# An RC Plasma Device for Sterilization of Root Canal of Teeth

**Article** *in* IEEE Transactions on Plasma Science · May 2009

DOI: 10.1109/TPS.2009.2015454



Xinpei Lu
Huazhong University of Science and Technology


Qing Xiong
Wuhan University


Zilan Xiong
University of California, Berkeley


Y. Xian
Huazhong University of Science and Technology

# An $RC$ Plasma Device for Sterilization of Root Canal of Teeth

Xinpei Lu, *Senior Member, IEEE*, Yinguang Cao, Ping Yang, Qing Xiong, Zilan Xiong, Yubin Xian, and Yuan Pan

***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/$O_2$ (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].

Manuscript received December 30, 2008; revised February 2, 2009 and February 8, 2009. First published April 3, 2009; current version published May 8, 2009. This work was supported in part by the National Natural Science Foundation under Grant 10875048 and in part by the Chang Jiang Scholars Program, Ministry of Education, People's Republic of China.

X. Lu, Q. Xiong, Z. Xiong, Y. Xian, and Y. Pan are with the Nuclear Fusion and Advanced Electromagnetic Technology Key Lab, Ministry of Education, and the College of Electrical and Electronic Engineering, Huazhong University of Science and Technology, Wuhan 430074, China (e-mail: luxinpei@hotmail.com; bear20031284@126.com; xzl729202@163.com; 316982393@qq.com; panyuan@mail.hust.edu.cn).

Y. Cao and P. Yang are with the TongJi Medical College, Huazhong University of Science and Technology, Wuhan 430074, China (e-mail: cyg0729@tjh.tjmu.edu.cn; 175272253@qq.com).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TPS.2009.2015454

For root-canal disinfection, the principal methods include mechanic cleaning, irrigation, laser irradiation, ultrasound, and application of hypochlorite and other antibacterial compounds [31]–[35]. Clinic studies show that there are about 10% of treatment failures when the traditional disinfection methods are used. The failures are mainly due to the presence of bacteria, which cannot be completely sterilized by the methods mentioned earlier [36], [37].

One potential method to improve the disinfection performance is by using atmospheric-pressure cold plasmas. It has been reported that atmospheric-pressure cold plasmas can kill various types of bacteria, virus, and so on [38]–[44]. However, due to the narrow channel shape geometry of a root canal, which typically has a length of few centimeters and a diameter of one millimeter or less, the plasma generated by a plasma-jet device is not efficient to deliver reactive agents into the root canal for disinfection. Therefore, to have a better killing efficacy, a plasma has too be generated inside the root canal. In other words, when plasma is generated inside the root canal, all kinds of reactive agents, including the short-lifetime species, such as charge particles, could play some roles in the killing of bacteria. Therefore, it will probably have much better killing efficacy. In this paper, a reliable and user-friendly plasma-jet device, which can generate plasma inside the root canal of a tooth, 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 heating, electrical shock, or other painful sensation. Preliminary inactivation experiment results show that it can efficiently kill *Enterococcus faecalis*, one of the main types of bacterium causing failure of root-canal disinfection treatment.

The rest of this paper is organized as follows. The experimental setup is described in Section II. Details of the experimental results, including the current and voltage waveforms of the discharge, the emission spectra, and the rotational and vibrational temperatures of the plasma, are presented in Section III. Finally, discussions and conclusions are given in Section IV.

## 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) submicrosecond 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-k$\Omega$ ballast resistor $R$ and a 50-pF capacitor $C$, where both the resistor and

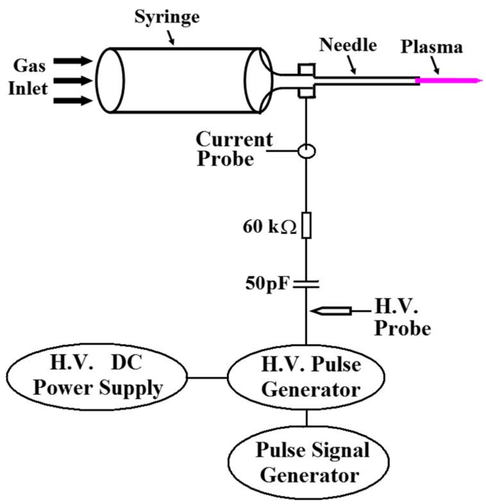



Fig. 1. Schematic of the experiment setup.

