Tolerance effect of a shock-free atmospheric plasma on human skin

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Abstract
In this work, a shock-free argon-fed plasma plume was generated by a variable-frequency power supply and the discharge characteristics were investigated from the voltage and current waveforms between 72 and 92 kHz frequencies. The higher electron temperature dominates the plasma chemical process and the average plasma temperature is about 30 °C under these conditions. The influence of non-thermal atmospheric plasma plume length and plume temperature on Ar gas flow is optimized at 7 sL/min. The average charge accumulation on the plume tip area and the dependence of flow rate on the plasma irradiation area were also explored. This atmospheric pressure plasma jet (APPJ) has been proposed for human-skin irradiation on different areas (even on the tongue) owing to its less painful, tingling and burning effect. Optical emission spectroscopy (OES) confirmed the presence of excited argon with reactive nitrogen (RNS) and oxygen species (ROS). This study contributes to a better understanding of non-thermal plasma effects on the human body which may find prospects for disinfection and prevention of different diseases during the current pandemic time.

Keywords Non-thermal atmospheric plasma · Shock-free plasma jet · Electrical characteristics · Flow rate · Plume temperature · In vivo plasma irradiation on human skin

1 Introduction
The interest in the research of cold atmospheric plasma (CAP) has accelerated in the last 20 years due to its profound application as a clinical plasma medicine [1–7]. The non-thermal or cold plasma ejected by an atmospheric pressure plasma jet (APPJ) constitutes a high concentration of reactive species [8]. In non-thermal plasma, the electron temperature is relatively high with a low degree of ionization.

Recent progress in CAP treatment offers promising opportunities in biomedical applications. The efficacy of APPJ in the field of plasma medicine is promising by inactivating fungal infections [8], cell surface damage [9] and DNA damage of mammalian cells, both in vitro and in vivo phases [10]. The plasma from APPJ is rich in radical species, reactive oxygen species (ROS) and reactive nitrogen species (RNS), which helps to mediate the plasma-cell and plasma tissue effects. CAP is introduced as a wound-healing agent for the treatment of several tumors [11, 12], accelerating blood coagulation and disinfection [13] and even for cancer cell treatments [14, 15]. The emergence of CAP as an alternative option in clinical plasma medicine is due to its antibacterial properties [16] and anti-inflammatory effects [17]. Inactivation of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) by APPJ surface treatment has opened a new research opportunity in the low-temperature plasma research trends [18]. The CAP from APPJ is readily effective for the treatment of human tissue, including treatment of psoriasis [19], decontamination of human hair fibers [20], accelerated re-epithelization of skin lesions [21] and improving human skin cell viability [22]. But most of these plasma irradiations are performed in vitro mode. The plasma needle and plasma torches have been successfully used earlier for the
different skin and dental treatments in vivo mode [23–25]. It is efficiently used for wound healing applications also [26]. The plasma treatments in superinfected dermatitis of different causes have shown positive results [27]. The application of APPJ in dermatology needs to be optimized in terms of efficacy and control, involving plasma-induced effects on the skin [28]. APPJ can be used to disinfect or treat bacterial, fungal and viral infections if the plasma plume can irradiate directly any part of the human skin (in vivo mode). The development of a shock-free CAP plume is always a challenging task. Besides, it is difficult and challenging to produce shock free plasma source. Secondly, the heating effect of plasma plume at higher radio frequency could lead to a burning sensation during the plasma irradiation to the human skin/body. In this range of plasma applications, local anesthesia may be needed during the plasma treatment.

In this study, a high-frequency power supply is designed which can generate a shock-free plasma plume, whose length is around 20 mm [29]. The electrical characterization of the plasma discharge is investigated from the voltage-current waveforms at a variable frequency. The total charge accumulation and absolute power gained during full-length plasma plume discharge are also examined. The plume length, surface micro-discharged area and temperature of the non-thermal plasma plume are measured as a function of the Ar gas flow rate. The proposed APPJ has underscored a trial run (in vivo) on human skin surfaces. One of the authors himself applied this discharge plume on his finger, forearm and tongue to check the instant effect of electrical shock and the post-sensational effect. The tolerance level of withstanding plasma irradiation on the human body without anesthesia is explored. Optical emission spectroscopy is employed to measure the reactive species content of the plasma plume.

