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Electrical and Optical Characterization of the Plasma Needle for Use in Biomedical Applications

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ABSTRACT: A plasma needle is a novel design of a plasma source at atmospheric pressure to achieve a nonthermal plasma jet. The advantage of the plasma needle is that it can be operated in open air, outside a vessel. The amount of plasma that is generated by a plasma needle is small (~1 mm), and the plasma is nonthermal. Temperature of the neutral particles and ions is approximately at room temperature, and the particles can suitably interact with living biological cells without damaging the cells. In this work, we report on electrical characteristics and optical emission spectra (OES) of a plasma jet, produced by a direct-current plasma needle that easily interacts with living cells (a human finger). Argon gas is used to run the needle, and the plasma jet is operated on a water-covered agar-gel surface instead of the human finger for stability during characterization. The electrical diagnostics of the plasma needle show that the discharge pulsates. Increased applied voltage increases discharge frequency without affecting discharge voltage or discharge current. The frequency of the discharge is found to increase almost linearly with increasing applied voltage. Using a Boltzmann's plot method from the data collected with OES, we found the estimated excitation temperature was almost independent of the applied voltage.

KEY WORDS: plasma needle, plasma torch, electron temperature, electronic excitation temperature

I. INTRODUCTION

A plasma needle device produces nonthermal, atmospheric pressure, glow discharge plasma. With a single-electrode configuration, the novel design of the plasma source at atmospheric pressure makes it possible to achieve a nonthermal plasma jet.[1–3] The advantage of a plasma needle is that it can be operated in open air, outside a vessel. The amount of plasma that is generated is small (~1 mm), and the plasma is nonthermal**.** Temperature of the neutral particles and ions is approximately at room temperature, and the particles can suitably interact with living biological cells without damaging the cells.[2–9] A plasma needle can be operated within a wide range of frequencies, including radio frequency,[1,10] alternating current (AC),[11–13] and DC (direct current).[2] This type of plasma can operate near room temperature, allows treatment of irregular surfaces, and has a small penetration depth. These characteristics give the needle great potential for use in the biomedical field.

Several experiments have shown that the plasma needle is capable of bacterial decontamination, localized cell removal without causing necrosis to treated or neighboring cells, and cancer-cell ablation.[4–7,9,14–19] It is believed that plasma particles, such as radicals and ions, and emitted ultraviolet light interact with the cell membranes and cell-adhesion molecules, causing cell detachment.[4,21] Due to the plasma needle's nonequilibrium nature, the electron temperature of the plasma needle is quite high (measured in electron volts), but the temperature of heavy plasma particles such as ions and radical neutrals is at room temperature. High-temperature electrons can interact with and destroy living bacteria, microorganisms, or microbes without affecting the living cell/human body as a result of the low energy (due to the low mass of the electrons). We found that the characteristic of electron temperature is necessary for properly implementing, understanding, scaling, and optimizing atmospheric pressure plasma for specific biomedical investigation.

In this work, we report on the electrical characterization and optical emission spectra (OES) of a plasma needle that functions on a DC power supply and can interact with living cells (a human finger). Argon gas is used to run the plasma needle, and the plasma jet is operated on a water-covered agar-gel surface instead of the human finger, for stability during the characterization (assuming that the plasma properties do not change considerably on contact with a human body and the water-covered agar-gel surface). We estimated the excitation temperatures, which also indicate the tentative behavior of plasma electron temperature, by using the Boltzmann plot method from OES data. To measure plasma properties, we also investigated the influence of applied DC voltage, ballast resistance, and the separation between the tip of the needle and the water-covered agar-gel surface.

