METHODS OF AIR DECONTAMINATION

REVIEW AND ANALYSIS OF A NOVEL MEDICAL DEVICE EMPLOYING NON-THERMAL PLASMA

WHITEPAPER

A/Professor, Dr Peter Speck,
Flinders University, South Australia – College of Science and Engineering.

Airborne transport of pathogens represents a significant source of infection in many settings, such as medical facilities, crowded locations, facilities that handle such pathogens, and, recently, quarantine facilities used to control spread of COVID-19. Current methods to remove or minimize spread of airborne pathogens typically employ HEPA (high efficiency particulate air) filters.

HEPA filters require significant amounts of energy to operate and need frequent maintenance. Further, HEPA filters can only treat air that passes through their media, while the effectiveness rate of these filters to capture and remove airborne pathogens remains dependent on the air velocity as well as the size of pathogens and particulates in relation to their rated most penetrating particulate size (PMMA), and their actual airflow velocities they operate within.

There are a number of alternative methods of inactivation, such as non-thermal plasma, and the use of ultraviolet (UV) radiation, although there are conflicting reports of the inactivation efficacy of UV radiation. Air purification systems are also relied on for removal of airborne contaminants such as volatile organic compounds (VOCs) and related compounds.

Studies undertaken by Flinders University reported that the PlasmaShield (PlasmaShield Pty, Australia) unit (PSU) was highly effective in inactivating the model microbes Escherichia coli, Staphylococcus epidermidis, bacteriophage MS2, and Cladosporium sp. fungus. Investigators at the University of Adelaide showed that the PSU was highly effective at removing the VOCs toluene, formaldehyde and isopropyl alcohol, and achieved a significant removal of ammonia, a non-VOC air contaminant.

Studies undertaken by the University of South Australia concluded that the energy consumption of the PSU is likely to be less than 5% that of comparable HEPA filtration systems.

The PSU has additional cost advantages over HEPA systems in that it obviates the need for annual filter replacement, and disposal of contaminated filters.

Plasma field technologies have potential advantages over HEPA filters for inactivation of microbes and in removal of airborne contaminants, both in efficacy and energy efficiency, and should be further developed for use in these settings.

INTRODUCTION.

Airborne transport of pathogens represents an important source of infection in numerous settings. A comprehensive review by Li and co-workers published in 2007 (1) concluded there is strong evidence showing association between air movements in buildings and transmission of infectious diseases such as measles, tuberculosis, chickenpox, influenza, smallpox and SARS. Airborne transmission in a laboratory is the likely route by which the victim in the last fatal case of smallpox acquired the virus (2). There is increasingly strong evidence for airborne transmission of SARS-CoV-2 (3, 4). Measures to prevent airborne transmission are important in many locations including crowded places, hospitals treating COVID-19 patients and in quarantine facilities intended to control spread of the virus (5). It is possible that the threat of airborne transmission of SARS-CoV-2 will be ongoing for many years to come. Airborne transmission of infectious pathogens also occurs during commercial air travel (6, 7). Fungal pathogens, such as Aspergillus fumigatus, are spread by airborne means (8). In many settings such as hospitals, laboratories and aircraft, there is a strong requirement for the efficient inactivation of airborne pathogens.

Several methods for inactivation of airborne pathogens are in use or development. Probably the most commonly used technology is HEPA ("high efficiency particulate air") filtration, and although this been in use for over 60 years (9, 10), the costs associated with the significant energy consumption of HEPA filters and the need for regular filter changes, and disposal of contaminated filters, have been raised as concerns (10, 11). Alternative methods of inactivation of airborne pathogens that are in use or which are under development include (i) ozone generation (12), (ii) use of ultraviolet (UV) radiation, possibly in combination with a catalyst such as titanium dioxide (13); and (iii) use of electrical fields of sufficient intensity to generate ionized gas, known as plasma (14).

With regard to ozone, it should be noted that exposure to ozone is associated with significant adverse cardiorespiratory health effects (15), and the use of ozone-generating air purification devices is strictly limited by law in the US State of California (16) and by the United States Environment Protection Agency (17).

The use of UV light in inactivation of airborne pathogens has shown promise, and Welch and co-workers found that a low level of UVC light exposure (short wavelength, 100-280nm) efficiently inactivates airborne aerosolized viruses, with a very low dose of 2 mJ/cm2 of 222-nm light inactivating >95% of aerosolized H1N1 influenza virus (18). However, a recent comprehensive review of 100 years of literature on the inactivation efficacy of UVC light described the data as "sparse” and noted that there are no studies of the effects of UVC on the human eye (19).