2 Materials and methods

2.1 Plasma jet and its characterization

Non-thermal or cold plasma is generated by atmospheric pressure plasma jet (APPJ) at room temperature through dielectric barrier discharge (DBD) phenomenon using Argon (Ar) gas as the carrier. Fig. 1 depicts a complete schematic diagram of the APPJ experimental setup including the executed measurement setup also. The proposed plasma jet consists of a two-electrode configuration, where the positive center-electrode is a tungsten needle of 1.5 mm in diameter and 10 cm in length. The outer aluminum foil is placed surrounding the quartz tube. The positive electrode is powered by a (70–100 kHz) pulsed (2–4) kVpp AC voltage power supply (as shown in fig. 1a). The feeding gas is (99.99% pure) Ar whose flow rate ($Q_{Ar}$ = 4–9 sL/min) is measured by a flow meter. The characterization of an APPJ depends on various parameters including the inter-electrode distance, type of discharge power supply, carrier gas and flow rate. The voltage and current waveforms are obtained using a high voltage probe (Lecroy, PPE 6 kV) and a current probe (Lecroy, CPO30). The high voltage and current probes are
connected between the electrodes and the digital storage oscilloscope (DSO: Wave Ace Teledyne Lecroy 2024, 200 MHz 2GS/s). A digital temperature controller cum indicator (Selec, DTC 208-2) with a type K thermocouple (Chromel/Alumel) is used to measure the temperature of the plasma plume. The temperature of the plume is also observed by a high-temperature infrared thermometer (Extech, 42570). The optical emission spectroscopy (OES) technique is used to detect the generated plasma species in the ambient air (by Ocean Optic Spectrometer). All the real-time snapshots of plume length and plasma-surface discharge are taken by a digital single-lens reflex camera with an effective 27 megapixels resolution. A ruler (cm) is used to measure the plume length from the nozzle. Fig. 1b shows the jet assembly with Ar gas flow direction within the tube. The envelope of the jet is made of Delrin material, whose operating temperature is about ~175 ºC, higher than Teflon. The plasma generation region within the quartz tube measures ~2 cm from the nozzle tip. The discharge takes place at a threshold discharge voltage near the orifice region. At a certain gas flow rate, the distribution of uniform charge particles at the jet orifice gets increased and a plasma plume came out of the orifice [13]. Fig. 1c shows the image of the proposed portable plasma jet which is lightweight and mobile with all its connections. It can be carried to remote places and assembled in no time with an Ar cylinder and power supply. With the self-initiation, one of the authors (Dr. Sadhan Chandra Das) himself applied this discharge plume on his finger, forearm and tongue to check the instant effect of electrical shock and the post sensational effect and the snapshots are taken by the camera.

2.2 High-frequency power supply

In this work, the power supply of the plasma jet is designed in a cost-effective way. Fig. 2 shows the block diagram of the APPJ power supply consisting of transistor-transistor logic (TTL) ICs, a high-frequency generator using low power LTC6900 IC and an H-Bridge driver using L298 IC. The circuit has protection for no clock pulse and over-current trip controls to protect the primary coil of the high-frequency transformer and the components of the driver circuits. A high-frequency high voltage step-up ferrite core transformer is connected at the output stage. The H-bridge consists of four power transistors which are driven by the TTL pulse signals. For logic high of the clock input pulse, one set of opposite diagonal transistors gets “ON”, so high pulse current flows in one direction through the primary coil of the ferrite core RF transformer to produce a half cycle (say positive) of AC high voltage across the secondary coil of the transformer. The other two diagonal transistors get “ON” due to TTL logic low clock input pulse, then high current flows in opposite direction through the primary coil of the transformer to produce the negative half cycle of AC high voltage across the secondary coil. At the output terminal of the secondary coil of the transformer, one inductor circuit is used in series to maintain the discharge with sufficient current.