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. Fig. 3 shows that the plasma is generated inside the root canal of a tooth with intense light emission. The tooth is held by the fingers.

The current and voltage waveforms of the discharge are shown in Fig. 4, where $V_a$ is the applied voltage, $I_{\text{tot}}$ is the total current (with gas flow: plasma on), and $I_{\text{no}}$ 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

Fig. 2. Photograph of the plasma plume. Applied voltage: 8 kV; pulse frequency: 10 kHz; pulsewidth 500 ns; working gas: He/$O_2(20\%)$; and total flow rate: 0.4 L/min.

current, i.e., the difference between $I_{\text{tot}}$ and $I_{\text{no}}$, 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 $V_{\text{needle}}$ 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, pulsewidth 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 $C^3\Pi_u - B^3\Pi_g(\Delta v = -2)$ 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

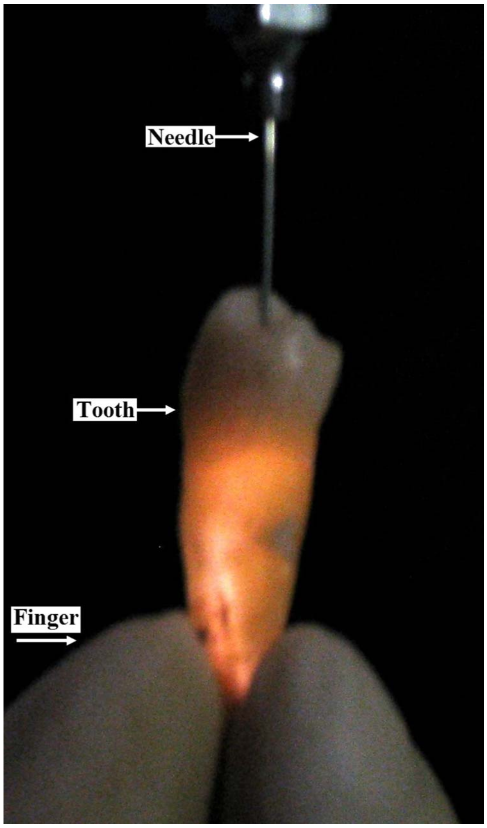



Fig. 3. Photograph of the plasma generated inside the root canal of a tooth. The tooth is held by human fingers. The operation conditions are the same as that of Fig. 2.

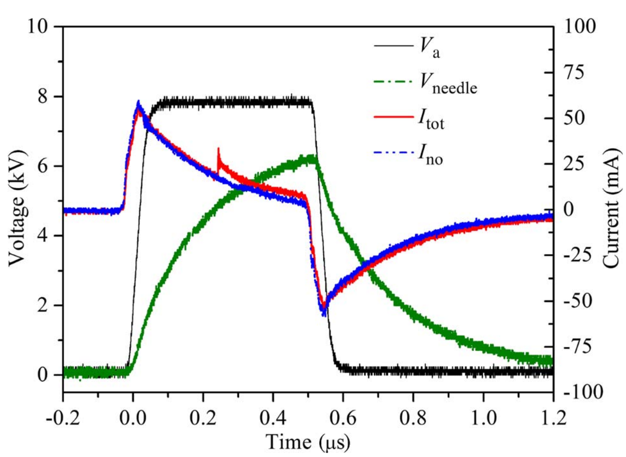



Fig. 4. Current and voltage waveforms of the discharge. Applied voltage: $V_a$; voltage on the needle: $V_{\text{needle}}$; total current: $I_{\text{tot}}$ (plasma on); and displacement current: $I_{\text{no}}$ (plasma off). The operation conditions are the same as that of Fig. 2.

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 $\pm 10$ 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.

