Generation and transport of cold plasma in metres-long tubing for plasma medicine application in endoscopy

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Abstract: Cold plasma medicine has been under growing focus because of the considerable potential of reactive species on cells and tissues. For applications in endoscopy, a DBD-based device has been developed that allows generation and transportation of low power, helium, cold plasma discharge at the end of a several metres long flexible tube. Electrical characterization, plasma plume intensity and interaction of the plasma with its environment showed promising results.

Keywords: Cold atmospheric plasma, DBD, flexible tube, endoscopy, medicine

1. Introduction

Cold Atmospheric Plasma (CAP) medicine has been under growing focus in the last two decades [1]–[3], mainly because of its convenient carrying medium (i.e. gas that can reach every interstice) and of the effect of its Reactive Species (RS). These RS and Reactive Oxygen Species (ROS) in particular have shown various biological effects on cells, such as the triggering of a cell-induced death (apoptosis) without inflammation [4], [5] which represent a powerful tool for treatment of tissues while reducing post-operative complications. More specifically, cold plasma combined with mini-invasive procedures such as therapeutic endoscopy might be particularly promising.

To our knowledge, only few studies report endoscopic applications of CAP at a pre-clinical stage. Two of them show similarities with the device proposed in this project: the plasma gun from GREMI targets cancer therapy with a nanopulsed neon plasma flushed through a capillary able to fit in an endoscope [6], [7] and the device developed by Polak et al. [8] consisting of argon CAP for decontamination of tubes in flexible endoscopy.

In this work, a system allowing to generate cold plasma through a Dielectric Barrier Discharge (DBD) in a helium gas flow and to transport this plasma in post discharge over several metres through an endoscope is presented. Electric measurements, plasma plume evolution with power, interaction of the system with its environment and evaluation of surface treatment by contact angle are detailed.

2. Material and methods

The plasma reactor used in this work (shown in **Fig. 1**) has similar features to the system developed by Kostov and al. [9]. Its core part consists of a tubular DBD-chamber made in quartz, connected upstream to a helium gas cylinder, an admission valve, and a flowmeter. The high voltage electrode consists of a copper tape wrapped around this chamber. The generator used is an AFS (G10S-V) coupled with an AFS 1-6kHz electrical transformer and power controlled. The chamber is plugged to a PTFE tube. A metallic wire is inserted partially into the dielectric chamber and extends until the end of the PTFE tube

Measurements were collected with a Tektronix DPO 3032 Digital Oscilloscope connected to a high voltage probe (Tektronix P6015A 1000x3pF 100mOhms) and a current monitor (Rogowski coil Pearson model 2877 output 1V/A) placed along the PTFE tube. Pictures were taken by a Nikon D90+ in manual mode, manual focus, ISO 1000, shutter speed 1”, focal 8 in a dark room. Contact angle measurements were taken on LDPE sheets treated with the cold plasma plume with a Kruss DSA-100 analyzed with the Drop shape Analysis software, by selecting the Tangent fit.

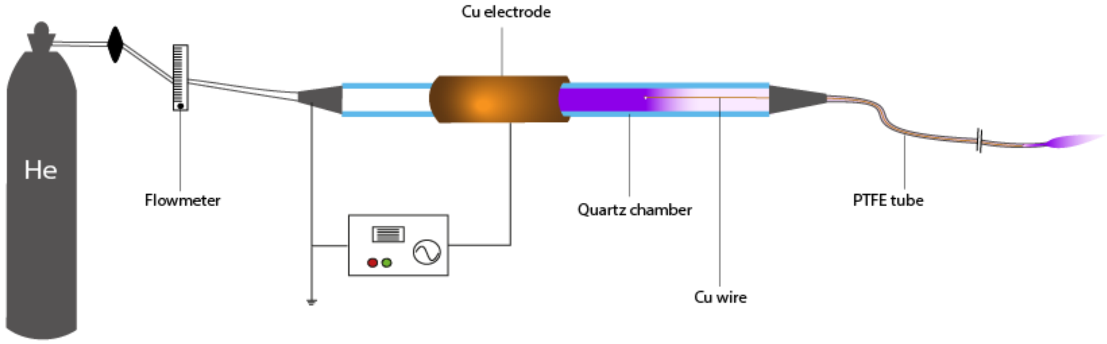

Fig. 1. Schematic setup of the DBD reactor (patent n° EP19153548.3 submitted [10])

3. Results

A study was carried on the power influence on the plume intensity and the current shape to assess the distinct states of the post discharge. **Fig. 2** shows the plasma plume at the end (230 cm) of the PTFE tube. A strong correlation can be observed between power and plume length. Above a certain threshold (40W), the plume length seems to reach a plateau.