II. EXPERIMENT

The plasma needle is comprised of a metallic needle covered by a coaxial Teflon tube terminating with a metallic end. Several well-machined Teflon pieces are arranged to feed the gas and electrical connection. The plasma needle, its operation, and components are shown in Fig. 1. The needle is powered by a high-voltage (0–15 kV, continuously adjustable) DC power supply through a ballast resistor (measured on the order of milliohms). A small amount of argon (delivered at a few milliliters per minute) passes through the hole of the metallic end to produce argon plasma. This helps to analyze the spectroscopic data. When a counter electrode such as a human finger or any other object is placed near the needle tip, plasma is produced. To characterize the plasma needle, the plasma jet is operated on a water-covered agar-gel surface for stability. An arrangement is made to adjust the separation between the tip of the plasma needle and the water-covered agar-gel surface. The current is measured by a set of Tektronix (Beaverton, OR) current probes (CT1, TCP 312A, and TCPA 300). Discharge voltages at the electrode are measured by a Tektronix voltage probe (P6015A). Voltage and current data are recorded with the help of a Tektronix oscilloscope (MDO 3034). The light from the plasma is collected by focusing a fiber optic cable and feeding it to an ASEQ Instruments (Vancouver, Canada) universal

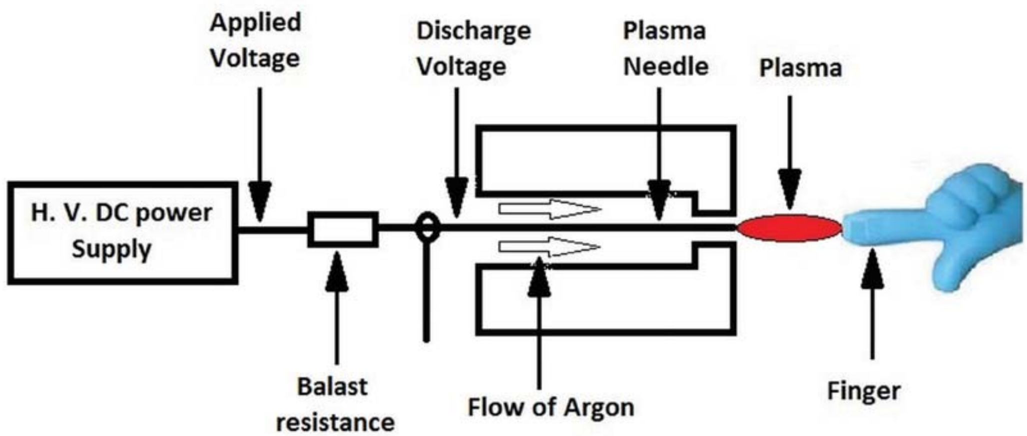

FIG. 1: Schematic of the plasma needle and its operation

serial bus spectrometer (model LR1). In this study, the applied DC voltage varied from 6.5 to 12.5 kV and ballast resistance from 10 to 75 MΩ. The separation between the tip of the needle and the water-covered agar-gel surface varied from 2 to 20 mm.

III. RESULTS AND DISCUSSION

A typical image of the plasma jet interacting with a human finger is shown in Fig. 2(a). We found that the plasma jet can continually contact the human finger without the occurrence of any sensation. However, the plasma jet is operated on the water-covered agar-gel surface to mimic the interaction of the plasma with living cells and to illustrate the stability of the plasma jet (Fig. 2[b]).

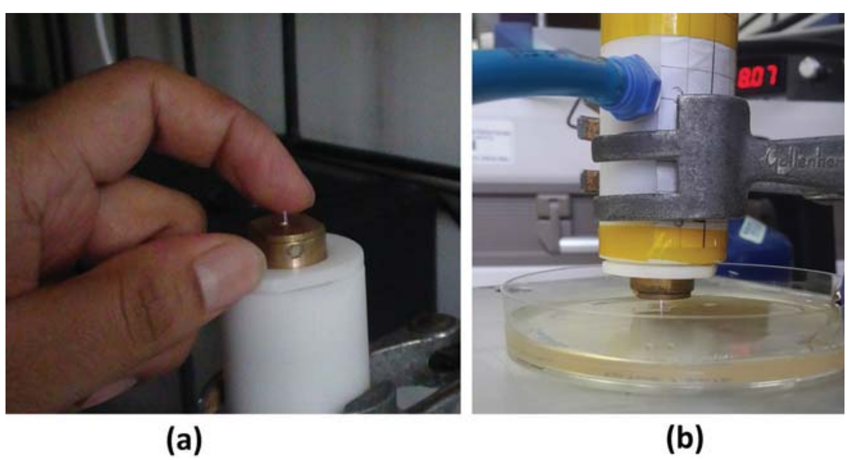

FIG. 2: Photographs of (a) the plasma jet interacting with a human finger and (b) the plasma jet operated on a water-covered agar-gel surface

