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Plasma-Activated Vapor for Sanitization of Hands

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ABSTRACT: Compliance with established hand hygiene protocols is extremely low in clinical units because these protocols mandate long hand-washing times. This phenomenon results in more numerous healthcare-associated infections and severely compromises the health of patients. Poor compliance is motivated by the hand-washing times required by soaps and sanitizers, which can be as long as 2 minutes. Cold atmospheric plasma is an alternative antimicrobial technology that can reduce the time required for sanitization to approximately 5 s. However, despite many advantages, existing plasma devices generate ozone as a toxic byproduct in high concentrations, so there is a need for a plasma-based hand sterilization system that: (1) produces enough reactive oxygen and nitrogen chemical species to achieve a microbial kill rate that is able to compete with existing hand-sanitizing technology and (2) counteracts the conversion of plasma into ozone. The design presented here used water vapor to perform these functions and to stabilize reactive plasma species. The plasma system delivers a plasma-activated water vapor mixture to a hand surface by the action of a humidifier that is much safer and more efficient than other plasma sanitization systems on the market. The operational prototype consists of three stages: ultrasonic water vapor generation, dielectric-barrier discharge plasma generation, and a dispensary tubing system. We have shown that the device is capable of disaggregating bacteria in 5 s with significant reductions in ozone concentrations through the use of water vapor.

KEY WORDS: plasma medicine, sanitization, healthcare-associated infections, ozone, hand hygiene

I. INTRODUCTION

Compliance with established hand hygiene protocols is as low as 43.2% in intensive care unit settings.[1] This compliance rate is far below the 90% recommendation from the Joint Commission.[2] Poor handwashing compliance has been associated with cross-transmission of healthcare-associated infections (HAIs) and heightened mortality rates in hospitals. The Centers for Disease Control and Prevention (CDC) has determined that one of the main reasons for substandard hand-washing compliance is the length of time required for these protocols; in fact, most physicians do not comply with the long hand-washing times required for effective sanitization.[3] For example, proper sanitization using alcohol-based sanitizers (ABS) requires approximately 30 s and using antimicrobial hand soap requires at least 1 min in order to be effective.[3] Nevertheless, the average duration of hand washing for health care personnel remains at around 4.7–5.3 s (Fig. 1).[3]

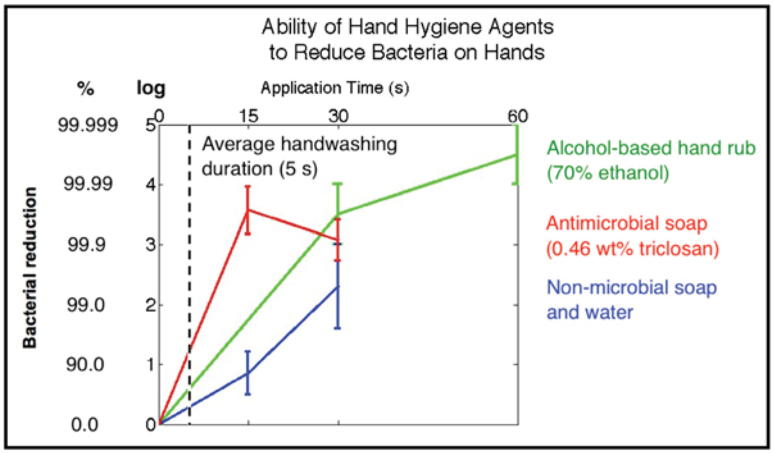

FIG. 1: Graphic of the average handwashing duration and bacterial reduction for three commonly used handwashing methods. Note the average handwashing duration of 5 s (dotted line).[4–6]

Cold atmospheric plasma (CAP) sterilization is an alternative to commonly used sterilization techniques due to its many advantages: it is fast, efficient, and safe in terms of chemical, radiative, and thermal damage.[7] Plasma can sterilize surfaces in less than 1 min and with a greater degree of bacterial inactivation than soaps.[8,9] When water is used as a carrier for plasma, the mixture remains active on the scale of days, significantly longer than the time required to wash one's hands. Despite its promise, plasma sterilization has not seen widespread implementation in the clinical setting for several reasons.