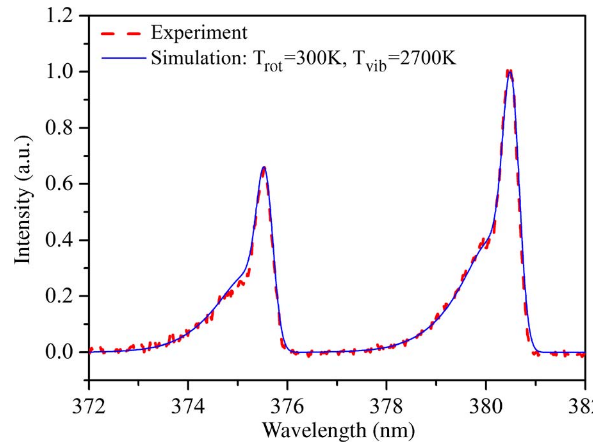



Fig. 5. Experimental and simulated emission spectra of $N_2$ second positive system. The operation conditions are the same as that of Fig. 2. The experimental spectra are from the plasma of 2 mm away from the needle tip.

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 pulsewidth of 500 ns), the total gas flow rate of 0.4 L/min $[\text{He}/\text{O}_2(20\%)]$, and the operational parameters of the spectrometer (grating: 1200 g/mm; slit width: 100 $\mu$m) 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 $\mu$L 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, pulsewidth 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

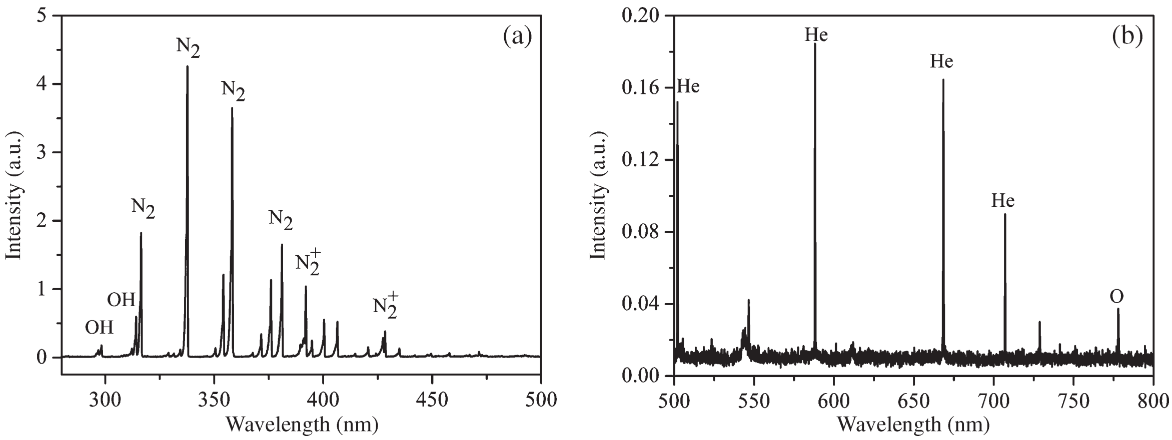



Fig. 6. Emission spectra of the plasma: (a) 280–500 nm and (b) 500–800 nm. The operation conditions are the same as that of Fig. 2.

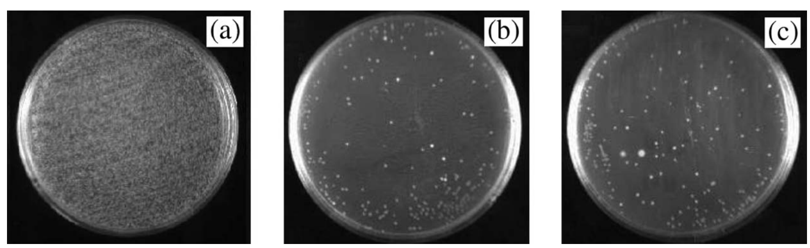



Fig. 7. Photographs of *Enterococcus faecalis* samples on agar in Petri dishes. About 200 $\mu$L of the diluted suspension containing bacterium concentrations of $10^6$ CFU/mL is evenly spread over each agar plate in Petri dish. (a) Control experiment with He/$O_2$(20%). (b) Working gas He/$O_2$(20%) (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-$\mu$L bacterial suspension of $10^6$-CFU/mL *Enterococcus faecalis* and a 10-$\mu$L 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-$\mu$L 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.