Figure 3 shows the electrical discharge characteristics of the plasma needle operating over the water-covered agar-gel surface, for an applied voltage of 10 kV. The electrical characteristics show that the discharge is pulsed in nature. We observed that increases in applied voltage augment the discharge frequency without considerably affecting discharge voltage and current. Discharge frequencies for different applied voltages are shown in Fig. 4. We found that discharge frequency increases linearly with increasing applied voltage. It is worth mentioning that the frequency of the discharge is almost independent of the applied voltage; however, a linear increment occurred below a threshold voltage. The observations in the present study agree with previously reported findings of liner increments of frequency that occur with increasing applied voltage below a threshold voltage.[2]

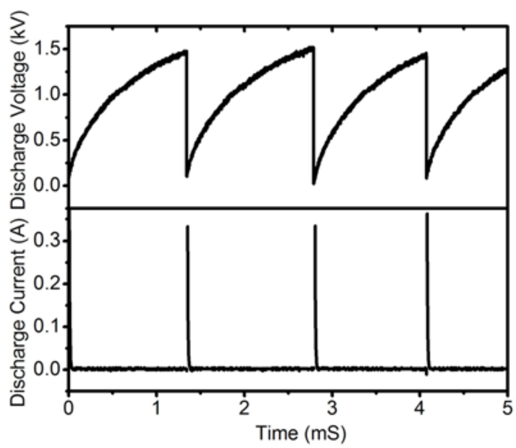

FIG. 3: Time evolution of the discharge current and discharge current of the plasma needle

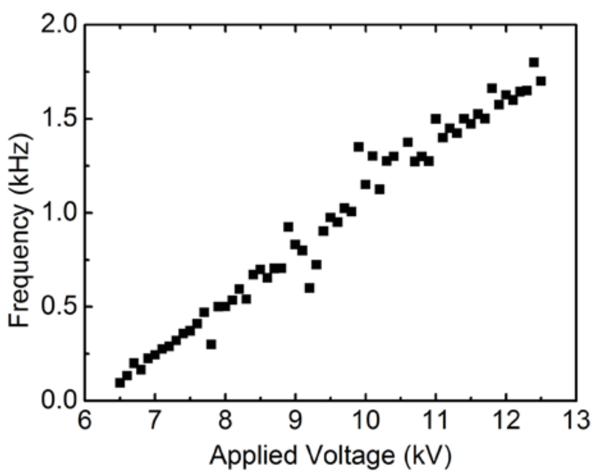

FIG. 4: Variation of discharge frequency with applied DC voltage

Typical OES spectra from the plasma needle are shown in Fig. 5. We found the Ar II lines to be more prominent. Ar II lines at 289.16, 289.67, 303.35, 308.5, 309.34, 329.36, 329.29, 330.72, 347.67, 351.43, 370.69, 379.04, 394.6, and 404.11 nm can be clearly seen in the spectra. However, the lines at 289.16 and 289.67 nm, 308.5 and 309.34 nm, and 329.36, 329.29, and 330.72 nm are superimposed to others due to the limitation of the spectrometer. For analysis of the OES spectra, those superimposed lines were ignored; we only considered the lines shown in Table 1.

On the basis of the emission spectral-line intensity, we were able to estimate excitation temperature of the plasma. Temperature could be calculated with either the intensity ratio of two lines or the Boltzmann plot method, and any error related to measurements were reduced by considering several lines using the Boltzmann plot method.[22,23]

Considering I_1 and I_2 to be the intensity of two different emissions at wavelengths λ_1 and λ_2, a ratio is given by[19]

$$\frac{I_1}{I_2} = \frac{A_1 g_1 \lambda_2}{A_2 g_2 \lambda_1} \exp\left[\frac{E_2 - E_1}{kT}\right], \tag{1}$$

where A is the Einstein coefficient of spontaneous emission (transition probability), g is the statistical weight of the upper level of transition, E is the energy of the upper level of