First, the application of CAP for medical uses is quite new, which makes devices expensive to purchase.[10] The use of liquid water as a carrier has some disadvantages. When bacteria are submerged in plasma-activated water, "neither electrons nor ions can interact directly with the surface of the bacteria since these electrons or ions are strongly absorbed by the liquid."[11] Using liquid water as a carrier also hinders the ability of CAP to interact with bacteria.

Many plasma devices also suffer from the nonspecific generation of ozone, which is a naturally occurring side product of plasma. The reactive plasma species that have a short half-life may recombine or radicalize O_2 as shown in Mechanism 1: generation of ozone from diatomic oxygen and reactive plasma species[12]:

$$O_2^- + e^- \rightarrow 2O^\bullet + e^-$$
$$O^\bullet + O_2 + M \rightarrow O_3 + M \text{ (with } M = N_2 \text{ or } O_2\text{)}$$

Although ozone has been shown to have some antimicrobial properties, its formation requires the consumption of reactive plasma species. In addition, it is a powerful oxidant and damaging to respiratory and mucous tissues at minute levels.[13] Although no extensive studies have been done on the dangers of ozone to humans, according to the CDC, ozone is acutely hazardous at concentrations of 5 ppm.[14] Plasma devices produce upwards of 100 ppm ozone.[8,9,15–17] Therefore, there is a need for a plasma sterilization system using an alternative delivery method that increases the effective plasma concentration and reduces or counteracts the conversion of plasma into ozone. In particular, such a device should have an ozone production of below 300 ppb ozone, which is the permissible short-term exposure limit set by the Occupational Safety and Health Administration (OSHA).[18]

To reduce the ozone produced by a plasma device, water vapor can serve as an ozone scavenger. It may increase effective plasma concentrations by forming radical species that consume ozone through Mechanism 2: conversion of ozone molecules into ROS[19]:

$$H_2O + e\text{-} \rightarrow H^{\cdot} + HO + e\text{-} \quad (1)$$

$$H^{\cdot} + O_3 \rightleftharpoons HO^{\cdot} + O_2 \quad (2)$$

$$HO^{\cdot} + O_3 \rightleftharpoons HO_2^{\cdot} + O_2 \quad (3)$$

$$HO_2^{\cdot} + O_3 \rightleftharpoons HO^{\cdot} + 2O_2 \quad (4)$$

Stable water clusters also form readily in atmospheric conditions through the interaction of water vapor and ions, which are a key constituent of reactive plasma species.[20] Because gaseous water vapor has a mean free path length 750 times longer than liquid water, it has an increased charge-carrying capacity and can increase the effective plasma concentration.[21,22] Due to its natural interaction with ions in forming a thermodynamically stable structure, water vapor can also be used as a carrier for plasma particles.[23] Given the attractiveness of using water vapor as a carrier and scavenger, a device was created that delivers stable, plasma-activated water vapor to a surface using a hand dispensary system.

II. MATERIALS AND METHODS

This prototype was designed with the purpose of providing a means to sanitize hands effectively in healthcare settings while catering to the average amount of time health care professional spend washing their hands. Unlike other conceptual plasma sanitization systems, this design utilizes water vapor to increase effective plasma concentrations and to scavenge the harmful ozone byproducts of plasma generation. This device achieves hand sanitization by utilizing a combination of plasma-activated air and water vapor. This device can be broken down into three key components: (1) water vapor is generated by an ultrasonic humidifier, (2) plasma is generated by dielectric-barrier discharge (DBD), and (3) the plasma/vapor mixture is applied onto the surface of hands (Fig. 2).

