ACTIVEPURE® TECHNOLOGY – THE PATH TO SAFE INDOOR AIR

30 April 2021

ABSTRACT

Airborne transmission of SARS-CoV-2 and other respiratory viruses through virus-containing aerosol particles and droplets has been established as a primary pathway for the spread of COVID-19 and similar infections.[1] Suitable infection prevention measures are imperative, especially in high-risk environments, including where many people convene indoors, as in schools and hospitals, and where masks cannot be worn, as in restaurants and company breakrooms.

We provide an overview of an advanced form of air purification technology called ActivePure, which is capable of safely suffusing an occupied indoor space with the same oxidative particles found to clean the atmosphere outdoors naturally.[2] ActivePure has its roots in NASA's development of Photocatalytic Oxidation (PCO), but multi-generational improvements have materially improved its efficacy from its PCO origins, and its safety was validated by U.S. Food & Drug Administration (FDA) clearance of the ActivePure Medical Guardian® as a Class II Medical Device in June 2020. We cover the safety and efficacy of this technology and compare it to other air-cleaning methodologies.

1. INTRODUCTION

Safe indoor air and surfaces are more important than ever, affecting viral transmission, student[3] and employee productivity[4], and overall health.[5] Currently, however, many indoor spaces rely on inefficient and traditional ventilation and filtration technologies, while newer technology is available that inactivates viruses safely. By the time pathogen-containing air is passed through a filter or by an ultraviolet (UV) light, it has already spread through a room and potentially infected people.

ActivePure solves this problem by taking the fight to the source. It goes directly to the pathogens themselves and neutralizes them. The process continuously energizes the air in the room, producing the same cleaning particles naturally found in the atmosphere[6] but absent from indoor spaces.

From the moment they are emitted, particles generated in the ActivePure process begin inactivating viruses, bacteria, and mold. They clean both the air itself and any surface that the air touches, producing a real-time reduction in disease-causing airborne pathogens.

2. TECHNOLOGY OVERVIEW

ActivePure recreates the organic process that continuously occurs in outdoor air to cleanse the atmosphere. Each breath of outdoor air contains billions of oxidative particles, including hydroxyl radicals[2] and hydrogen peroxide.[7] These oxidizers are the atmosphere's primary self-cleaning mechanism. They continuously break down the megatons of pollutants that humans put into the air each year.[2] By contrast, without sunlight indoors, these cleansing particles are normally missing from interior environments. ActivePure technology restores the naturally occurring oxidizer particles to levels that will destroy pathogens.

To recreate this process indoors, the ActivePure system uses energetic photons from a UV-C (high-energy ultraviolet radiation) bulb to excite and release electrons from a proprietary photocatalyst, made from a base of titanium dioxide -- a naturally occurring semiconductor. Electrons are the negatively charged particles inside atoms, and once they are released, they interact with H_2O and O_2 in the ambient air, causing the same natural oxidizers to form that are produced in outdoor air when ultraviolet sunlight rays interact with the atmosphere: hydrogen peroxide (H_2O_2), hydroxide

(OH^-), hydroxyl radicals (•OH) and superoxide ($•O_2^-$).[7–9]

These oxidizers spread throughout the space at tremendous speed. When they encounter an organic molecule, they strip away an electron, beginning a series of reactions that quickly render a pathogen inert and no longer infectious.[10] After the oxidizer has altered the cell wall or viral envelope[11], the organism continues to decompose into its most basic, organic (and completely benign) components – usually CO_2 and H_2O.

3. SAFETY

ActivePure was developed with safety as its primary focus, using nature as a guide. The process is completely safe for humans. The compounds it generates are all well below the safety thresholds required by OSHA and other agencies for continuous exposure.[12] Independent laboratory tests have shown that ActivePure does not increase levels of ozone or Volatile Organic Compounds (VOCs) in the ambient air; instead, ActivePure actually reduces ozone and VOCs. ActivePure products meet the regulatory and safety standards of every state in which they are sold.