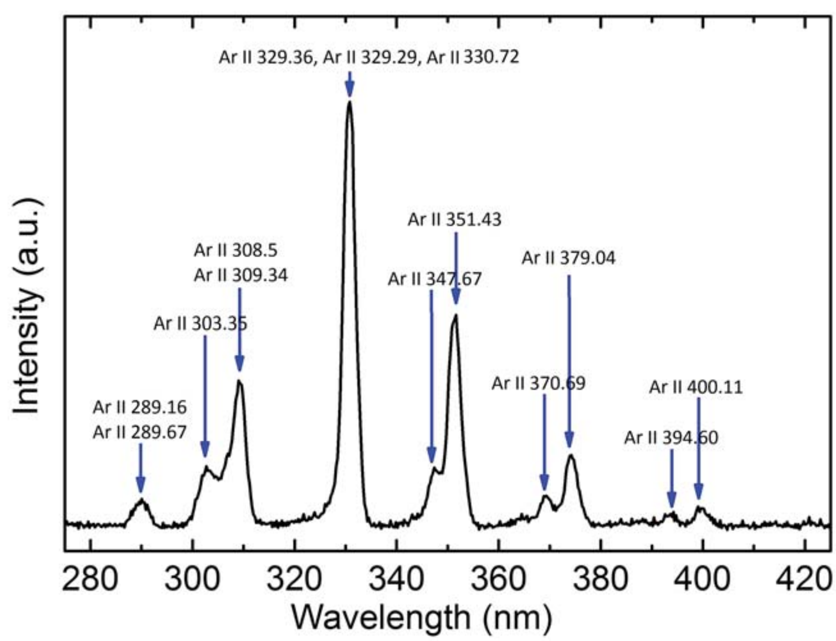

FIG. 5: Typical OES spectra of plasma produced by the plasma needle on a water-covered agar-gel surface. Ar, Argon

TABLE 1: Details of the spectral lines used to estimate the excitation temperature from OES spectra

Ion	**Wavelength (nm)**	A_{ki} **(S^{-1})**	E_k **(cm^{-1})**
Ar II	303.35	9.9×10^6	172213.8798
Ar II	347.67	1.25×10^8	183797.4473
Ar II	351.43	1.36×10^8	183797.4473
Ar II	370.69	2×10^5	159706.5337
Ar II	375.04	1×10^5	159393.3850
Ar II	394.60	1.5×10^8	195864.7296
Ar II	400.11	6×10^5	172213.8798

OES, optical emission spectra

the transition, k is Boltzmann's constant, and T is temperature. The plasma temperature can be calculated using Eq. (1) based on the line intensity ratio by measuring spectral intensity of two lines. However, the Boltzmann plot method is more accurate and reliable than the line intensity ratio method, because several spectral lines are involved with the Boltzmann method. In general, the intensity I_k for a spectral line may be expressed as[23]

$$\ln\left[\frac{I_k \lambda_k}{g_k A_k}\right] = \ln\left(l \frac{hc}{4\pi} \rho_0\right) - \frac{E_k}{kT}, \tag{2}$$

where l is the path length, h is Planck's constant, c is light velocity, and ρ_0 is density of atoms. By plotting the left-hand term as a function of E_k, for several spectral lines, the slope ($1/kT$) can be evaluated (the inverse of which gives the temperature), because the first term on the right- hand side is constant and does not depend on the particular spectral line. We present in Table 1 the details of the spectral lines that we used to estimate the temperature using the Boltzmann plot method. Figure 6 shows the Boltzmann plot of emission spectra of the plasma jet produced by the plasma needle. The operating parameters are 7 kV applied voltage, 30 MΩ ballast resistance, and 5 mm separation between the needle tip and water-covered agar-gel surface.

Table 2 shows excitation temperature calculated from OES using the Boltzmann's plot method for different applied voltage with ballast resistance of 75 MΩ and 5 mm of separation between the needle tip and water-covered agar-gel surface. We found that the relationship between varying excitation temperature and changing discharge voltages was almost negligible. It is worth noting that for a plasma needle operated with an AC power supply, excitation temperature has been reported to augment with increasing peak voltage.[2] However, the present experiment revealed that the excitation temperature did not change considerably with applied voltage in the case of a plasma needle operated by a DC power supply.