In the first stage, water vapor is generated using an ultrasonic humidifier (Pure n' Natural Travel Humidifier). The vibration of a small plate in the humidifier provides suf-

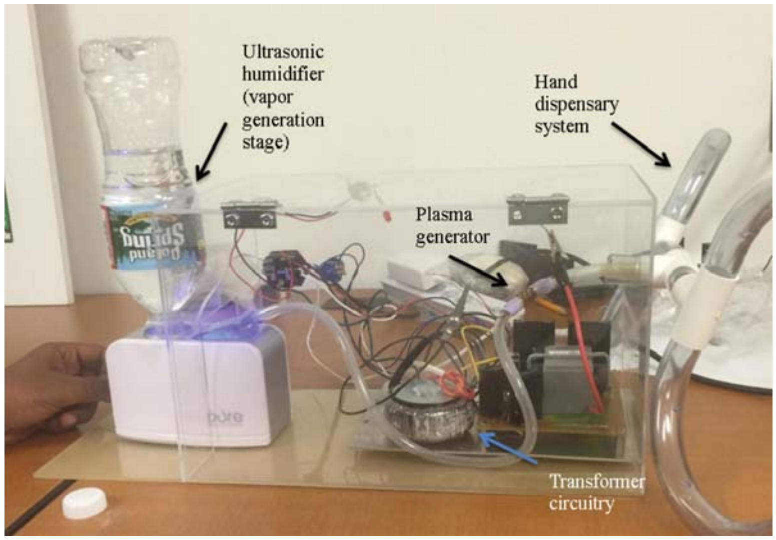

FIG. 2: Overview of the operational prototype. The stages have been labeled for clarity.

ficient energy to vaporize water an average rate of 2.7 oz/h. The humidifier is designed to output a steady stream of water vapor with a single outlet, creating an air current that is directed toward the plasma generation stage using flexible ⅜-inch PVC tubing (Fig. 3).

In the second stage, CAP is generated via DBD. The plasma generator was constructed previously at the Drexel Plasma Institute and is diagrammed in Fig. 4.[24] The cylindrical high-voltage electrode surrounds the grounded electrode at a gap distance of 0.32 cm (1/8 inch). At this gap distance, according to Paschen's law, 10.24 kV must be applied to induce ionization of air molecules at standard temperature and pressure conditions. The electrical components of the design are capable of transforming the 120 V_{AC} output from a wall socket to a range of 4–25 kV and 20 kHz, which is sufficient to ionize air molecules. The key component in accomplishing this high voltage is transformer winding (part no. CHT-0126G; Ramsey Electronics). The dielectric used is a 6.4 mm (1/4 inch) diameter quartz tube, with wall thickness of ~0.05 cm (0.02 inch) and a length of 25 mm (1 inch). This quartz tube is connected to the 3/8-inch PVC tubing via a 3D-printed adapter. With the application of the high voltage to the electrodes, small electrical streamers form between the electrodes, generating reactive oxygen and nitrogen species.[25] The incoming water vapor interacts with the charged plasma particles as described previously.

In the third stage, the particles maintain their forward velocity due to the air current generated by the humidifier. The particles are directed toward the hands via tubing and deposited directly on the surface of the skin via small orifices (Fig. 5). At this point, they interact with any present microorganisms and eliminate them. It is the user's responsibility to ensure adequate coverage of all surfaces of the hands by moving his or her hands throughout the 5 s of application, similar to washing hands. The diameter of each deposi-

