Multijet atmospheric plasma device for biomedical applications

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ABSTRACT: We describe new multijet low-temperature plasma discharge systems designed for a variety of biomedical applications. These systems are capable of providing stable plasma jet channels between the nozzles and either biomaterial or metallic and dielectric surfaces at atmospheric pressure. The proposed direct discharge electrode arrays allow reaching rather extensive areas of treatments.

KEY WORDS: atmospheric plasma; plasma sources; biomedical applications

I. INTRODUCTION

Plasma medicine is a new multidisciplinary area of research in physics, chemistry, engineering, and life sciences with broad applications in medicine. Due to the controllability of the physical and chemical parameters, low-temperature atmospheric plasmas find applications across an enormous range of health care procedures. Numerous *in vivo* and *in vitro* experiments prove that the low-temperature atmospheric plasmas have valuable effects on health with great application potentials: bacterial, fungicidal, and viral; chronic wounds healing; blood coagulation; disinfection and sterilization; cardiovascular regulation; immune system facilitation; cancer cell proliferation arrest and apoptosis; biofilm destruction, etc.[1–9] In spite of such a wide area of applications and high demand for new effective treatments, the understanding of interactions of plasmas with living cells and tissue remains rather limited.

Plasmas find applications in different areas of medicine (see Fig. 1) because of their versatility. For example, plasma allows efficient disinfection in seconds (gaseous form of plasma provides a possibility to deliver treatment to narrow cavities and fissures otherwise unreachable for fluid disinfection); reactive species and active agents can be quickly delivered on a molecular level to the selected tissue, thereby preventing skin irritation and allergic reactions; tunability of composition and torch scalability allow quick optimization of treatment strategy.

Interactions between living systems and plasmas can be carried out by means of any of plasma's agents: neutral gas, charged particles, excited atoms/molecules, reactive species (such as NO, O_3, OH, O_2^-), UV light, electrical field, and heat. Thus, various constituents of plasma can affect biological, physical, and chemical processes in living cells, tissue, and microorganisms. However, the basic understanding of mechanisms of plasma effects on different components of living systems is in the early beginning. For a review of biological roles of the various constituents of low-temperature plasmas see

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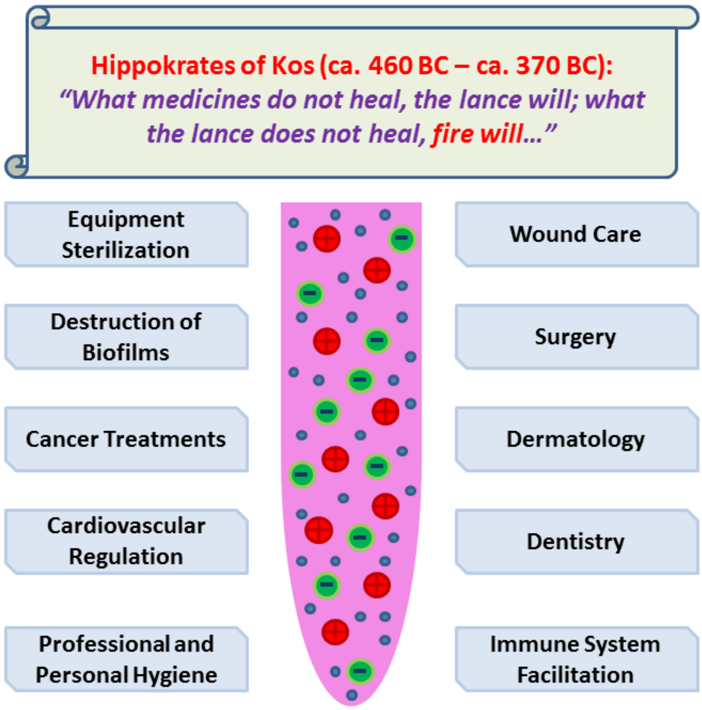

FIGURE 1. Main areas of plasma applications.

Refs. 3, 8, 10, and 11. Different parameters of plasma, such as mixture of ions/electrons and their spatial and energy distributions, temperatures, absorbed power, light emission spectrum, jet shape, and ambient conditions, have strong influence on its usability and potential applications. For example, to achieve the therapeutic effect across the treated area a jet with uniform distributions of the plasma's parameters should be produced.