Table 2 shows the variation of temperature with ballast resistance for 8 kV of applied voltage and 5 mm of separation between needle tip and water-covered agar-gel

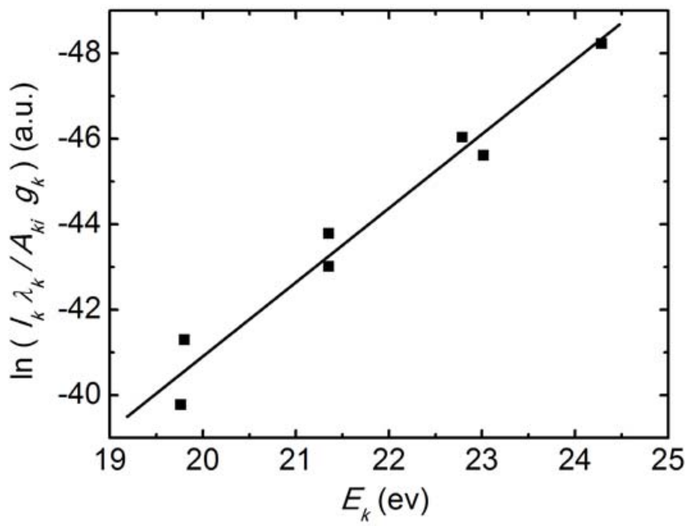

FIG. 6: Typical Boltzmann's plot for the plasma jet produced by plasma needle

TABLE 2: Estimated excitation temperature of plasma for different applied voltages, ballast resistance, and separation between the tip of the plasma needle and the water-covered agar-gel surface

Applied voltage (kV)	T_{exc} (eV)	Ballast resistor (MΩ)	T_{exc} (eV)	Separation (mm)	T_{exc} (eV)
7	0.587	15	0.5671	2	0.6878
8	0.602	20	0.5672	3	0.6432
8.5	0.588	25	0.5671	4	0.6045
9	0.5994	30	0.5675	5	0.5903
9.5	0.5866	35	0.5677	6	0.5296
10	0.5983	40	0.5689	7	0.5285
10.5	0.5797	45	0.5705	8	0.5221
11	0.6027	50	0.5725	9	0.5225
11.5	0.5948	55	0.5753	10	0.5123
12	0.5817	60	0.5765	11	0.5122
13	0.5778	65	0.5771	12	0.5134
—	—	75	0.5791	13	0.5121
—	—	—	—	14	0.5021
—	—	—	—	15	0.5043
—	—	—	—	16	0.5212
—	—	—	—	17	0.523
—	—	—	—	18	0.5123
—	—	—	—	19	0.52011
—	—	—	—	20	0.52012

surface. Temperature augments slightly with increasing ballast resistance; however, below a threshold value of resistance, the variation in temperature is almost negligible. Table 2 also shows the temperature variation with separation between the needle tip and the water-covered agar-gel surface for 8 kV applied voltage and 75 MΩ ballast resistance. We found that the variation of separation between the tip of the plasma needle and the water-covered agar-gel surface did not show any considerable change in temperature when separation was > 5 mm. However, considerable increases in temperature occurred when the separation is < 5 mm.

IV. CONCLUSIONS

We used a plasma needle that was developed using a DC power source. The plasma jet produced by the plasma needle easily interacted with the human body without causing any sensation. We carried out both electrical and optical characterization of the plasma needle. It was observed that increased applied voltage augmented discharge frequency without affecting discharge voltage or discharge current. The frequency of the discharge was found to increase almost linearly with increasing applied voltage. We used the Boltzmann plot method from OES spectra to estimate excitation temperature of the plasma. In contrast to an AC plasma needle, with which the temperature increases with applied peak voltage, the temperature of the plasma jet produced by the DC plasma needle on a water-covered agar-gel surface was found to be almost independent of applied voltage. The temperature augmented with increasing ballast resistance above a threshold value of the resistance, below which the temperature was found to be almost constant. Changes in separation between the tip of the plasma needle and water-covered agar-gel surface did not show any considerable variation in temperature when separation was > 5 mm. However, considerable increases in temperature occurred when the separation was < 5 mm. It can thus be concluded that to apply a plasma needle with the required constant electron temperature, it is necessary to maintain a minimum separation between needle and object.

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