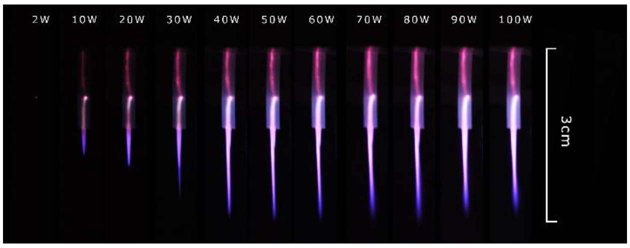

Fig. 2. Picture of plasma plume at the end of the PTFE tube for input power from 2 to 100W

Fig. 3 gives the shape of the current for a power increasing from 2W to 100W. A change in the post discharge state can clearly be observed. First between 2W (no ionized helium) and 10W, which is simply the ignition of the discharge. Then, when increasing the power, a second state appears between 30W and 40W. From this power value, all the curves of current present a peak. As observed by Fang et al. [11], the current is periodic but shaped differently from half-positive and half-negative cycles.

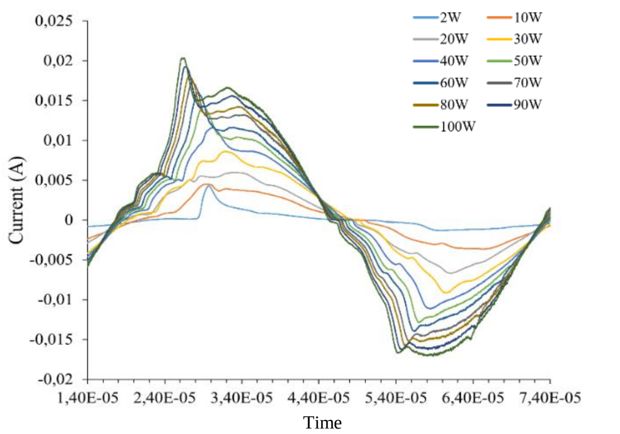

Fig. 3. Current shape evolution as a function of the input power (from 2W to 100W). Measured 30 cm from the electrode.

To better understand the behaviour of the post-discharge and the transport of plasma in the tube, the current in the tube was measured with Rogowski coils at different distances from the high voltage electrode at a power of 50W. **Fig.4** shows a compilation of curves of current obtained along the tube at 50cm interval. A linear decrease along the tube is observed, with a very low current (in red) at the output, solely consisting of sporadic peaks.

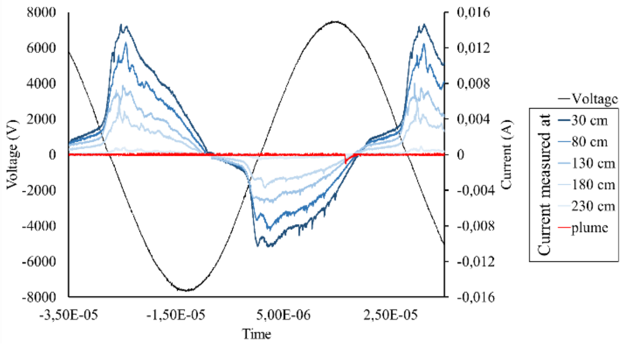

Fig. 4. Current evolution along the tube

When repeating the measurements for tubes of different total lengths and computing RMS current at each point (see **Fig. 5**), the linear decrease proves to be highly consistent, with an average slope of $-32 \pm 2.9\ \mu A/cm$.