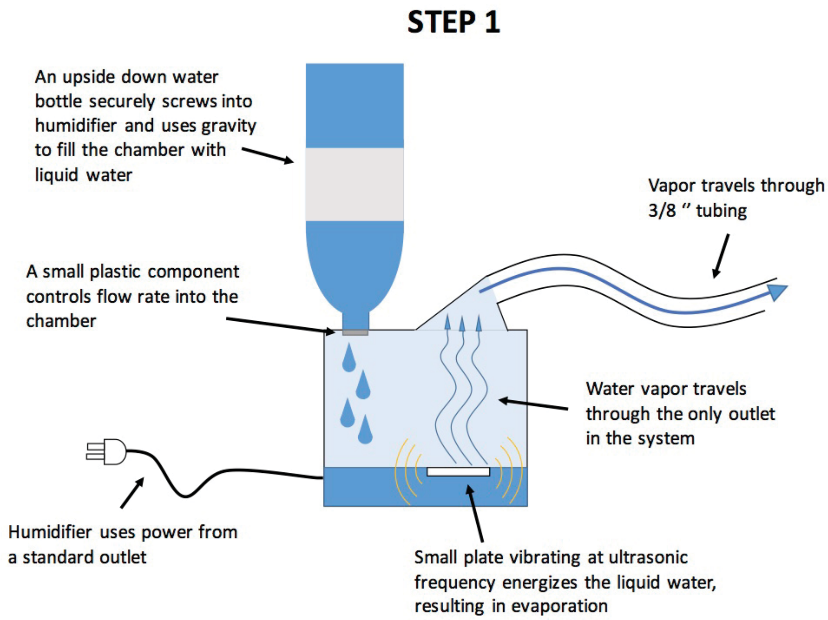

FIG. 3: Water vapor generation stage by ultrasonic humidification. The humidifier produces an average moisture output of 79.84 mL/h, corresponding to a volumetric flow rate of 3470 L/h. Flexible PVC of 3/8-inch outer diameter secures the humidifier to the plasma generator.

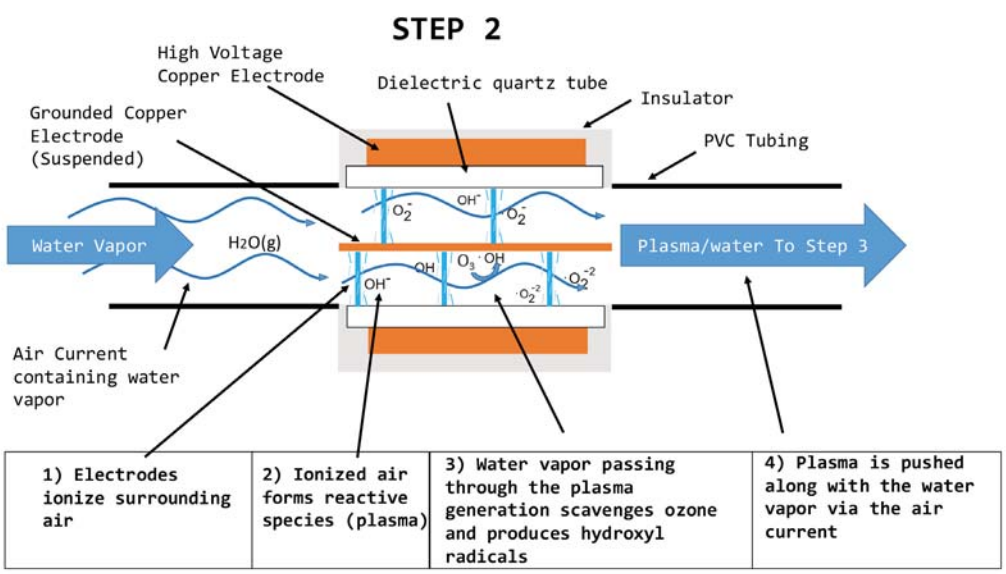

FIG. 4: Cross-sectional diagram of the plasma generation phase. There are two copper electrodes: the high-voltage electrode wraps around the outer edge of the quartz tube and the low-voltage electrode is suspended at the center. Water vapor generated in the humidification stage is driven through this stage by an air current.

