$ (20%)), and the operational parameters of the spectrometer (grating: 1200 g/mm; slit width: 100 μm) are unchanged. Fig. 6(a) and (b) shows the emission spectra from 280 to 800 nm. It clearly indicates that excited O, OH, N$_2$, N$_2^+$, and He are present in the plasma plume. It is well known that species such as O and OH play an important role in the killing of bacteria.

Furthermore, the preliminary inactivation experiment results are presented next. The bacterial samples that are treated by the plasma are prepared as follows: Enterococcus faecalis, one of the main types of bacterium causing failure of root canal treatment, is selected for this experiment. An overnight culture containing approximately $10^8$ CFU/mL is prepared (CFU: colony-forming unit). Then, the culture is diluted to $10^6$ CFU/mL for the experiments. A diluted suspension of 200 μL containing bacterium concentrations of $10^6$ CFU/mL is evenly spread over each agar plate in Petri dish. Afterward, it is treated by the plasma for 4 min immediately. After the plasma treatment, it is incubated for 24 h at 37 °C. For control experiments, the samples are treated by the working gas flowing at the same flow rate with power off. All the experiments reported in this paper are repeated four times, and the results are consistent with the same experimental conditions. For all the inactivation experiments reported in this paper, the pulse frequency of 8 kHz, pulsed width of 500 ns, and applied voltage of 8 kV are fixed. The distance between the Petri dishes and the tip of the needle is also fixed at about 2 mm. Fig. 7(a)–(c) shows the experiment results. Areas where bacteria are killed look like uncontaminated agar (black), while areas that were not affected change color (gray) and appearance significantly
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Fig. 6. Emission spectra of the plasma: (a) 280–500 nm and (b) 500–800 nm. The operation conditions are the same as that of Fig. 2.

Fig. 7. Photographs of Enterococcus faecalis samples on agar in Petri dishes. About 200 μL of the diluted suspension containing bacterium concentrations of $10^6$ CFU/mL is evenly spread over each agar plate in Petri dish. (a) Control experiment with He/O$_2$(20%). (b) Working gas He/O$_2$(20%) (total flow rate of 0.4 L/min). (c) Working gas Ar/O$_2$(20%) (total flow rate of 0.4 L/min). Bacterial samples are about 2 mm away from the needle tip. During the treatment, the Petri dishes are moving along the vertical and horizontal directions across the Petri dishes center to achieve maximum affected areas. The treatment time is 4 min for both (b) and (c).

as the bacteria grow there. As we can see from Fig. 7(a), when the plasma is off, He/O$_2$(20%) gas flow has no effect on the growth of the bacteria. When the plasma is on, Fig. 7(b) shows that the growths of bacteria are affected significantly. Since this device can also be operated with Ar/O$_2$ mixtures, Fig. 7(c) shows the inactivation experiment when Ar/O$_2$(20%) is used. According to Fig. 7(b) and (c), the inactivation efficacy has no obvious difference between He/O$_2$(20%) and Ar/O$_2$(20%). To save space, the control experiment results for Ar/O$_2$(20%) are not shown here since they look similar with that of Fig. 7(a).

Finally, the preliminary experimental results on real disinfection of the tooth root canal with this device are reported. The experimental procedure is described as follows: six extracted single-rooted teeth with straight canals were selected. All tooth root canals were enlarged to a size of 50# (International Organization for Standardization) with Ni–Ti hand instruments. Before inoculation, the specimens were sterilized by an autoclave. Then, a 10-μL bacterial suspension of $10^6$.CFU/mL Enterococcus faecalis and a 10-μL brain heart infusion broth were inoculated into six of the prepared root canals using sterile microsyringes. Next, the samples were incubated for 24 h under anaerobic conditions at 37 °C in anaerobic bags. After incubation, a residual medium inside the root canals was removed with sterile paper points. Afterward, the six infected teeth were randomly assigned to either a positive control (three samples) or a plasma treatment group (three samples). For the positive control group, the samples were treated by the flowing gases for 10 min with plasma off. For the plasma treatment group, the samples were treated by the plasma for 10 min. The operating conditions of the plasma were the same as that of Fig. 2. After the treatment, the samples were rinsed with 1-mL physiological saline for about ten times. Next, a 50-μL collected suspension was seeded onto each agar plate. The plates were incubated for 24 h in anaerobic atmosphere at 37 °C, and CFU of each plate was calculated. The results show that the CFUs for the three positive controls are 263, >300, and >300 (too many to be counted), respectively. The CFUs for the three plasma-treated samples are 1, 2, and 4, respectively. About 2-log reduction is achieved, but the root canals were not completely sterilized in this experiment. We are optimizing our experimental procedure, and we wish that we will have better experimental results in the near future.

IV. CONCLUSION

In conclusion, a cold plasma-jet device is reported. The HV electrode of the device is connected to the pulsed dc voltage power supply through the series-connected capacitor and resistor. The device can generate a plasma inside the root canal of the tooth without causing any harm. The gas temperature of the plasma is at room temperature. Preliminary inactivation experiment results show that it can efficiently kill Enterococcus faecalis, one of the main types of bacterium causing failure of root-canal treatment in several minutes.
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