Ultimately, to address the most demanding challenges in biomedicine, it is crucial to have plasma devices with tightly controlled parameters. This is highly important for further experimental *in vitro* and *in vivo* studies of interactions of plasmas with biological objects and tissues. In this work, we report on engineering of a new installation for low-temperature atmospheric plasma with multijet discharge area providing a wide area of homogeneity of the main plasma characteristics. New constructions of electrodes providing a big area of nonthermal plasma at atmospheric pressure with special configurations of discharges are suggested.

II. MULTIJET DISCHARGE SYSTEM

For treatments of large surfaces (e.g., extended chronic wounds), where the spatial distributions of the plasma parameters should be homogenous through the targeted area, we suggest a new multijet discharge system consisting in either one or two arrays of quartz nozzles. The developed RF torch-barrier discharge is capable of generating stable atmospheric plasma with parameters similar to those reported in Refs. 12–17, which are suitable for biomedical applications. Basically, a dielectric layer was placed on the inner walls of each metallic nozzle, as illustrated in Fig. 2. The RF power absorbed in this system can be adjusted in a way that the so-called RF barrier torch discharge is generated near the sharp edge of the insulated metal power electrodes. The working gas flowing through the nozzles stabilizes these barrier-torch discharges and, therefore, well-defined discharge channels are created. The advantage of this system is that the metal surface of the power electrode is insulated from direct interaction with the high-density plasma. Therefore, the chemical processes in the plasma are not affected by the metallic RF electrode surface.

The photographs of light emission from the RF multi-torch barrier discharges with 9 and 18 nozzles for a quartz surface are depicted in Fig. 3. The dimensions of the quartz tubes were analogous to the quartz tube in a single nozzle shown in Fig. 2. The distance between the nozzle outlet and the surface was 10 mm in order to set up a stable multijet operation. Helium flow through each nozzle was set to Q = 600 sccm. Similar stable plasma jets were generated between the multijet discharge system and aluminum surface. The emitting plasmas were spatially well localized near each one of the treated surfaces, thus showing the applicability of the proposed multijet system for treatments of

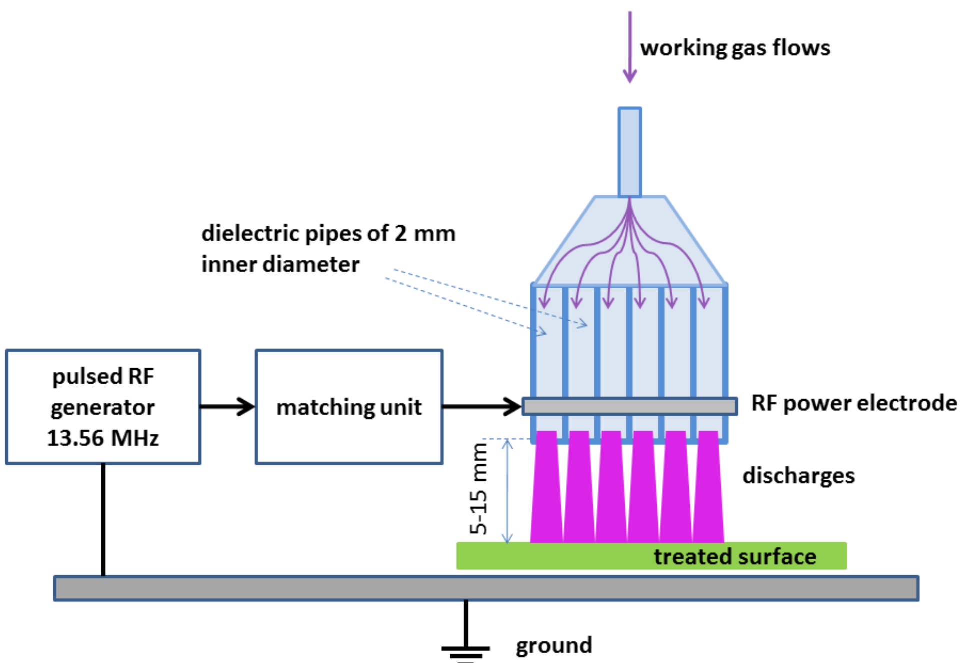

FIGURE 2. Multijet discharge system.