There are two trip control circuit blocks, (i) a no-pulse trip signal generator and (ii) over the current trip signal generator. Due to any reason, if the clock pulse oscillator circuit stops, a huge DC current flows through the primary coil of the transformer to damage the primary coil and the driver H-bridge circuit. In this case, the no-pulse trip signal generator generates a low TTL logic signal at the input of the AND gate and the output of it becomes LOW to make ENABLE input of the H-bridge circuit low for disabling it. So no current flows through the primary coil of the transformer. On the other hand, the over-current trip control circuit generates TTL low voltage, when the current through the H-bridge is more than a preset value. In this case, it is set for a value of 4 A current.
3 Results and discussion

3.1 Electrical characterization

The current-voltage characteristic is the most important electrical parameter of plasma generation. It is influenced by the plasma jet configuration and input power supply [30]. Fig. 3 shows the time trace of applied voltage and discharge current during Ar plasma discharge at the highest length with gas flow rate at $Q_{Ar} = 7$ sL/min. Fig. 3a, b, and c shows the correlation between the typical applied voltage and spike profile of discharge current with fair weak micro-peaks at three different fixed applied frequencies ($f$) of 92, 82 and 72 kHz. The peak-to-peak applied voltage ($V_{p-p}$) and discharge current ($I_{p-p}$) has increased with a decrease in applied frequency ($f$) for fixed bias voltage across H-bridge.

The relation between the intensity of discharge current and applied voltage depends on the mechanism of energy distribution through the length of the jet tube [31]. A short time period attributes to an increase in electron density, thereby increasing the discharge current [32, 33]. The repetitive short pulse voltages influence the electron population to increase ionization and excitation [34]. In the dielectric barrier discharge mechanism of the plasma jet, the dipole moments get reversed continuously due to the influence of high-frequency voltage. The noisy peaks in the discharge current are present due to the existence of Ar ions, electrons and other charge carriers during the discharge plasma plume and the continuous recombination of ions and electrons. Furthermore, an increase in applied voltage also enlarges the plume length. The enhanced electric field causes more electrons to strike the Ar atoms, influencing the Ar species of the plasma to come out in the effluent. A higher plume length is obtained due to the increased driving voltage ($V_{p-p} = 3.5$ kV) owing to enhanced plasma density [35, 36]. Owing to the highest plume length, other characterizations are performed keeping 72 kHz as default. The low pulse duration of $\sim 13.88$ µs in discharge current helps in forming a shock-free plasma plume, which can be touched with a bare hand.

The discharge current is leading the applied voltage resembling a capacitive behavior. The delay between the positive peak of the voltage pulse and that of the first peak discharge current pulse is $\sim 9$ µs. This distance is majorly influenced by the gap distance [37]. The net reactance increases with a decrease in frequency, which thereby increases the phase angle. The Lissajous pattern of the corresponding voltage and current is shown in Fig. 3d, e, and f.

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Fig. 3 Waveforms of the applied voltage and discharge current during plasma discharge from APPJ at variable applied frequency: a 92 kHz, b 82 kHz and c 72 kHz. The corresponding Lissajous patterns at: d 92 kHz, e 82 kHz and f 72 kHz.
The width of the patterns has enlarged since repetitive time periods are shown [38]. All the Lissajous patterns depict the symmetrical discharge voltage and current waveforms for both polarities [39]. Since the major axis of the formed ellipse is in the second and fourth quadrants, the slope is negative and the phase angle lies between 90° to 180°. The approximated phase angle obtained from the patterns is shown in Table 1. The phase angle is calculated from equation (1), where D and d are the two amplitudes as shown in Fig. 3g.

\[ \phi = \sin^{-1} \frac{d}{D} \]  

(1)

The phase angle is found to decrease with an increase in applied frequency. In this study, a current-voltage phase relationship during plasma discharge is established with a change in frequency. The phase difference is mainly caused due to the capacitive effect of the APPJ. A uniform charge distribution takes place on the surface of the tube during plasma formation. In DBD plasma, the air gap between the walls of the quartz tube acts as a capacitor. Hence, a huge amount of charge accumulation takes place at the surface which is driven by continuous Ar gas flow. A prolonged plasma plume outside the tube orifice is generated since the charge formation is higher inside the tube. The loss is higher at 72 kHz frequency compared to 92 kHz. At high frequency, more charge is appearing in the plasma plume which increases the plasma density. Therefore, an uncomfortable sensation can be felt at a higher frequency, when plasma is irradiating the human skin surface. A better shock-free plasma plume can be generated with higher loss.