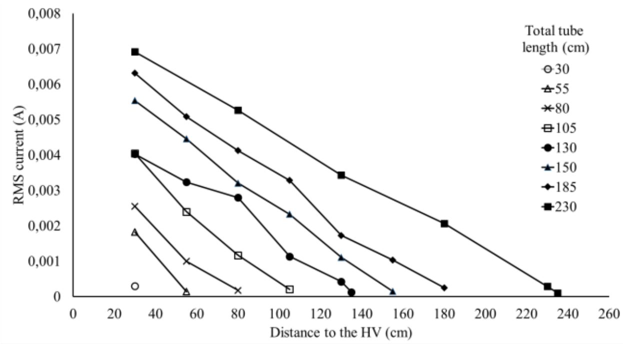

Fig. 5. RMS current evolution for different tube lengths

The current losses are likely to be capacitive leaks all along the dielectric tube, explaining the higher current for longer tube presenting a lower impedance because of their extended surface. While tube length determines the current at the start of the tube, the current at its end is similar for all lengths, with values around 0,2 mA. This low value allows to touch it, as shown in **Fig. 6**.

Fig. 6. The plasma current and temperature are compatible with contact with skin

Table 1. Contact angle analysis of treated LDPE sheets

		Position from plume impact (cm)					Treatment average
		2	1	0	-1	-2	
Treatment (power and duration)	control	103	103	103	103	103	103
	50W 30s	91	81	88	98	96	91
	50W 120s	92	71	62	85	95	81
	80W 30s	92	91	69	83	86	84
Position average		92	81	73	88	92	

The interaction of the plasma system with its environment is very dynamic since contact with the tube or the plasma plume influences the whole system with change in plasma intensity and current, along with a visible increase in photon emission. The influence of the contact between the endoscope and the tube when this latter is inserted through the working channel is illustrated on **Fig. 7** with an important but reasonable current increase in the endoscope.

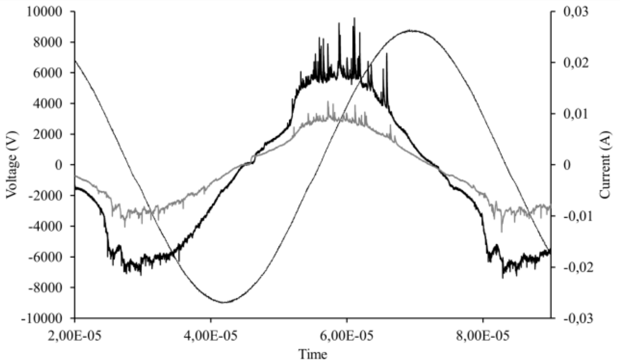

Fig. 7. Current in an endoscope (in black) and in air (in grey)

However, no significant change in current shape or behaviour is observed and the plasma comes out properly at the end of the tube (see **Fig. 8**) which is very promising for future applications.

Fig. 8. Cold plasma plume exiting the endoscope

Finally, the surface treatment effect of plasma plume was assessed on LDPE sheets by measuring the modification of wettability by contact angle after a treatment with the plasma plume at 3 cm of the sample. The influence of position with respect to the plasma plume impact on the sheet, of the power injected in the system and of the treatment duration were investigated. Results are presented in **Table 1**. In terms of position, the plasma treatment has a significant effect at every measured point (0 being just underneath the plume, other values at x cm from it) with a difference of at least 5° compared to the control sample. The effect is however much more significant directly under the plasma plume. Treatment duration also shows a significant effect with a 10° difference when averaging the positions for the treatments at 30s and 120s, mainly because of a stronger effect at position 0. Finally, power has a similar effect with a 7° average drop and a stronger treatment under the plume, which is consistent with the results presented before showing a stronger plasma at higher power even though both power values used here are in the “plateau” aforementioned.

This highlights the importance of three crucial parameters; position of the plume, treatment duration and power. These will be critical in further tests and for a fine tuning of treatment effect for medical applications.

4. Conclusion

An explorative study has been carried out on a new method for transporting cold atmospheric plasma over long distances. Analysis of power influence on plasma plume intensity exhibited several types of plasma behaviour. The evolution of the current along the flexible tube demonstrated capacitive current leaks in the PTFE tube. The current at the output of the tube (i.e. at the plume) is quite constant, regardless of its length. Contact angle analysis showed the influence of plasma plume position, treatment duration and power, while proving the efficiency of the surface treatment.
Therefore, this work shows the efficiency of combining DBD configuration and a metallic wire inside a flexible tube for transport. Results presented here are promising for the development of cold plasma medical devices in the field of flexible therapeutic endoscopy.

5. References

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