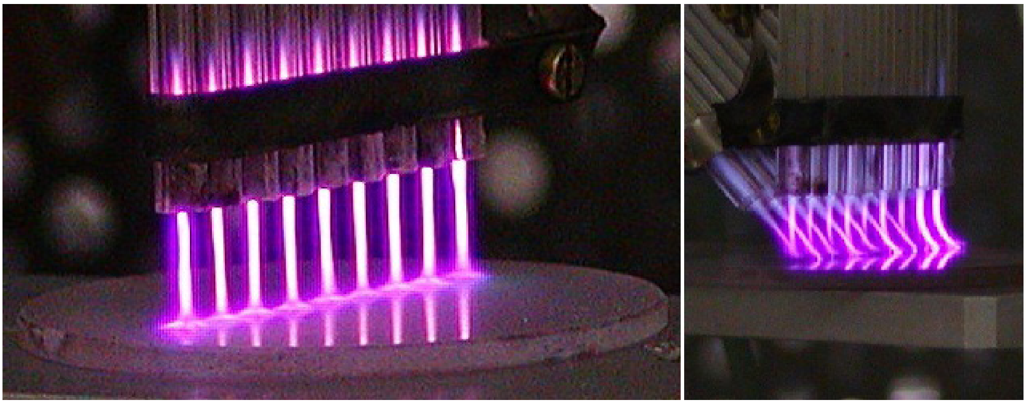

FIGURE 3. Photographs of light emission from multijet discharges: single array of 9 nozzles (on the left) and double array of 18 nozzles (on the right).

various types of surfaces. The plasma was characterized by emission spectroscopy. An example of optical emission spectra is shown in Fig. 4, where strong He lines together with an N_2 band are visible. Weak lines of rotational structure of OH radicals were found on the background of the strong N_2 band. Rotational lines of OH radicals (308 nm, Q branch) were used for calculations of rotational temperature of these molecules, $T_R \cong$ 400 K. The vibrational temperature, $T_V \cong$ 3300 K was estimated using the second positive system of N_2 molecule bands (0, 3) and (0, 2). Our system can be tuned to produce rather large areas of plasma, which would be an advantage for sterilization of surgical instruments and surfaces as well as for antiseptic treatments of human tissue. Moreover, in the double array multijet discharge system the target area can be modified by adjusting the inclination angle of one of the nozzle arrays.

In order to demonstrate the possibility of the surface treatment of thermally sensitive substrates (e.g., living cells, tissue, and microorganisms) using the multi-nozzle system, a pulse-modulated RF multijet discharge was tested on PVC and skin surface. The experimental setup and the geometrical features were analogous to those shown in Fig. 2. The distance between the treated surfaces and the nozzle outlet was set to 5–10 mm. The length of the duty cycle was 5.0 ms and the active part of the duty cycle was 50 μs when maximum RF power $P_{RF} \approx$ 600W was applied on the discharge with a matching unit. On the other hand, the mean power absorbed in the discharge throughout the time of treatment was low enough to avoid noticeable surface heating. To prove this, we generated four plasma jets from the four-nozzle system upon a finger (Fig. 5). The plasma jets remain stable even on discharging upon a nonflat a surface, as can be seen from Fig. 5. The gas temperature of such plasma jets can be measured by a thermocouple of K type at 5 mm distance from a nozzle as a function of the parameter, $s = t_p/T$, (where T is the pulse period and t_p is the power pulse duration) for the modulation frequency 200 Hz (see Fig. 6). Thus, a limited gas temperature range implies absence of thermal damage of living cell or tissue during similar plasma treatments. In these plasma devices