Fig. 4a shows the instantaneous charge accumulation and fig. 4b shows the absolute discharge power dissipated during Ar plasma discharge as a function of time. The effect of different applied frequencies is observed in all the waveforms for a single period. The peak-to-peak instantaneous charge at 82 kHz and 92 kHz frequency is comparable at ~1.06 µC. However, a negligible increase in peak-to-peak charge of 1.16 µC is observed at 72 kHz. This low charge accumulation at the plume tip area is very much suitable for human trials because it has a low-risk factor.

The absolute power was calculated from the instantaneous current and voltage values. The evaluation of the absolute power depicts the maximum power output at 72 kHz with ~27 W, followed by ~18 W at 82 kHz and ~17 W at 92 kHz. The power dissipation of the plasma jet is very close to previous reports, which has the potential for antibiotic treatments in vivo mode [40]. The phase lead-lag relationship is almost comparable at the three fixed frequencies. The maximum possible pulse width of ~3.5 µs at 82 kHz and 92 kHz is almost comparable. But at 72 kHz, the lowest pulse width is obtained at ~2.3 µs. Therefore, 72 kHz frequency is considered the standard frequency in this case for the other measurements. The energy required for such power dissipations (in watt range) is in micro-Joules due to the narrow pulses (in µs). The power is transferred only during the rise and fall of the applied voltages in µs duration [37]. The obtained electrostatic forces influence the charge accumulation at the plasma-cell membrane interface [41].
3.2 Impact of Ar gas flow rate

Figure 5 shows the different plume length snapshots of Ar plasma discharge and their dependence on gas flow rates. The plume lengths are measured by keeping the frequency of the applied voltage at 72 kHz as default. Fig. 5a shows that plasma discharge initially starts at a 4.5 sL/min flow rate, showing a bluish pink color near the orifice of the plasma tube. Fig. 5b–e shows the increase in plume length with increasing gas flow rate. A maximum plume length of 2.11 cm is obtained at a 7 sL/min flow rate. Fig. 5f–h shows the decreasing plume length images after achieving the maximum length, with the further increase in flow rate. The decrease in plume length at a higher flow rate is very similar to previous reports [42]. The increase in gas flow rate enhances the electric field profile near the jet nozzle which influences a higher propagation velocity of the plasma plume propagation in the surrounding atmosphere. An increase in plume length is the resultant outcome [33, 43]. The diameter of the plume enlarged negligibly at higher gas flow above 7.5 sL/min, as shown in Fig. 5g and h. At a higher flow rate (above 7.5 sL/min), the gas exerts more pressure to push out the plasma species and create turbulence inside the tube [39, 44]. Initially, the ionization wave enters the surrounding air with increased velocity but when the discharge reaches its maximum distance, the velocity begins to decrease [45, 46]. At a relatively higher gas flow rate (below 7.5 sL/min) the density of the uniformly distributed charged particles is increased and that affects the plasma plume length [47]. An excessive gas flow creates a turbulence effect inside the plasma jet tube and due to this turbulence the majority of the charged particles recombine inside the discharge tube and the length plume becomes shorter. The plume is characterized by different colors from the bottom region to the top region using a dark background. The electrons residing in the conduction band jump to the valence band, by emitting energy at different wavelengths with different colors. The energy of the top of the plume near the nozzle (bluish pink-white region) emits the highest energy with enhanced plasma chemistry, whereas those at the tip of the plume (bluish-violet region) emit less energy [46]. The bluish pink-white color is due to the presence of argon species, and the bluish violet color is due to nitrogen species included in the plasma from the surrounding air [38, 48]. This study inferred a conclusion that the tip of the plume
of the proposed jet should be used for irradiation purposes at a 7 sL/min flow rate.