## REFERENCES


[1] R. Dorai and M. J. Kushner, "A model for plasma modification of polypropylene using atmospheric pressure discharges," *J. Phys. D, Appl. Phys.*, vol. 36, no. 6, pp. 666–685, Mar. 2003.

[2] P. Chu, "Plasma-treated biomaterials," *IEEE Trans. Plasma Sci.*, vol. 35, no. 2, pp. 181–187, Apr. 2007.

[3] K. N. Ostrikov, S. Kumar, and H. Sugai, "Charging and trapping of macroparticles in near-electrode regions of fluorocarbon plasmas with negative ions," *Phys. Plasmas*, vol. 8, no. 7, pp. 3490–3497, Jul. 2001.

[4] M. Laroussi, "Low temperature plasma-based sterilization: Overview and state-of-the-art," *Plasma Process. Polym.*, vol. 2, no. 5, pp. 391–400, Jun. 2005.

[5] J. Kolb, R. Joshi, S. Xiao, and K. Schoenbach, "Streamers in water and other dielectric liquids," *J. Phys. D, Appl. Phys.*, vol. 41, no. 23, p. 234 007, Dec. 2008.

[6] J. L. Walsh and M. G. Kong, "Contrasting characteristics of linear-field and cross-field atmospheric plasma jets," *Appl. Phys. Lett.*, vol. 93, no. 11, p. 111 501, Sep. 2008.

[7] G. Fridman, A. Brooks, M. Galasubramanian, A. Fridman, A. Gutsol, V. Vasilets, H. Ayan, and G. Friedman, "Comparison of direct and indirect effects of non-thermal atmospheric-pressure plasma on bacteria," *Plasma Process. Polym.*, vol. 4, no. 4, pp. 370–375, May 2007.

[8] Z. Machala, E. Marode, M. Morvova, and P. Lukac, "DC glow discharge in atmospheric air as a source for volatile organic compounds abatement," *Plasma Process. Polym.*, vol. 2, no. 3, pp. 152–161, Aug. 2005.

[9] C. Jiang, A. A. Mohamed, R. H. Stark, J. H. Yuan, and K. H. Schoenbach, "Removal of volatile organic compounds in atmospheric pressure air by means of direct current glow discharges," *IEEE Trans. Plasma Sci.*, vol. 33, no. 2, pp. 1416–1425, Aug. 2005.

[10] P. Bruggeman, L. Graham, J. Degroote, J. Vierendeels, and C. Leys, "Water surface deformation in strong electrical fields and its influence on electrical breakdown in a metal pin-water electrode system," *J. Phys. D, Appl. Phys.*, vol. 40, no. 16, pp. 4779–4786, Aug. 2007.

[11] W. Zhu, N. Takano, K. H. Schoenbach, D. Guru, J. McLaren, J. Heberlein, R. May, and J. R. Cooper, "Direct current planar excimer source," *J. Phys. D, Appl. Phys.*, vol. 40, no. 13, pp. 3896–3906, Jun. 2007.

[12] R. P. Mildren and R. J. Carman, "Enhanced performance of a dielectric barrier discharge lamp using short-pulsed excitation," *J. Phys. D, Appl. Phys.*, vol. 34, no. 1, pp. L1–L6, Jan. 2001.

[13] R. Vidmar, "On the use of atmospheric-pressure plasmas as electromagnetic reflectors and absorbers," *IEEE Trans. Plasma Sci.*, vol. 18, no. 4, pp. 733–741, Aug. 1990.

[14] M. Laroussi, "Interaction of microwaves with atmospheric-pressure plasmas," *Int. J. Infrared Millim. Waves*, vol. 16, no. 12, pp. 2069–2083, Dec. 1995.

[15] K. Ostrikov, "Colloquium: Reactive plasmas as a versatile nanofabrication tool," *Rev. Mod. Phys.*, vol. 77, no. 2, pp. 489–511, Jun. 2005.

[16] T. Shao, P. Yan, K. Long, and S. Zhang, "Dielectric-barrier discharge excitated by repetitive nanosecond pulses in air at atmospheric pressure," *IEEE Trans. Plasma Sci.*, vol. 36, no. 4, pp. 1358–1359, Aug. 2008.