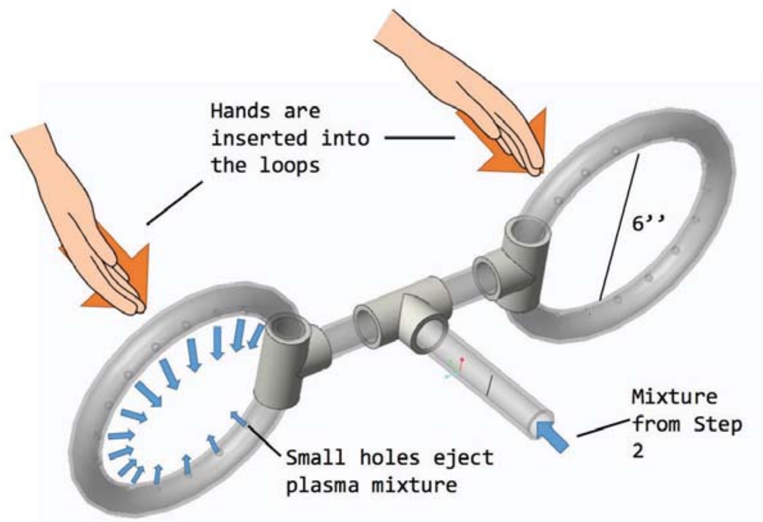

FIG. 5: Hand dispensary tubing system. The output from step 2 contains plasma-treated water vapor clusters, which are passed through the PVC tubing and deposited onto the user's hands through 18 3/16-inch holes along the inner edge of the rings.

tion ring is 6 inches because the average width of a human hand is slightly greater than 3 inches for males: this ring size is large enough for the hand to fit comfortably, but small enough for sufficient coverage. The user is requested to rotate their hands 180° clockwise and counterclockwise to provide a more even coverage to all parts of the hand.

III. RESULTS AND DISCUSSION

To develop a successful design, the first requirement was for the plasma-activated vapor device to kill bacteria as effectively as current sanitization methods, but within 5 s. A test of the antimicrobial function of the device was considered successful if there was disaggregation, or reduction in *E. coli* colony area, after plasma treatment comparable to ABS- and soap-treated controls. *E. coli* bacteria have been used to test the efficacy of DBD plasma in the past and bacterial disaggregation is a metric that has been used to evaluate the efficacy of sanitization methods such as soaps.[24,26] In the control group, *E. coli* bacteria (16000:1 dilution) were spread onto agar plates using the streak method and incubated for 24 h. Positive controls were then treated with mock antimicrobial soap (0.2% SDS) and ABS (8.75% ethanol solution). The experimental plates were treated with plasma-activated vapor produced at voltages between 4 and 22 kV and for time periods ranging from 5 to 20 s. It was observed that all positive control and experimental plates except the 4 kV application had a significantly lower average colony area than the control plate (Fig. 6). This is consistent with the bactericidal properties of ABS and antimicrobial soaps and confirms that these treatments do interact with *E. coli*. Although a 4 kV application was ineffective because no plasma is produced below the breakdown