Plasma-generating devices for inactivation of airborne pathogens have been demonstrated to be effective, for example Tanaka and co-workers using "plasma assisted catalytic technology", claimed a sterilization rate against noroviruses that "may be more than 99.99% -below the detection limit" (20). However, a drawback of this device is that it to an extent relies on ozone for its efficacy (20). Non-ozone generating plasma devices deserve further examination and development in the setting of air purification.

Air purification devices are also important for removal of airborne contaminants such as volatile organic compounds (VOCs) and non-VOCs such as ammonia (21).

The PlasmaShield unit (PSU) uses a corona discharge device to produce a plasma region, in three stages, through which is drawn the air to be purified. In this system the air and its contents that pass through the device are subjected to powerful electric fields. In view of the current coronavirus pandemic, investigations of the PSU ability to destroy virus infectivity are of critical importance.

Evaluations of the PlasmaShield filter-less air purification technology (22) have been undertaken to assess, first, its ability to inactivate airborne microbes (23, 24), second, its ability to remove VOCs and related compounds (25), and third, its potential for saving energy compared to HEPA filtration (26).

METHODS

Antimicrobial testing.

The following microbes were used: (i) Escherichia coli (a model Gram-negative bacteria, found in the gut and which is often isolated in hospital settings), (ii) Staphylococcus epidermidis (a model Gram-positive bacteria, found on human skin, and also associating with hospital-acquired infections, especially in immune-compromised individuals), (iii) bacteriophage MS2 (a model virus, a bacteriophage, being a virus that infects E. coli, and often used in assessment of air purification systems (27)), and (iv) Cladosporium sp. (a model fungus, commonly isolated in the environment).

There were two components to the antimicrobial testing, which was undertaken by the College of Science and Engineering, Flinders University:

1. Direct testing of viable microbe numbers exiting the PSU and collected using an air sampler, after the microbes were directly introduced into the input air using a nebulizer (24), as shown in Figure 1.

2. Field testing, in which microbe numbers were measured in a room supplied with air through the PSU, with the PSU either turned on or off (23).

Bacteria numbers were determined by colony counts on agar plates. Bacteriophage numbers were determined by counting plaque numbers, that is, the holes (plaques) in bacterial lawns on plates, caused by the presence of lytic viruses such as MS2.

VOC and related compounds testing.

Testing at the University of Adelaide was done for these VOCs: formaldehyde, toluene, and isopropanol; and for the non-VOC ammonia (25). The testing method used ducting attached to the PSU, with the test substances introduced into air flowing through the PSU, and testing ports located before and after the PSU. Calibrated PhoCheck Tiger Photo Ionisation Detector (PIDs) were used with correction factors to establish qualitatively the concentrations of toluene and isopropanol. Formaldehyde concentrations were determined by collecting air samples onto 2,4 dinitrophenyl hydrazine coated glass fibre filters. The analysis of the collected formaldehyde samples was carried out by a verified method for formaldehyde: 'Health & Safety Executive (HSE), Method for determination of Aldehydes in air (MDHS 102)' that utilises a High-performance Liquid Chromatography (HPLC) Ultraviolet (UV) analysis. The ammonia concentration before and after the PSU was measured using a calibrated direct reading instrument: an MX6 Ibrid meter fitted with an ammonia sensor.

Estimation of the energy-saving potential of the PSU.
Testing and estimation was undertaken by the Future Industries Institute of the University of South Australia (26). Their investigators visually confirmed the air purification ability of the PSU by means of smoke clearance testing. They measured air pressure drop across the PSU and its power consumption and modelled its annual power consumption per unit of floor area to be supplied with filtered air, in units of kWh/m^2 and $\$/m^2$, the latter by assuming a cost for electricity at (AU$0.15/kWh).