[17] G. Nersisyan and W. G. Graham, "Characterization of a dielectric barrier discharge operating in an open reactor with flowing helium," *Plasma Sources Sci. Technol.*, vol. 13, no. 4, pp. 582–587, Nov. 2004.

[18] K. H. Becker, K. H. Schoenbach, and J. G. Eden, "Microplasmas and applications," *J. Phys. D, Appl. Phys.*, vol. 39, no. 3, pp. R55–R70, Feb. 2006.

[19] F. Leipold, A. Fateev, Y. Kusano, B. Stenum, and H. Bindslev, "Reduction of NO in the exhaust gas by reaction with N radicals," *Fuel*, vol. 85, no. 10/11, pp. 1383–1388, Jul./Aug. 2006.

[20] J. Kolb, A. Mohamed, R. Price, R. Swanson, A. Bowman, R. Chiavarini, M. Stacey, and K. Schoenbach, "Cold atmospheric pressure air plasma jet for medical applications," *Appl. Phys. Lett.*, vol. 92, no. 24, p. 241 501, Jun. 2008.

[21] X. Lu, T. Ye, Y. Cao, Z. Sun, Q. Xiong, Z. Tang, Z. Xiong, J. Hu, Z. Jiang, and Y. Pan, "The roles of the various plasma agents in the inactivation of bacteria," *J. Appl. Phys.*, vol. 104, no. 5, p. 053 309, Sep. 2008.

[22] K. H. Becker, U. Kogelschatz, and K. H. Schoenbach, *Non-Equilibrium Air Plasmas at Atmospheric Pressure*. London, U.K.: IOP Publishing Ltd., 2005.

[23] M. Teschke, J. Kedzierski, E. G. Finantu-Dinu, D. Korzec, and J. Engemann, "High-speed photographs of a dielectric barrier atmospheric pressure plasma jet," *IEEE Trans. Plasma Sci.*, vol. 33, no. 2, pp. 310–311, Apr. 2005.

[24] S. Babayan, J. Jeong, V. Tu, J. Park, G. Selwyn, and R. Hicks, "Deposition of silicon dioxide films with an atmospheric-pressure plasma jet," *Plasma Sources Sci. Technol.*, vol. 7, no. 3, pp. 286–288, Aug. 1998.

[25] J. Shi, D. Liu, and M. Kong, "Effects of dielectric barriers in radio frequency atmospheric glow discharges," *IEEE Trans. Plasma Sci.*, vol. 35, no. 2, pp. 137–142, Apr. 2007.

[26] M. Laroussi and X. Lu, "Room-temperature atmospheric pressure plasma plume for biomedical applications," *Appl. Phys. Lett.*, vol. 87, no. 11, p. 113 902, Sep. 2005.

[27] J. Shi, F. Zhong, J. Zhang, D. Liu, and M. Kong, "A hypersonic plasma bullet train traveling in an atmospheric dielectric-barrier discharge jet," *Phys. Plasmas*, vol. 15, no. 1, p. 013 504, Jan. 2008.

[28] X. Lu, Z. Jiang, Q. Xiong, Z. Tang, and Y. Pan, "A single electrode room-temperature plasma jet device for biomedical applications," *Appl. Phys. Lett.*, vol. 92, no. 15, p. 151 504, 2008.

[29] B. Sands, B. Ganguly, and K. Tachibana, "A streamer-like atmospheric pressure plasma jet," *Appl. Phys. Lett.*, vol. 92, no. 15, p. 151 503, Apr. 2008.

[30] D. Kim, J. Rhee, B. Gweon, S. Moon, and W. Choe, "Comparative study of atmospheric pressure low and radio frequency microjet plasmas produced in a single electrode configuration," *Appl. Phys. Lett.*, vol. 91, no. 15, p. 151 502, Oct. 2007.

[31] M. Colak, S. Evcil, Y. Bayindir, and N. Yigit, "The effectiveness of three instrumentation techniques on the elimination of Enterococcus faecalis from a root canal: An in vitro study," *J. Contemp. Dent. Pract.*, vol. 6, no. 1, pp. 94–106, Feb. 2005.