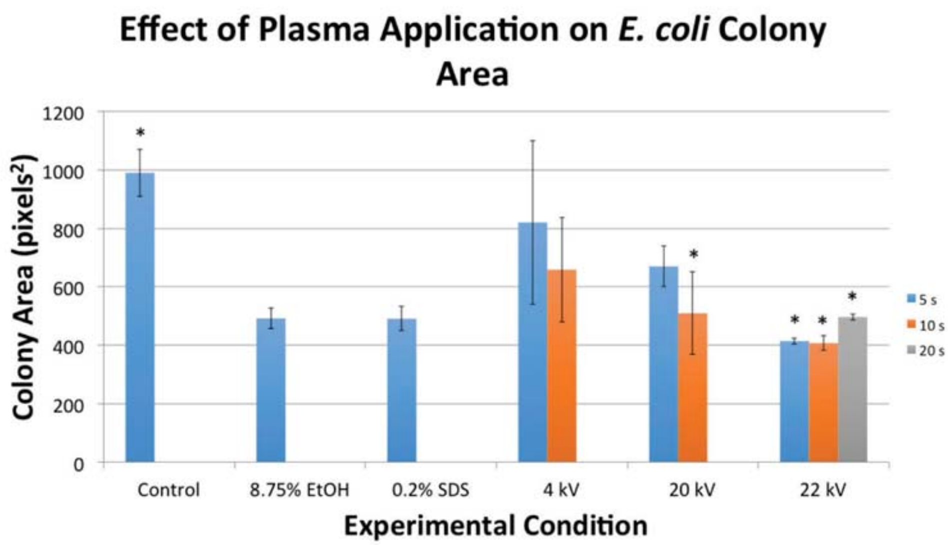

FIG. 6: Effect of plasma application on *E. coli* colony area. Various controls were implemented for current hand sanitization methods, three voltage settings were used, and the application time ranged from 5 to 20 s. Asterisks denote equivalent or lower colony area compared with ethanol and sodium dodecyl sulfate (SDS) controls ($p < 0.05$).

voltage of air, the test was successful in showing that plasma treatments reduce colony area significantly compared with an untreated control. Importantly, the difference in colony area between the positive controls and a 5 s application of plasma produced at 22 kV was statistically insignificant ($p < 0.05$).

The device was also considered to meet specifications if there was a reduction in ozone production below 300 ppb after the addition of the vapor generation stage. An ozone monitor (2B Model 202, InDevR, Boulder, CO) was used to measure the concentration of ozone at the output of the plasma generator. A calibration measurement was taken with the device turned off, revealing an atmospheric ozone concentration of approximately 10 ppb. A total of six different experimental conditions were tested, from 4 to 22 kV and with and without additional humidification (Fig. 7). A two-sample *t* test was performed to check for statistical differences between the groups. It was concluded that the addition of water vapor reduced ozone concentrations significantly at the 4 and 22 kV voltages. Analyses were not performed for the 20 kV voltage setting because data were only obtained from one trial. In the test conducted at 20 kV, we saw an increase in ozone production when water vapor was introduced, which was atypical and inconsistent with all of the other tests conducted. This could be attributed to the lack of testing trials conducted at that specific voltage and further studies must be done. It may be concluded that the administered volumetric flow of water vapor is enough to scavenge oxygen radicals and prevent ozone generation significantly during the device's operation.

