

# Development of Nonthermal Plasma-Assisted Hand Sanitization

Charles Bailey,<sup>a,\*</sup> Krishnateja Pemmaraju,<sup>b</sup> Michael Phan,<sup>b</sup>  
Arvind Radhakrishnan,<sup>b</sup> & Alvin Thomas<sup>a</sup>

<sup>a</sup>School of Engineering, Drexel University, Philadelphia, PA; <sup>b</sup>School of Biomedical Engineering, Drexel University, Philadelphia, PA

\*Address all correspondence to: Charles Bailey, 938 Emerald Bay, Laguna Beach, CA 92651; shicktopher@gmail.com

**ABSTRACT:** Proper hand sanitization is an important practice necessary to reduce the spreading of nosocomial infections and is crucial in medical settings such as clinics, waiting rooms, and emergency rooms. Currently, insufficient measures are taken to reach the standards: medical professionals claim that the required time for current techniques frequently exceeds the time they have available. Thus, the manner in which liquid hand sanitizer is used today does not sufficiently sterilize the hands. There is a clear and documented prevalence of user error in the application of hand sanitizer and, as such, its usage does not achieve the sterilization requirement. The plasma-assisted hand sanitization system, presented in this paper, consists of three stages: first we generate small droplets in the air, next we treat these droplets in dielectric barrier discharge plasma, and finally we apply this plasma-treated mist to the user's hands. We report on the generation of plasma in the presence of droplets and show the antimicrobial activity of these droplets.

**KEY WORDS:** plasma medicine, sterilization, disinfection, hand washing, hospital hygiene

## I. INTRODUCTION

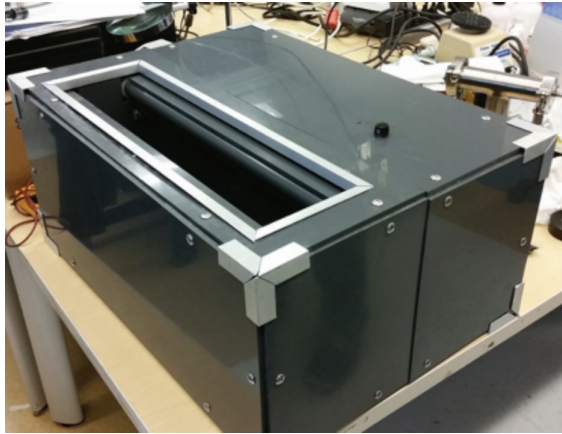
The *American Journal of Infection Control* states proper hand sanitation results from 2 min of hand washing, with 30 s of scrubbing with soap, or the application of liquid hand sanitizer for a full minute.<sup>1</sup> Proper hand sanitization is an important practice that needs to be conducted in medical settings in order to satisfy hand hygiene standards for medical staff.<sup>1</sup> Microorganisms reside on almost every surface, and while the skin serves as a protective barrier against harmful pathogens, they can still be introduced internally through openings in the body including incisions made during surgery.<sup>2-4</sup> In the United States alone, the CDC estimates 1.7 million health-care associated infections each year that result in approximately 99,000 deaths.<sup>5</sup> To avoid infection, medical staff is directed to follow hand sterilization protocol throughout the day to minimize the chances for infection.<sup>6,7</sup> Because the most common mode of pathogen transmission is via the hands, hand hygiene is maintained with proper hand washing technique or with the use of alcohol hand sanitizer.<sup>8,9</sup> Currently, insufficient measures are taken to reach these standards. One hypothesis is that the practice of proper hand sterilization takes up too much time, in the eyes of many health-care workers.<sup>5,10</sup> The Centers for Disease Control and Prevention state the average time hospital personnel spend washing their hands is no greater than 15 s, falling incredibly short of the 2 min it should take to fully

wash one's hands.<sup>1</sup> If, however, health-care workers followed proper hand sterilization protocol during an 8 h shift, that person would spend an average of 56 min of hand washing, or 18 min using alcohol hand sanitizer. Observational studies have shown that medical staff wash their hands up to 30 times per shift on average.<sup>1</sup> With the increasing threat of antibiotic-resistant pathogen strains, it is necessary to find a more effective and efficient means of hand sterilization that will reduce levels of harmful microbes in hospitals, as well as increase compliance due to the decreased time of sterilization. Our proposed solution intends to be more efficient compared to commercial alcohol sterilization products that are currently on the market. To be commercially viable, such a device should be able to achieve a 5-log reduction (99.999%) in bacteria and other pathogens, in 5 s or less. By spraying plasma-treated water droplets on the hands, we hope to achieve this high standard and decrease the potential for user error by providing sufficient coverage. We envision a system similar to the Dyson Airblade hand dryer, for example. The device will turn on automatically through infrared sensors for a few seconds and turn off with an audible and visual alert that the hands are disinfected and can be removed.<sup>11</sup>