3.3 Plasma irradiation with micro-discharge

This study aims to relate the plasma irradiation area with the gas flow rate. Fig. 6 shows the snapshots of the plasma surface micro-discharge irradiating different surface diameters (S) of a 4 cm² target floating aluminum (Al) plate at different Ar flow rates. The surface micro-discharge is measured by keeping the frequency of the applied voltage at 72 kHz as default. Fig. 6a–e shows the increasing area of the irradiating surface of the plates with a maximum value of 1.2 cm (Smax) at a 7sL/min flow rate. The surface area diameter then decreases to 0.4 cm (Smin) on a further increase to 8 sL/min.

There are two factors that are responsible for this spiral-like plasma behavior: (1) the surface charges distribution is non-uniform on the inner surface of the tube and (2) the non-uniform distribution of charged particles inside the tube. Both these effects are affected by the turbulent flow of the gas. The turbulent flow appears due to high gas flow through a small area. The snapshots also show how the surface micro-discharge of Ar plasma irradiates the metal plate with multiple strand lines. Higher discharge intensity and weak micro-sparks are observed through the naked eye when the plasma plume is brought in contact with the metal conducting plate. A large number of plasma species and radicals generated at the interface of the plasma plume can be responsible for the disinfection of different pathogens [18]. This characterization work sets out an understanding and explores the plasma micro-discharge formation which allows the device to be used as a promising source for biomedical and materials processing.

3.4 Effect of plasma plume temperature

In medical and biological applications, the temperature of the plasma plume is the most dominant parameter due to the sensitivity of plasma-living cell interaction [49]. The temperature of the non-thermal plasma plume should be ≤40 °C for application to biological tissues [16]. Fig. 7 shows the temperature measurement of the Ar plasma plume at variable Ar gas flow rate by two different processes. The temperatures are measured at the tip of the plume keeping the frequency of the applied voltage at 72 kHz and gas flow rate at QAr = 7 sL/min as default. All the temperatures are presented in standard deviation form with an error bar of ±1.0–1.5 °C. The temperature measured through

**Fig. 6** Snapshots of surface micro-discharge on a floating Al plate with an irradiated surface diameter at different gas flow rates; a 5 sL/min, b 6 sL/min, c 6.5 sL/min, d 7 sL/min, e 7.5 sL/min and f 8 sL/min

**Fig. 7** Variation of plasma plume temperature as a function of gas flow rate measured by two different methods

![Fig. 6](image_url)

![Fig. 7](image_url)
A thermocouple lies between 38 and 26 °C for a gas flow between 5.5 and 8.5 sL/min. This is comparable with the values (36–23 °C) measured through an IR thermometer. Both the temperature curves are depicting the same temperature-gas flow linear relationship. An optimized flow rate of 7 sL/min is established which irradiates the highest surface area when treated to any metal surface. The temperature of the Al plates is measured after plasma irradiation of 60 sec by an IR thermometer. The temperature ranges between 39 and 44 °C when gas flow is varied between 5 and 7 sL/min. When the gas flow rate is 7 sL/min, the plume temperature is close to room temperature (~30 °C). The higher electron temperature dominates the plasma chemical process by keeping the average plasma temperature close to 30 °C in these conditions. The highest temperature is always found at the bottom of the plasma-surface interaction region. The plume temperature is expected to be in equilibrium since it is deduced from rotational temperature [50]. The recorded temperature of the plasma plume is very close to the earlier reported rotational temperatures [51]. The observations depict that at different gas flow rates, the temperature lies within the range of the human tolerance rate (35–40 °C). This enables the irradiation of sensitive surfaces of the human body through the plasma jet without any risk of thermal damage [52].

The temperature of the plume is favorable for all kinds of plasma treatment to soft tissues of living organisms. The low-temperature profile of the plasma plume is due to the low pulse width of the obtained discharge current and absolute power. If the short pulse width is less than the characteristic time of the onset of the plasma transition, then low-temperature plasma is ejected [34]. However, the temperature of the middle of the plume region is close to 43 °C and the bottom of the plume near the nozzle of the tube is nearly 57 °C. The ion temperature is more near the nozzle than at the tip of the plume. Since the proposed plasma jet is designed for plasma irradiation for biomedical applications through the tip of the plume, the temperature of the plume tip is shown.

