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Analysis of Reactive Species in a Plasma Flow for Medical Treatment

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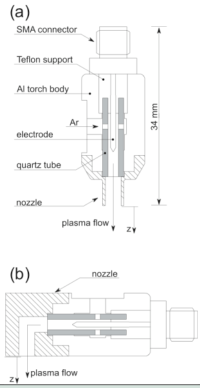
Abstract

Chemical characteristics and bactericidal properties of two low-temperature atmospheric-pressure Ar plasma devices were investigated: one of them with UV and the other with almost no UV on treated samples. The control of the UV radiation was achieved by two nozzles. One has a straight shape, and the other has a 90°-bent. The bent nozzle blocks the light produced inside the torch whilst allowing the plasma gas to reach the samples. The use of the straight nozzle allows the treatment by both the plasma gas and UV. We demonstrate that even an almost UV-free plasma treatment has bactericidal properties. Our measurements suggest that reactive species represent the main bactericidal factor of our low-temperature plasma.

Experimental Setup

In our group, a small microwave plasma torch has been developed for the purpose of living tissue disinfection. The torch consists of a 24 mm long aluminum tube, a quartz glass and a titanium powered electrode of 1 mm in diameter with a sharpened tip. The powered electrode is placed coaxially in the quartz tube covered by the aluminum tube. The plasma was produced between the tip of the powered electrode and the surface of the quartz tube using a microwave power of 1.7 W at 2.45 GHz and Ar (purity 99.998 %) flow of 500 sccm. The plasma produced inside the torch flows out from the nozzle (2 mm in diameter). In order to control the UV power on the sample, two nozzles have been developed: one has a straight and the other a 90º-bent shape (depicted with slanted lines in figure (a) and (b)). When the straight nozzle is used, the light from the plasma production region reaches the sample. The bent nozzle allows almost no plasma-produced light on the sample. However, it does not block the plasma flow (see figure (b)).



Analysis of plasma flow

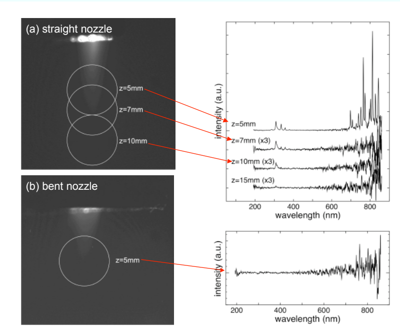
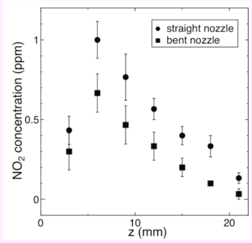
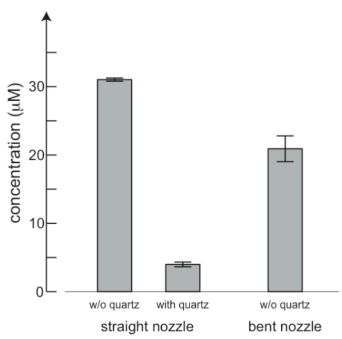


Figure (a) and (b) show a side view of the plasma flow below the torch with the straight or bent nozzle, respectively. The plasma density in the flow with the straight nozzle was higher than that with the bent nozzle. In figure (c), the spectra (at various distances) from the plasma produced by the torch equipped with the straight nozzle are shown. The circles in figure (a) and (b) show the field of view for the spectroscopic measurements. According to the spectroscopic measurements, Ar dominates in the vicinity of the nozzle (multiple lines in the long wavelengths). Besides, the line at 309 nm indicates the presence of OH in this area. As *z* increases, the light intensity decreases. The presence of reactive species is evident in the plasma flow equipped with the straight nozzle from the lines in UV. Because of the low plasma density, no clear signal was detected in the plasma flow produced with the bent nozzle as shown in figure (d).



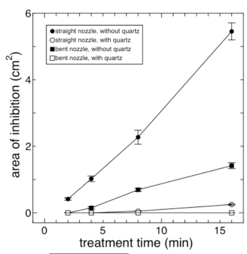
As shown in the figure, the usage of the straight nozzle allowed us to achieve higher concentrations of NO_2 in the plasma flow than the bent nozzle. At *z* = 6 mm, the maxima of NO_2 concentration were ~1 ppm and ~0.65 ppm with the straight and bent nozzles, respectively. A relatively high concentration of NO_2 at *z* = 6 mm is an indication of an effective mixing of the plasma flow from the torch with the ambient air around this position.

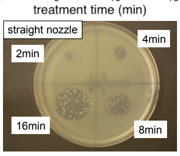
Plasma interaction with liquid



In order to investigate plasma interactions with liquids, we measured H_2O_2 concentration in 100 μl of de-ionized water treated with plasma for 10 minutes. Our measurements show that the concentration of H_2O_2 produced in water by plasma irradiation with the straight nozzle (~31 μM) was higher than that obtained with the bent nozzle (~21 μM). There are two processes that can contribute to the observed production of H_2O_2 in water: the diffusion of the plasma-generated reactive oxygen species from the gas phase and UV-induced photolysis of water molecules.

Bactericidal effect (*E. coli*)





In order to compare bactericidal properties of the UV-rich (with the straight nozzle) and UV-free (with the bent nozzle) plasmas, we irradiated a solid agar medium inoculated with *E. coli* with plasmas produced by the two torch configurations. The results of the experiments with the two types of plasmas are summarized in the figure. Independently of the type of nozzle used, a positive correlation between the diameter of the agar surface area cleared of bacteria and duration of the plasma treatment was observed. However, the diameter of the bacterial growth inhibition area was smaller for the bent nozzle. This decrease in the bactericidal efficiency is explained by the geometry of the bent nozzle –resulting in an over 100-fold reduction of UV power and also in a lower density of reactive species at the sample position. Nevertheless, the results of this experiment show that UV-free plasmas have a significant bactericidal capacity. Such plasmas can be used for medical applications without any limitations due to the mutagenic effect of the UV radiation.
In additional experiments, bactericidal effects were compared for treatment with and without the quartz glass. These experiments showed that UV radiation was not the main bactericidal agent in our device.

Summary

- By changing the nozzle shape, the plasma flow with almost no light can be applied to samples.
- The UV-free plasma flow is weaker in reactive species density than the plasma with UV due to the shape of the nozzle. However, the UV-free plasma flow still has a bactericidal effect which is due to reactive species and charged particles.
- Both the plasma with the straight and bent nozzles can produce hydrogen peroxide in water. Partially, this production is by UV light.