[32] M. Menezes, M. Valera, A. Jorge, C. Koga-Ito, C. Camargo, and M. Mancini, "In vitro evaluation of the effectiveness of irrigants and intracanal medicaments on microorganisms within root canals," *Int. Endod. J.*, vol. 37, no. 5, pp. 311–319, May 2004.

[33] I. Heling and J. Chandler, "Antimicrobial effect of irrigant combinations within dentinal tubules," *Int. Endod. J.*, vol. 31, no. 1, pp. 8–14, Jan. 1998.

[34] L. Bergmans, P. Moisadis, W. Teughels, B. Meerbeek, M. Quirynen, and P. Lambrechts, "Bactericidal effect of Nd : YAG laser irradiation on some endodontic pathogens ex vivo," *Int. Endod. J.*, vol. 39, no. 7, pp. 547–557, Jul. 2006.

[35] N. Gutknecht, R. Franzen, M. Schippers, and F. Lampert, "Bactericidal effect of a 980-nm diode laser in the root canal wall dentin of bovine teeth," *J. Clin. Laser Med. Surg.*, vol. 22, no. 1, pp. 9–13, Feb. 2004.

[36] U. Sjogren, D. Figdor, S. Persson, and G. Sundqvist, "Influence of infection at the time of root filling on the outcome of endodontic treatment of teeth with apical periodontitis," *Int. Endod. J.*, vol. 30, no. 5, pp. 297–306, Sep. 1997.

[37] L. Peters and P. Wesselink, "Periapical healing of endodontically treated teeth in one and two visits obturated in the presence or absence of detectable microorganisms," *Int. Endod. J.*, vol. 35, no. 8, pp. 660–667, Aug. 2002.

[38] S. P. Kuo, D. Bivolaru, S. Williams, and C. Carter, "A microwave-augmented plasma torch module," *Plasma Sources Sci. Technol.*, vol. 15, no. 2, pp. 266–275, May 2006.

[39] Y. Tang, X. Lu, M. Laroussi, and F. Dobbs, "Sublethal and killing effects of atmospheric-pressure, nonthermal plasma on eukaryotic microalgae in aqueous media," *Plasma Process. Polym.*, vol. 5, no. 6, pp. 552–558, 2008.

[40] J. Goree, B. Liu, D. Drake, and E. Stoffels, "Killing of S. mutans bacteria using a plasma needle at atmospheric pressure," *IEEE Trans. Plasma Sci.*, vol. 34, no. 4, pp. 1317–1324, Aug. 2006.

[41] R. Sladek, E. Stoffels, R. Walraven, P. Tielbeek, and R. Koolhoven, "Plasma treatment of dental cavities: A feasibility study," *IEEE Trans. Plasma Sci.*, vol. 32, no. 4, pp. 1540–1543, Aug. 2004.

[42] E. Stoffels, I. Kieft, R. Sladek, L. Van den Bedem, E. van der Laan, and M. Steinbuch, "Plasma needle for *in vivo* medical treatment: Recent developments and perspectives," *Plasma Sources Sci. Technol.*, vol. 15, no. 4, pp. S169–S180, Nov. 2006.

[43] R. Sladek, E. Stoffels, R. Walraven, P. Tielbeek, and R. Koolhoven, "Investigation of possibilities of plasma treatment for dental caries," in *Proc. 14th IEEE Int. Pulsed Power Conf.*, Dallas, TX, Jun. 15–18, 2003, pp. 1109–1111.

[44] R. Sladek, S. Filoche, C. Sissons, and E. Stoffels, "Treatment of *Streptococcus mutans* biofilms with a nonthermal atmospheric plasma," *Lett. Appl. Microbiol.*, vol. 45, no. 3, pp. 318–323, Jun. 2007.

[45] G. Faure and S. M. Shkol'nik, "Determination of rotational and vibrational temperatures in a discharge with liquid non-metallic electrodes in air at atmospheric pressure," *J. Phys. D, Appl. Phys.*, vol. 31, no. 10, pp. 1212–1218, May 1998.