3.5 Plasma-human skin interaction

The current research is directed primarily at the shock-free and non-thermal effects of plasma plumes of the highest length on human skin. Fig. 8 shows the irradiation of a shock-free atmospheric plasma plume applied on different human body surfaces. During this irradiation, the frequency of the applied voltage is 72 kHz and the gas flow rate is maintained at $Q_{Ar} = 7$ sL/min. A non-clinical pilot study of CAP irradiation is conducted on three regions of the volunteer’s human body, a) fingertip (Fig. 8a, b) skin of left arm (Fig. 8b and c) exposed tongue (Fig. 8c) for 30 sec, respectively. All the precautions have been taken when the plasma irradiations are performed on a human volunteer.

This plasma application has been performed in the presence of an expert skin specialist and a dentist. In this study, no signs of irritation, infection, redness, or inflammation in any part of the volunteer’s body are observed immediately and even after several days. This is the first time a direct exposure of the non-thermal plasma is made on the tongue of the human body, which is considered the most sensitive skin surface. Since plasma propagates away from the high voltage electrodes in the free surrounding air, no electric shock or damage is incurred by the target cells or tissues [53]. The peak-to-peak instantaneous voltage at the tip of the plume is too low in this APPJ, which can not harm the target cells. The electrical conductivity of human skin depends on the biochemical and biophysical structure of the organ.
For DBD-modeled plasma jet irradiation, the skin acts as an electrode, through which a small fraction of discharge passes in mA [1]. The high frequency of the power supply generates low pulse durations of the discharge current across the skin creating a shock-free plasma effect. The effective resistance and capacitance in the biological model of the human body are considered as 60 pF and 1 MΩ [51, 54]. Therefore, the total reactance of a human body at 72 kHz frequency is ~37 kΩ. The effective capacitance of our designed plasma jet is 0.15 nF. Comparing the biological model, the net reactance of the plasma jet at 72 kHz frequency is ~14.7 kΩ. The effective resistance of the jet at 72 kHz frequency is ~47.2 kΩ. Both the resistance and reactance of the plasma jet are much lower than the biological human model values. The non-thermal atmospheric plasma generated from the high-frequency electric discharge induces electro-therapy which can treat different dermatological acute conditions [28]. This plasma plume offers a practical plasma therapy that can replace the conventional therapy of using perishable drugs for skin treatment. The thermal effect which may burn out the skin immediately is also negligible owing to the low temperature of the plume. Besides electrical safety and thermal effects, the risk factors concerning in vivo experiments include UV radiation and the induction of free radicals in the tissue [55]. The effects of UV radiation in Ar-fed non-thermal plasma do not cause any potential risk for the target tissues [56]. The induction of free radicals in non-thermal atmospheric plasma is beneficial for cell layers of the tissue as it helps in bacterial decontamination and disinfection of the skin surface [28, 57]. In recent times, it is necessary to break the transmission cycle for human infection of SARS-CoV-2. The disinfection of metal and plastic surfaces from SARS-CoV-2 is effective by Ar-fed APPJ [18]. This viral infection may spread from the hands to the respiratory tract through the mouth of the human being. The plasma plume of the proposed jet has a calm and pacifying effect in treating both hands and tongue in a noninvasive, harmless and ethical way. Since the clinical study is beyond the scope of this study, the proposed APPJ can be used efficiently for the said purpose on different body surfaces of the human body. A thorough clinical study by varying the irradiation duration may come up with interesting future aspects of APPJ in live human trials without anesthesia.