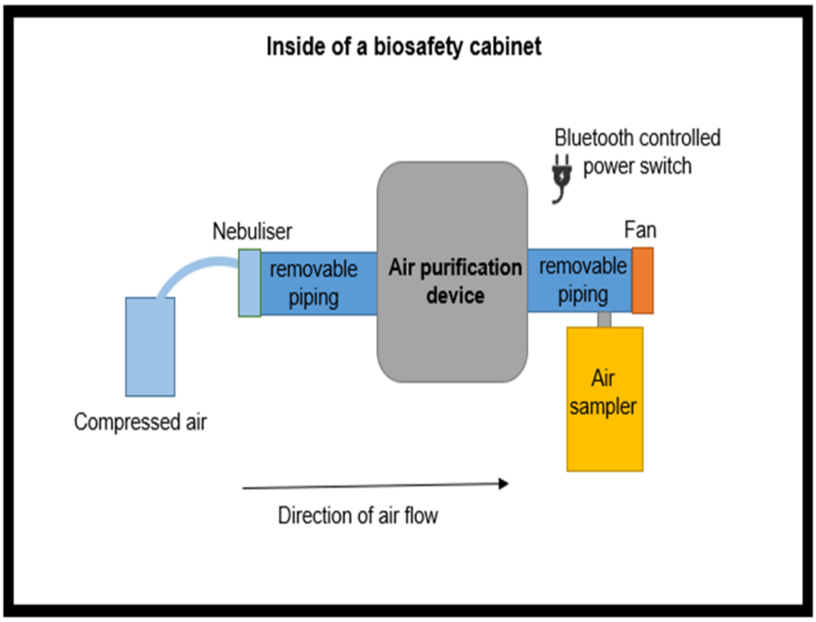

Figure 1: Diagram of the PSU experimental setup

RESULTS

Microbe inactivation.

1. Direct testing of PSU.
The plasmaSHIELD statistically significantly (P<0.05) reduced the microorganism concentrations compared with the negative control (24). The plasmaSHIELD achieved statistically significant (P<0.05) reduction in the microorganism concentrations compared with the negative control (24) on Gram-positive and Gram-negative pathogens. It was also demonstrated that the plasmaSHIELD could achieve removal efficiencies of up to 3 x log10, 4 x log10, 8 x log10, and 2 x log10, for E. coli, S. epidermidis, MS2 and Cladosporium sp. respectively. For Cladosporium sp. and E. coli the maximum log10 removal by the plasmaSHIELD was achieved; however, for S. epidermidis and MS2 it was not and the maximum log10 removal capacity of the plasmaSHIELD could be even greater for these microorganisms. In the case of MS2, further testing is underway to precisely measure the PSU inactivation efficiency by quantifying the effects of the multiple decontamination modes of action.

2. Field testing of PSU.
Air from two locations within three consulting rooms in a medical clinic was sampled for one hour with the PlasmaSHIELD turned on (PlasmaSHIELD on during sampling and for a minimum of 1 hour prior to sampling) (23). The sampling was then repeated with the PlasmaSHIELD turned off.
A statistically significant (P<0.05) reduction in viruses (virus-like particles) per litre of air (VLP/L), bacteria (bacteria-like particles) per litre of air (BLP/L) and total microbes (VLP + BLP) per litre of air (VLP + BLP/L) was observed with the PlasmaSHIELD turned on compared with the PlasmaSHIELD turned off.
Removal of volatile organic compounds (VOCs) and related air contaminants.

Results for Formaldehyde, Toluene and Isopropyl Alcohol.
The PSU reportedly demonstrated very high efficiency in removal of formaldehyde, achieving a reduction rate of at least 93% in a continuous single-pass test with air velocity of 1 m/sec (25). The rate of toluene removal under the same operating conditions was even more effective with the PSU achieving a reduction rate of at least 97%. The isopropanol removal rate was also highly effective, with

the PSU achieving a consistent reduction rate of at least 92% in single-pass continuous test.

Results for non-VOC ammonia

The PSU achieved a removal rate of ammonia an efficiency of 23% to 29% at single-pass continuous flow rate of 1 m/sec air velocity.

Energy saving potential of PlasmaShield device.

A report by the University of South Australia calculated for various hospital spaces the annual cost savings in HEPA vs PSU of AU$3.9/sqm (recovery room) to AU$13.3/sqm (operating or delivery rooms) (26). This was based on an electricity cost of $0.15/kWh, however in real life electricity can be more than double this cost. These investigators also commented on the PSU not requiring annual filter changes nor the need to dispose of a contaminated filter.

DISCUSSION

The positive results with the PSU should be compared to the performance of the predominant current method, HEPA filters, a 60-year-old technology.

There are numerous deficiencies with HEPA filters. For example, HEPA filters clog with continued use, adversely affecting the dynamics of airflow through these filters (28).