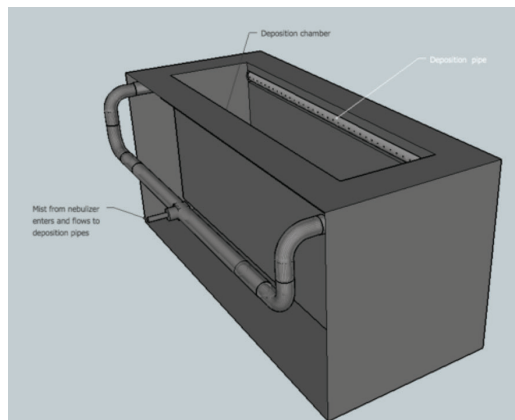
## II. MATERIALS AND METHODS

The constructed proof of concept system was designed to fit the need for a hand sterilization device that offers better performance and efficacy than previous methods as well as potentially increase hand hygiene compliance within hospitals. The device utilizes plasma-activated antimicrobial water droplets to effectively sterilize users' hands. The approach and main advantage in the design is cost effectiveness. We used affordable materials and existing components to prove that this device can be built in an economical fashion. To achieve this method of sterilization, water acts as the plasma-treated solution, and three key stages can be identified. The liquid water is atomized in stage 1, treated in stage 2 with a dielectric barrier discharge (DBD) plasma to reach floating potential and is given antimicrobial properties, and finally applied to the user's hands in stage 3, utilizing the deposition pipes.

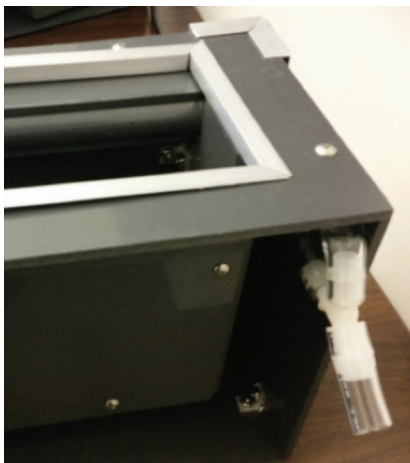
The atomizing component used in the final proof of concept was a Spider Neb II, which can be purchased for \$35.00 (Drive Medical, Model No. 18021). Water is pumped from a well within the contained atomizer to a piston-powered compressor and vaporized into droplets under 5  $\mu\text{m}$  in diameter at 11 l/min airflow rate under a maximum pressure of 40 psi. A PVC tubing network channels the droplets from the nebulizer, through the DBD chamber, and then to the deposition pipes (Figs. 1–4). The 5/8 in. tube connects to the terminus of the nebulizer as well as the adapters for the deposition pipes. The 1/4 in. tube connects the 5/8 in. tube to the DBD chamber and vice versa on droplet treatment. The DBD chamber is comprised of a quartz tube measuring 1/4 in. in inner diameter and a wall thickness of  $\sim 0.02$  in. Two copper wires were used as the electrodes: the cathode coiled around the outer dielectric wall, and the anode centered inside the quartz dielectric.



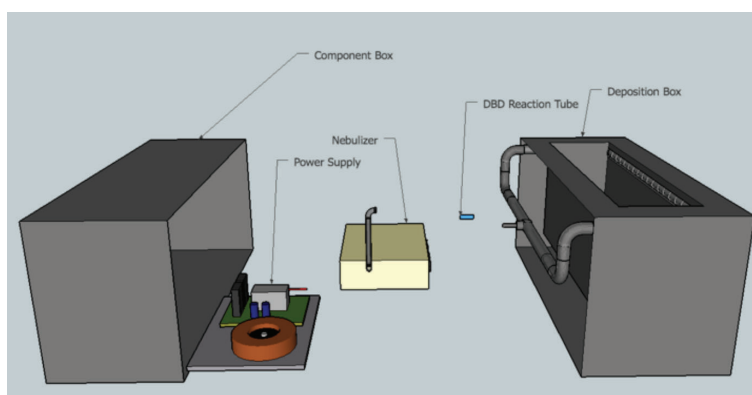
**FIG. 1:** Photograph of the plasma-assisted hand sanitizer with plastic casing