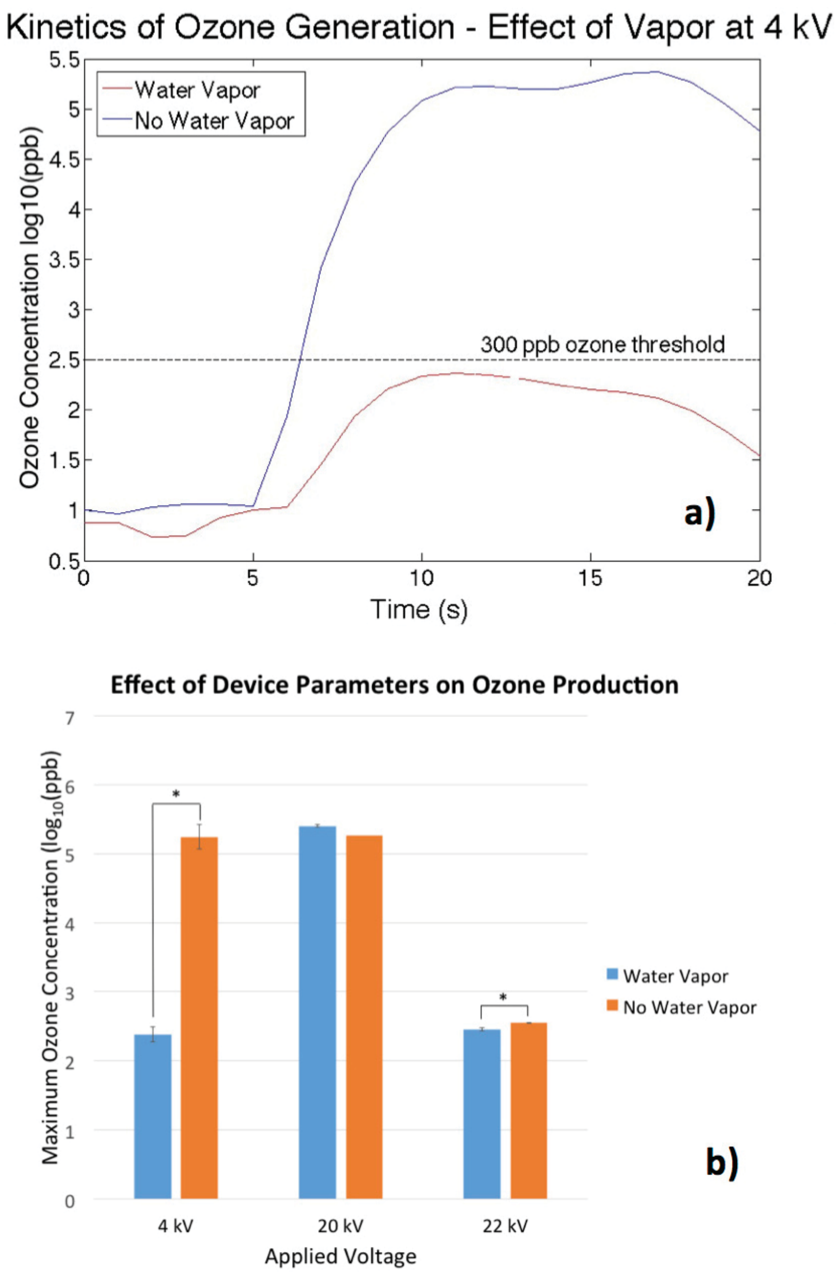

FIG. 7: (a) Kinetics of ozone generation at a 4 kV operating voltage with and without humidification. The dotted line represents the 300 ppb threshold and a steady delivery of water vapor keeps ozone concentrations below this level at all time points. (b) Ozone production of the plasma device at various applied voltages and in the presence or absence of humidification. Asterisks denote a statistically significant difference in ozone concentration after administration of water vapor.

IV. CONCLUSION

Based on the testing results, the plasma device successfully achieves a bacterial colony disaggregation comparable to soaps and ABS in 5 s. It also produces water vapor that acts both as a carrier and ozone scavenger, reducing ozone concentrations to below the 300 ppb OSHA threshold.

CAP for hand sanitization purposes has distinct advantages over its alcohol- and soap-based counterparts. Because the sanitization time of plasma-activated vapor is comparable to the average hand-washing time of healthcare providers, an increase in hand hygiene compliance and a decreased incidence of HAIs is expected. Studies have shown that mortality, cost, and length of hospital stays were significantly higher in patients with HAIs compared with patients without HAIs.[27] However, current DBD plasma products have undesirable characteristics, such as the production of significant amounts of ozone and use of carriers that interfere with bacterial inactivation properties. Conversely, the device described here uses water vapor to counteract ozone production while stabilizing reactive plasma species to be applied to the hand.

To better the design and mitigate some of the risks that are associated with ozone, a fan exhaust system may be implemented to siphon ozone out of the dispensary tubing and into a disposal system. The circuitry seen in Fig. 2 may also be better isolated from the vapor components as a prophylactic measure against leakage. Optimization of the geometry of the hand dispensary system is also highly recommended and specific tests may be performed to assess the hand surface coverage of plasma-activated vapor. Finally, integration of a “smart” feedback system will allow for constant monitoring of the quality of plasma production. Using modalities such as electrical conductivity, optical spectra, and acoustic emission, the user can remain informed throughout the device’s runtime. In summary, we developed a device that uses water vapor as an ozone scavenger and a carrier molecule for CAP delivery to human hands.

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