It has been reported that small viruses may penetrate HEPA filters: Heimbuch et al working at the United States Air Force Research Laboratories, demonstrated that MS2 coli phage aerosols penetrate HEPA filters: at a face velocity of 2 cm/sec, a nebulized challenge of ~10^5 viable plaque forming units (PFU) per litre of air resulted in penetration of ~1 -2 viable PFU per litre of air (29).

There is a high pressure drop across HEPA filters, as discussed above, with resulting high energy use. As mentioned above, HEPA filters have the high costs of regular filter changes and of disposal of contaminated filters.

STRENGHTS OF PLASMASHIELD

The PSU is designed to have three stages of action, to which the manufacturer has given the following designations:

1. Electron beam irradiation. The PSU creates an electron beam gun that uses electrons to inactivate microorganisms.

2. Electroporation. An intense electric field ruptures cell membranes and inactivates microorganisms.

3. Oxygen-reactive species: the PSU is designed to generate reactive species such as ozone that mediated the destruction of microbes and the breakdown of VOCs and related air contaminants.

The PSU has no filters that require maintenance, and as detailed above, its running costs are much lower than those of a HEPA filter.

OZONE AS AN AIR PURIFICATION AGENT

The handling of ozone by the PSU is important. Ozone is an effective disinfectant for many microbes (30), but as noted above its use is severely restricted in some jurisdictions because of its adverse health effects.

The PSU as a corona discharge device would be expected to produce ozone (31) and in practice this is the case. However, the PSU is reportedly designed to carefully manage and mitigate ozone production. This is achieved in 3 ways: (i) the reactor geometry is designed to generate ozone only in the entry stage of the reactor, and this ozone contributes to the inactivation capability, and the exit stage of the reactor is designed to eliminate and destroy ozone; (ii) a CuO/MnO_2 catalytic converter placed after the exit stage of the reactor converts any residual ozone to oxygen; (iii) the PSU is fitted with an ozone meter that provides a constant monitoring feedback loop which immediately disables the device should ozone be detected above the calibrated background level. Testing of ozone concentration to ensure compliance is by an ozone meter approved by the US EPA and operated in accordance with UL standard 867 s40. Thus, all ozone produced in the PSU is contained within the device.

FUTURE STUDIES

The antimicrobial efficacy of the PSU should be tested on mixed populations of microbes, and in varying relative humidity.

Testing using a human coronavirus would provide knowledge more directly applicable to the current COVID pandemic. The biosafety level of SARS-CoV-2 means that it is not feasible to safely conduct air quality research involving the aerosolization of this virus and therefore an appropriate surrogate must be used. The Australian Therapeutic Goods Administration (TGA) recently announced that manufacturers wishing to make label claims of efficacy against COVID-19 for products should use human coronavirus 229E (HuCoV-229E) as a surrogate (32). This testing is underway at Flinders University.

CONCLUSION

There is an ever-increasing need, in multiple settings, to effectively decontaminate air and to remove airborne pathogens. Currently this is typically attempted using HEPA filters, however this technology, which is over 60 years old, has significant disadvantages. There is promising data confirming that the PlasmaShield air bio-decontamination device inactivates airborne contaminants, irreversibly destroys airborne microbes, and does not introduce harmful by-products such as ozone into the ambient environment.