**FIG. 2:** Three-dimensional schematic of the plasma-activated droplet deposition chamber with front and rear deposition pipes



**FIG. 3:** Photograph of the deposition chamber with exposed tubing network

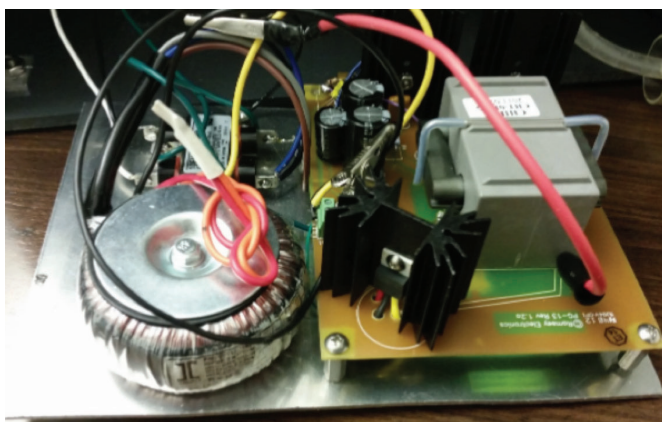


**FIG. 4:** Exploded schematic view of the plasma-assisted hand sanitizer showing larger components (wiring and connecting tube from nebulizer are hidden to better show parts)

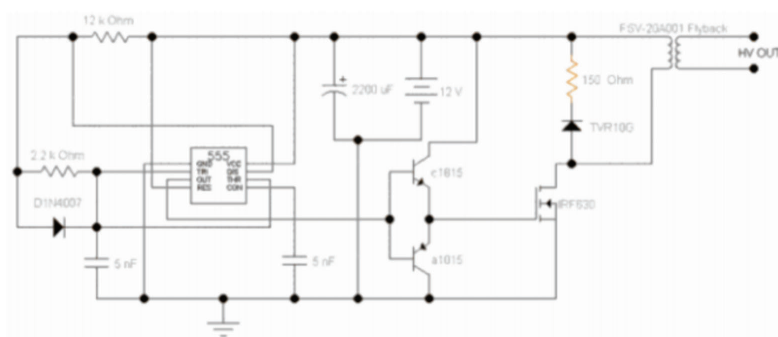
To provide power to the DBD chamber, a separate closed-circuit system draws a nominal 120 V from a standard wall outlet and amplifies the voltage to 17 kV using a transformer and greatly reduces the current (to  $\sim 2$  mA) as seen in the power supply circuit diagram (Figs. 5 and 6). The output voltage of this circuit leads to the high-voltage (HV) electrode of the DBD component of the device. The plasma-treated mist is then carried through the tubing network, from the DBD chamber to the deposition pipes, where it is applied to the hands (Figs. 7 and 8). The deposition pipes are thick-wall PVC pipes  $3/4$  in. in diameter with 36 0.0625 in. diameter holes, which act as the terminals for the mist. The deposition pipes are housed in a chamber measuring  $18 \times 5 \times 8$  in. ( $L \times W \times D$ ) where the hands can be comfortably inserted. In this fashion, the hands will pass through two “curtains” of antimicrobial mist when inserted into the deposition chamber of the device, similar to how the Dyson Airblade functions while drying hands.

### III. RESULTS AND DISCUSSION

To begin specifying our design, our first priority of the plasma-assisted hand sterilization device was to provide an effective antimicrobial treatment. Our research shows that atomized water droplets are capable of achieving up to 5-log kill of bacteria (see Fig. 9). The antimicrobial testing was performed using a control group of *E. coli* bacteria cultures, which were compared to a treatment group of cultures. For the control group, *E. coli* bacteria was spread onto agar plates using the streak plate method and incubated overnight. The treated plates were exposed to the plasma mist for 15 s treatments at an airflow rate of 11 l/min. As seen in Fig. 9, the antimicrobial test demonstrated a significant efficacy to sanitize a surface. Another focus of our design was to make the device user friendly and not prone to user error. We established that the device would