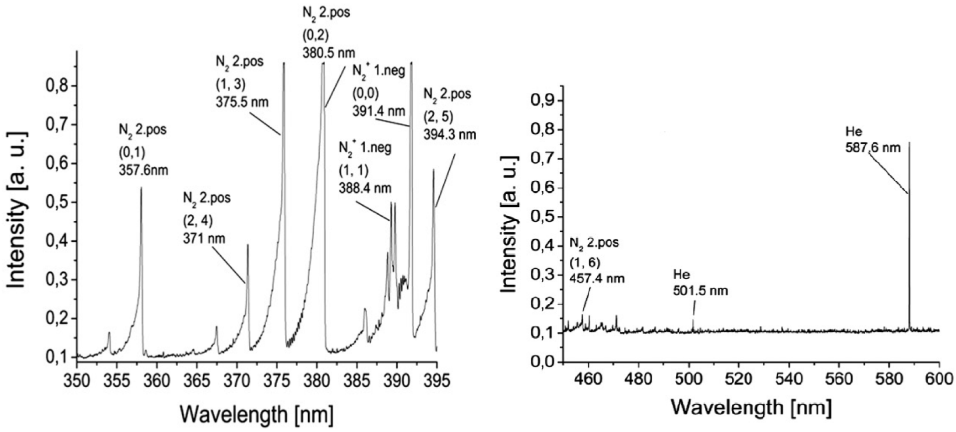

FIGURE 4. Optical emission spectrum of plasma with He taken at P_{RF} ≈ 600W.

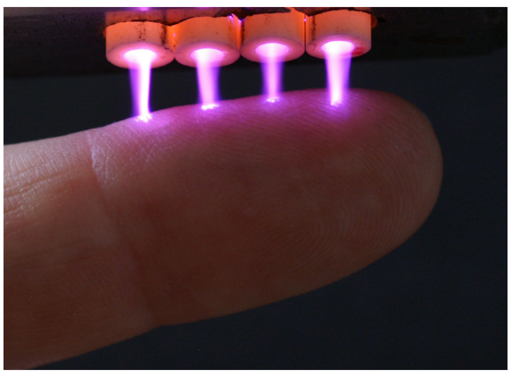

FIGURE 5. Photographs of light emission from the four-jet discharge system upon a finger.

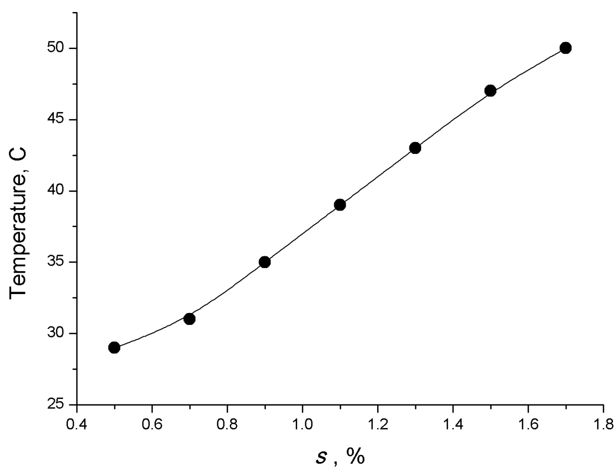

FIGURE 6. Gas temperature measured as a function of the *s* parameter at P_{RF} ≈ 600 W.

the temperature can be easily tuned by adjusting the pulse duty factor. Furthermore, we were able to generate the stable barrier-torch discharges by using mixtures of He, Ar, O_2, and N_2. Such a possibility of controlled gas composition variation is quite important because ions of different types can play a key role in microorganism inactivation and wound healing by plasmas.[3,4]

III. CONCLUSIONS

A low-temperature plasma system allowing tiny variations of gas composition was designed for a wide spectrum of biomedical applications. The described device is capable of generating stable plasma discharges with the same chemical and physical parameters as those required for disinfection, wound healing, and cancer treatment. The proposed system is easily tunable by changes of gas mixture and its pressure, RF power, and pulse duty factor. The main advantage of the proposed discharge system is its ability to produce a large plasma area. This would allow correct administration of plasma treatments during a reduced time of patient exposure to plasma. In our forthcoming papers we are going to report experimental results from the study of interactions of plasmas generated by the proposed multijet discharge system and living objects.

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