Figure 9 shows the bar diagram of different sensation effects (non-painful, tingling and heating/burning) caused after plasma irradiation to the volunteer under the experiment. The distance between the nozzle of the jet to the tongue surface is measured and named in different plume regions. Four different regions of the plume length are considered while touching the human tongue. The volunteer is having normal blood pressure and body temperature, with no past records of itching or allergy. These sensations are experienced by the volunteer after the irradiation duration of 30 sec. The blood pressure of the volunteer remains normal after the irradiation. The experiments are conducted 3 times on the volunteer and shown as an average of data recorded. The bottom of the plume signifies that the plume is touching the dorsal surface of the tongue with intense intensity. Similarly, the upper-middle and lower-middle part of the plume touches with medium intensity. A mild intensity of the plume is sensed at the top (tip) of the plume, where the full length of the plasma is touching the upper surface of the tongue. Even the intense intensity does not cause any harm to the extrinsic muscle of the tongue. The non-painful effect gradually increases from the bottom of the plume (50%) to the tip of the plume (90%). The tingling and burning sensations are higher as the plasma goes deeper into the live tissues of the tongue or lingual papillae. The tingling effect and burning effect are quite less (~20 %) at a 2.0 cm distance between the nozzle to the tongue. The tolerance effect of plasma irradiation of human skin is therefore explored by the tip of the plume for better sensations. In vivo plasma irradiation on sensitive parts of human skin by the top/tip of the plume is recommended for better and withstanding sensations. It can be concluded that the preliminary results of our study revealed that non-thermal plasma irradiation of the proposed APPJ is feasible for all parts of human skin treatment without any risk of tissue damage [11].

3.6 Optical emission spectroscopy

Figure 10 shows a typical optical emission spectrum of Ar plasma plume at room temperature and in atmospheric pressure conditions. Fig. 10a shows the argon and oxygen spectral lines in the visible (600–800 nm) spectrum and Fig. 10b...
shows the OH and N₂ emissions in the near-ultraviolet range (300–400 nm) [58]. The APPJ is operated at a frequency of 72 kHz and Q_{Ar} = 7 sL/min. The spectrum is acquired along the line of sight perpendicular to the tip of the plasma plume at a resolution of 0.02 nm.

Figure 10a and b are plotted in log scale and the main emission lines are labeled. The presence of excited Ar is confirmed in the range between 667.6 nm to 794.8 nm [38, 48]. The recombination of atomic oxygen with free electrons leads to the emission of O₂ ions at 615.4 nm, which owes its transition line from 4d^5D to the 3p^5P state [59]. Two minor peaks of O are found at 715 nm and 777 nm [48, 60]. D. Popović et al. have explained the atomic oxygen spectral line at 777 nm is actually a triplet from the 3s-3p transitions [61]. Figure 10c separately shows the magnified spectrum of the excited OH radicals from the air in the range of 307 nm to 311 nm [39]. Figure 10d shows the dominance of molecular nitrogen emissions at 337.1 nm and 357.6 nm, notably the N₂ second positive system [62, 63]. The intensity of the spectral lines is proportional to the concentration of the excited species and the electrons that have energy greater than the threshold from the ground state. The plasma plume color also confirms the presence of Ar and N₂ as discussed in sec 3.2. The surrounding air quickly diffuses into the jet where the energetic electrons excite and ionize the nitrogen molecules [48]. The reduced peaks of nitrogen are due to the penning ionization of N₂ and the charge transfer to N₂⁺ [50]. The presence of reactive oxygen and nitrogen species (RONS) signifies the effectiveness of the plasma at the biological tissue interface [40, 49].

4 Conclusion

A shock-free plasma plume is successfully generated by a variable frequency power supply. It is revealed that human skin (body) can easily tolerate 70 kHz to 90 kHz without any anesthesia. The shock-free property of the plasma plume is only due to its effect on and off time duration of the total pulse (~13.92 µs). The APPJ expelled a maximum plume length of 2.11 cm at 72 kHz frequency. The maximum plasma plume length is obtained at an Ar flow rate of 7 sL/min. A low plume temperature of ≤ 30 °C is obtained below 7 sL/min flow rate. The non-thermal plasma is irradiated to different parts of human skin, including the most sensitive organ, the tongue and the person did not experience any electrical shock. The after-effect of plasma tip irradiation is scaled as highly non-painful with mild tingling and heating effect at an optimized flow rate. The proposed APPJ can be effective in human trials in any part of the skin for disinfection treatment. This work unveils the potential of the plasma jets at the interface between plasma physics and skin biology.

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Author contributions All the authors have contributed equally to this research work.

Data access statement The data and supplementary video that support the findings of this study can be availed from the corresponding author, upon reasonable request.

Declarations

Conflicts of interest The authors declare that there is no conflict of interest.

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