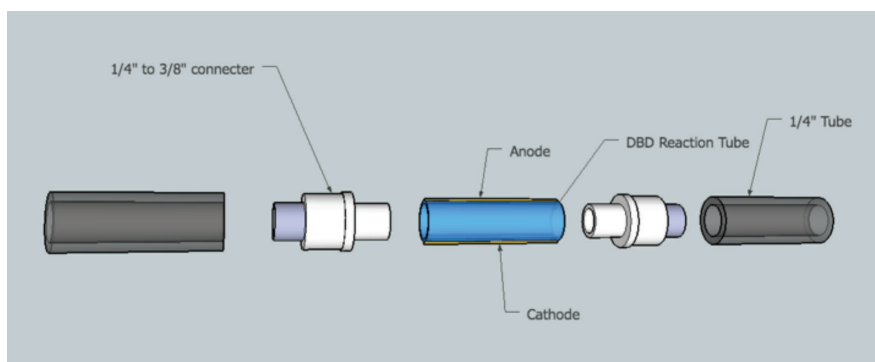


**FIG. 5:** Photograph of the high-voltage power supply

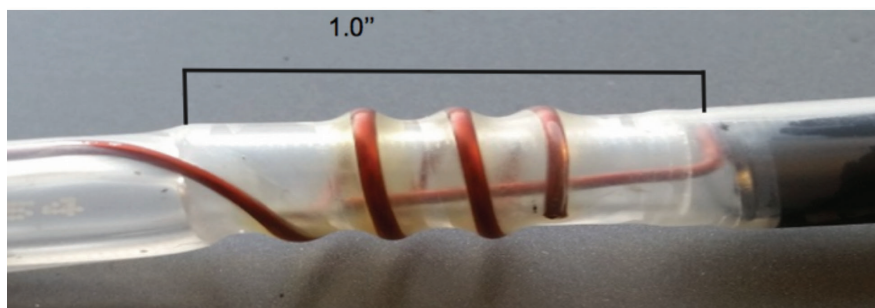


**FIG. 6:** Circuit diagram of the high-voltage power supply

contain infrared sensors in combination with an atomizer that would spray onto the user in a hands-free fashion. To compete with previous products, we established the average coverage of the hand to be  $>80\%$ , since a recent study released by The National Center for Biotechnology Information found that liquid hand sanitizers offer 60–82% of coverage.<sup>12,13</sup> Through each treatment of plasma-treated water droplets, we observed that 100 ml of water will be used and that the water storage for the atomizer has to be  $>100$  ml. In addition, the device is ready at the time when the user puts their hands in the device because it receives a signal from the infrared sensors that initiates the power supply to charge the DBD and starts the atomizer, having water droplets immediately pass through the charged DBD plasma. By observing the study of male workers and hand sizes, we specified the dimensions,  $18 \times 8 \times 5$  in., of our encasing—big enough to fit the general public. Last, since our target audience includes primarily health-care workers, we needed to create a device that could be powered from a common power outlet within a hospital (110 V for the United States).



**FIG. 7:** Exploded schematic view of the DBD chamber and connecting tubes, adapters, and wires that make up part of the tubing network. Not shown: HV and grounded wires between reaction tubes and power supply



**FIG. 8:** Photograph of the 1/4 in. quartz DBD reaction tube with HV and grounded electrodes. Not shown: HV and grounded wires from the high voltage power supply

In order to hold a competitive advantage over existing products that offer hand sanitation, a number of design constraints have been developed. First, because this product falls under a biomedical application, it will ultimately need to pass FDA approval. NTP will also charge each droplet to its floating potential. This will cause every droplet to now hold a negative charge, allowing deposition of droplets onto a neutral surface. This will be critical in attempting uniform coverage of the antimicrobial droplets by not allowing oversaturation of sanitizer, but instead, be distributed amongst the surface to areas commonly missed. There will be no potential risk of electrical shock or burns from the reaction chambers to the users' hands as the electrical components, as well as the deposition box, will be insulated. Expanding more on the safety constraints, the NTP does decrease the pH of the water droplets creating an acidic output; however, the pH is near that of Pepsi, representing no corrosive threat to skin contact.<sup>14</sup> Prior research demonstrated the effectiveness of pairing bioactive liquids and xerography in the form