**Xinpei Lu** (M'06–SM'07) received the Ph.D. degree in electrical engineering from the Huazhong University of Science and Technology, Wuhan, China, in 2001.

From 2002 to 2006, he was a Research Associate with the Applied Plasma Technology Laboratory, Old Dominion University, Norfolk, VA. Since 2007, he has been with Huazhong University of Science and Technology, where he is currently a Professor (ChangJiang Scholar) with the College of Electrical and Electronic Engineering. He is also with the Nuclear Fusion and Advanced Electromagnetic Technology Key Lab, Ministry of Education, Huazhong University of Science and Technology. His research interests include low-temperature plasma sources and their applications, modeling of low-temperature plasmas, plasma diagnostics, discharge in liquid, and pulse power technology. He is the author or coauthor of about 50 scientific articles and the holder of four patents in these areas.

Dr. Lu has served as a Guest Editor of the IEEE TRANSACTIONS ON PLASMA SCIENCE and as Session Chair at the International Conference on Plasma Science for several years.

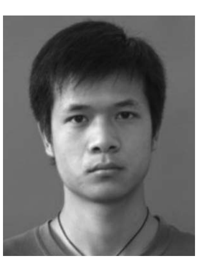
**Yinguang Cao** received the B.S. degree in stomatology from the West China College of Sichuan University, Chengdu, China, in 1984, and the Ph.D. degree from the Medical College, University of Duisburg–Essen, Duisburg, Germany in 2003.

He is currently a Professor and Chief Physician with the Department of Prosthodontics and Implantology, TongJi Medical College, Huazhong University of Science and Technology, Wuhan, China. His research areas include the oral infected disease and alveolar bone regeneration and implantology. He is the author or coauthor of more than 50 scientific articles, reviews, and textbook chapters.

Dr. Cao is the recipient of several awards, including the award of National Natural Science Foundation of China and University Award.

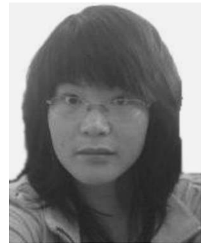
**Ping Yang** is currently working toward the Ph.D. degree in TongJi Medical College, Huazhong University of Science and Technology, Wuhan, China.

Her research interests are focused on the clinic scientific research in prosthodontics, periodontology, and oral implantology.



**Qing Xiong** received the B.E. degree in electrical engineering from Southwest Jiaotong University, Chengdu, China, in 2007. He is currently working toward the Ph.D. degree in the College of Electrical and Electronic Engineering, Huazhong University of Science and Technology, Wuhan, China.

His research interests are focused on the diagnostics and applications of atmospheric pressure nonequilibrium plasma sources.



**Zilan Xiong** received the B.E. degree in electrical engineering in 2008 from Huazhong University of Science and Technology, Wuhan, China, where she is currently working toward the M.S. degree in the College of Electrical and Electronic Engineering.

She is devoted to the study of plasma medicine and the applications of atmospheric pressure nonequilibrium plasma sources.

**Yubin Xian** received the B.S. degree in 2007 from Huazhong University of Science and Technology, Wuhan, China, where he is currently working toward the M.S. degree in the College of Electrical and Electronic Engineering.

His research interests are focused on atmospheric pressure nonequilibrium plasmas and their applications.

**Yuan Pan** received the degree in electrical engineering from Huazhong University of Science and Technology, Wuhan, China, in 1955.

He was with the Institute of 401, the Institute of 585, the Institute of Plasma Physics of CAS, the Joint European Tokamak, and the Fusion Center of University of Texas. He is currently a Professor and the Honorary Dean of the College of Electrical and Electronic Engineering, Huazhong University of Science and Technology. He is also with the Nuclear Fusion and Advanced Electromagnetic Technology Key Lab, Ministry of Education, Huazhong University of Science and Technology. His main research interests include magnetic confinement nuclear fusion, high power pulse source technology, superconducting electric power, and pulse power technology. He is the author or coauthor of about 100 scientific articles in these areas.

Mr. Pan is a member of the Chinese committee of experts of International Thermonuclear Experimental Reactor. He was elected as a member of the Chinese Academy of Engineering in 1997.