REFERENCES

1. Li Y, et al. Role of ventilation in airborne transmission of infectious agents in the built environment - a multidisciplinary systematic review. Indoor Air. 2007;17(1):2-18.
2. Shooter R. Investigation into the cause of the 1978 Birmingham smallpox occurrence. London: Her Majesty's Stationery Office; 1978.
3. Liu Y, et al. Aerodynamic analysis of SARS-CoV-2 in two Wuhan hospitals. Nature. 2020;582(7813):557-+.
4. Morawska L, et al. Airborne transmission of SARS-CoV-2: The world should face the reality. Environ Int. 2020;139:3.
5. Noorimotlagh Z, et al. A systematic review of possible airborne transmission of the COVID-19 virus (SARS-CoV-2) in the indoor air environment. Environ Res. 2021;193:6.
6. Mangili A, et al. Transmission of infectious diseases during commercial air travel. Lancet. 2005;365(9463):989-96.
7. Mangili A, et al. Infectious Risks of Air Travel. Microbiol Spectr. 2015;3(5):10.
8. Latge JP. Aspergillus fumigatus and aspergillosis. Clin Microbiol Rev. 1999;12(2):310-+.
9. Zhang YP, et al. Can commonly-used fan-driven air cleaning technologies improve indoor air quality? A literature review. Atmos Environ. 2011;45(26):4329-43.
10. Earnest GS, et al. Guidance for Filtration and Air-Cleaning Systems to Protect Building Environments from Airborne Chemical, Biological, or Radiological Attacks. In: Department of Health and Human Services CfDCaP, National Institute for Occupational Safety and Health, editor. Cincinatti: Department of Health and Human Services; 2003. p. 78.
11. Fisk WJ, et al. Performance and costs of particle air filtration technologies. Indoor Air. 2002;12(4):223-34.
12. Kowalski WJ, et al. Bactericidal effects of high airborne ozone concentrations on Escherichia coli and Staphylococcus aureus. Ozone-Sci Eng. 1998;20(3):205-21.
13. Bono N, et al. Effect of UV Irradiation and TiO2-Photocatalysis on Airborne Bacteria and Viruses: An Overview. Materials. 2021;14(5):19.
14. Lai ACK, et al. Evaluation of cold plasma inactivation efficacy against different airborne bacteria in ventilation duct flow. Build Environ. 2016;98:39-46.
15. Day DB, et al. Association of Ozone Exposure With Cardiorespiratory Pathophysiologic Mechanisms in Healthy Adults. JAMA Intern Med. 2017;177(9):1344-53.
16. Assembly Bill No. 2276, Ozone: indoor air cleaning devices., State of California (2006).
17. Good Up High, -Bad Nearby, United States Environmental Protection Agency (2003).
18. Welch D, et al. Far-UVC light: A new tool to control the spread of airborne-mediated microbial diseases. Sci Rep. 2018;8.
19. Hessling M, et al. The impact of far-UVC radiation (200-230 nm) on pathogens, cells, skin, and eyes - a collection and analysis of a hundred years of data. GMD Hyg Infect Control. 2021;16:17.
20. Tanaka Y, et al. Preventing the spread of norovirus-like infections by the airborne route using plasma assisted catalytic technology (PACT). J Vet Med Sci. 2018;80(9):1459-62.

Manisalidis I, et al. Environmental and Health Impacts of Air Pollution: A Review. Frontiers in Public Health. 2020;8:13.

22. VOSSOUGHI KHAZAEI S, inventor. A gas purifying apparatus. Patent number WO 2018/035571 Al. 01 March 2018.
23. Whiley H, Ross, K. . TECHNICAL REPORT: Field study validation of the PlasmaSHIELD microbial air purification capabilities. Bedford Park: School of Science and Engineering, Flinders University. , 2020.
24. Whiley H. Technical report: Validation Study of PlasmaShield System. College of Science and Engineering, Flinders University. , 2019.
25. Crea J, Tkaczuk, M. Testing Conditions for the Evaluation of plasmaSHIELD™ Non-Thermal Plasma Air Purification and Disinfection System with Common Air Contaminants. Adelaide: Adelaide Exposure Science and Health, The University of Adelaide, 2018.
26. Belusko M, Alemu, A. . Investigation into the Energy Saving Potential of the Filter-Less Plasma Shield Technology. Adelaide: Future Industries Institute, University of South Australia; 2019 December 20, 2019. Report No.
27. Young RY. BACTERIOPHAGE LYSIS - MECHANISM AND REGULATION. Microbiol Rev. 1992;56(3):430-81.
28. Cheng L, Kirsch, R,. Wiegmann, A., Gervais, P-C., Bardin-Monnier, N., Thomas, D. PLEATLAB: A PLEAT SCALE SIMULATION ENVIRONMENT FOR FILTRATION SIMULATION. Filtech Proceedings 2013.
29. Heimbuch B, Wu., CY, Wander, Joseph D. . VIRAL PENETRATION OF HIGH EFFICIENCY PARTICULATE AIR (HEPA) FILTERS. In: LABORATORY AFR, editor. Tyndall Air Force Base, Florida: US Air Force; 2009. p. 40
30. Kim JG, et al. Application of ozone for enhancing the microbiological safety and quality of foods: A review. J Food Prot. 1999;62(9):1071-87.
31. Kogelschatz U. Dielectric-barrier discharges: Their history, discharge physics, and industrial applications. Plasma Chem Plasma Process. 2003;23(1):1-46.
32. Therapeutic Goods Administartion: Surrogate viruses for use in disinfectant efficacy tests to justify claims against COVID-19. Canberra, ACT: Department of Health, Australian Government.; 2020 [10/09/2020]. Available from: https://www.tga.gov.au/surrogate-viruses-use-disinfectant-efficacy-tests-justify-claims-against-covid-19