**FIG. 9:** Agar plate with *E. coli* bacterial colonies (left). *E. coli* bacterial colonies treated with plasma water after 15 s (right). This shows the antimicrobial properties of plasma

of microparticle and nanoparticle deposition onto a surface.<sup>15</sup> The research consisted of developing a method of biochemical substance patterning, or printing for micro- and nanoscale resolution on planar and nonplanar substrates. One of the many goals of this experiment was to uniformly cover the surfaces with the plasma droplets. The research concluded that by using DBD plasma and an aerosol, uniform coating was achieved.<sup>15</sup> This phenomenon of using a charged particle's electrostatic forces to evenly coat a 2D or 3D surface was demonstrated in theory but has also been extensively proven through rotary-bell painting, laser printing, and modern pesticide techniques.<sup>16–18</sup> It is important to note that 100% coverage is an unrealistic constraint to achieve; however, 90% or even 85% coverage is still more than the 76% conventional hand washing and liquid hand sanitizers achieve, especially in a time scale of 5 or 10 s.<sup>19,20</sup> An added characteristic of using antimicrobial micron-sized droplets instead of liquid is the reduced amount of disinfectant needed. A person using the plasma-assisted hand sanitizer sees a significant reduction of volume over conventional hand washing. Plasma-activated water droplets will require no more than 3 ml to completely coat a hand with a surface area of 0.54 m<sup>2</sup>.<sup>21</sup> Finally, this device will need to be able to be easily integrated into a facility with little cost. As the only inputs are electricity and water, the device can be wall mounted, running from the building's water supply and power grid. This product can also exist in a portable form, running from a battery or generator and a water reserve. With a current prototype cost of under \$200 for parts, not including the constrained atomizer, future iterations will be able to be built for well under \$100. The atomizer presently in use has variable settings and is used for research that requires very precise droplet properties. This atomizer can be easily replaced with existing atomizers that will both greatly reduce the cost and maintain the necessary droplet characteristics.

To effectively produce plasma over the DBD propagation tube, the distance between the two electrodes must be only a few millimeters when working under our DBD voltage of 20 kV after the standard 110 V wall voltage passes through the step-up transformer. Paschen's law describes the relationship between gap distance and ionization breakdown voltage as

$$V = \frac{apd}{\ln(pd) + b}$$

where  $V$  is the breakdown voltage,  $p$  is the pressure of the gas in atmospheres or bar, and  $d$  is the distance of the gap between electrodes in meters. and  $b$  are Townsend coefficients seen in the breakdown of the gas into ions. From Paschen's law, we can see that as the gap distance increases, the voltage must increase on higher and higher orders of magnitude to overcome the distance. Because of this gap distance constraint, the back-pressure from the tube connectors and the resulting decrease in diameter lowered the gas exit pressure and also became a point of high condensation of the water droplets. To avoid this problem, an increase in the number of DBD propagation tubes might mitigate the pressure differential, however, there still needs to be an investigation on whether or not the inherent power diffusion across the additional DBDs will cause the overall plasma-induced antimicrobial efficacy to diminish. Returning to the problem of water loss to the walls of the tubing, a hydrophobic coating or material could resolve the issue. Time allowing, we would have liked to investigate our options in this area. The problem was partially resolved with minimizing the amount of tubing used in the network as well, however, this did not solve it entirely. To address the issue of even and sufficient coverage, optical sensors will be implemented into a later-generation prototype to help with the user input for maximum coverage efficiency. The DBD, pump, and atomizer would activate as the optical sensor detects movement in the proximity of the deposition chamber. The DBD, pump, and atomizer would continue to run for a 10 s cycle to provide a sufficient amount of antimicrobial droplets. The user would be responsible to slowly insert and remove his or her hands to ensure that the droplets are deposited along the length of the hands. This will aid in the user input need to use the device. Eventually we would like to see an autonomous system measure the rate at which the user inserts and removes their hands with visual and audio feedback to communicate when the hands are or are not effectively coated.

#### IV. CONCLUSION

The positive impacts of the presented plasma-based system on society and health-care providers are numerous. While this is an open question, the reduction in time required for medical professionals to spend on hand washing should increase the rate of compliance, thus reducing overall rate of hospital infections. Though the device is mostly automated, there is still possibility of improper use if the users' hands are not properly exposed to the plasma-treated mist; if the mist is not properly applied, there will not be appropriate levels of sterilization and so a false sense of cleanliness may result. Additionally, malfunction in the plasma-treatment apparatus could cause a similar manner of false security.

From an environmental perspective, the manufacture and use of the device has both positive and negative impacts. The production of the device would require the use of



synthetic materials as well as transport of specially made components, resulting in pollution from the by-products of transport and plastic production. The usage of the device presents a negative environmental impact insofar as the production of power to operate the device may come from nonrenewable resources. Otherwise the device presents little environmental concern: the reactive specs within the plasma-treated water decay at high rate, meaning that any waste water from the device would not present dangers to local ecosystems; the operation does not produce amounts of greenhouse gasses and so would not contribute to air pollution either.

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