ActivePure devices have been shown to be safe in laboratory studies, FDA review, and worldwide installations. The technology is used in health care settings, where it has been deployed to decrease hospital-acquired infections. ActivePure's Medical Guardian device has been cleared by the FDA and is the subject of a double-blind clinical trial at the Cleveland Clinic to measure its impact on reducing surgical-site infections.

ActivePure is qualitatively different from other forms of PCO technology, which use older, less effective photocatalyst formulas. These conventional formulas have been shown to produce toxic byproducts such as formaldehyde and ozone, but ActivePure's proprietary photocatalyst creates a more efficient reaction that avoids creating any harmful intermediaries.[13] Some people confuse ActivePure's proprietary technology, which is unique, with these outdated versions of PCO-based technology.

4. EFFICACY

ActivePure has demonstrated efficacy through testing in FDA-compliant, independent laboratories where it was proven to inactivate rapidly a wide array of viruses, bacteria, and mold.

Testing by Biosafety Level 3 and 4 laboratories at the University of Texas Medical Branch in Galveston, which does extensive research for the CDC and the U.S. military, found that ActivePure destroyed at least 99.96% of a high concentration of airborne SARS-CoV-2 virus (the cause of COVID-19) in three minutes.* According to the report: "Since no virus was detected using the experimental device, the true percent reduction was likely greater than 99.99% in every case."[14] Additional testing has shown a greater than 99.98% reduction on surfaces within seven hours.[15]

The ActivePure device that received FDA clearance in June 2020 was found to safely reduce the concentration of the following six airborne pathogens by at least 99.9% in 30 minutes:† [16]

- MS2 bacteriophage RNA virus, which is non-enveloped and thus harder to inactivate than SARS-CoV-2 (the virus that causes COVID-19), whose envelope is more vulnerable.[17]
- PHI-X174 bacteriophage DNA virus, a surrogate for Hepatitis C and HIV
- Staphylococcus epidermis gram-positive bacteria, a surrogate for Methicillin-resistant Staphylococcus aureus (MRSA), a major cause of hospital-acquired infections.
- Erwinia heribcola gram-negative bacterium, surrogate for the black plague-causing bacterium.
- Aspergillus niger fungal mold, the cause of black mold disease.
- Bacillus globigii bacterial endospore, which is generally considered among the most difficult pathogens to destroy,[17] where ActivePure technology reduced concentrations by 99.98% in 30 minutes.

* These results have not yet been cleared by the FDA but have been submitted to the FDA for clearance.

† These results have been cleared by the FDA in the ActivePure Medical Guardian as a Class II Medical Device.

> According to Aerosol Research and Engineering Laboratories, the independent testing agency, endospores like Bacillus globigii "are an extremely resilient structure…that are resistant to UV radiation, desiccation, chemical disinfectants and severe temperatures." These spores "are routinely used as a surrogate for weaponized anthrax."[18]

ActivePure technology has also been successfully tested against pollen particles, lowering allergic reactions,[19] as well as yeasts and molds.[20]

A list of pathogens against which ActivePure has been tested with success includes:

- SARS-CoV-2 – RNA Virus (Cause of COVID-19)
- H1N1 Influenza (Swine Flu)
- H5N8 Influenza (Bird Flu)
- Murine Norovirus – RNA Virus
- PhiX-174 - DNA Virus
- MS2 Bacteriophage - RNA Virus
- MRSA (methicillin-resistant Staphylococcus aureus)
- Methicillin-resistant Staphylococcus epidermis
- Staphylococcus epidermidis (gram +)
- E. coli (gram -)
- Salmonella enterica (bacterium)
- Legionella pneumophila (bacterium)
- Clostridium difficile (endospore)
- Bacillus globigii (bacterial mold and a C. difficile & anthrax surrogate)
- Erwinia herbicola (gram -)
- Listeria monocytogenes (gram +)
- Candida auris (fungus)
- Botrytis cinerea (fungus)
- Sclerotinia sclerotiorum (fungus)
- Aspergillus versicolor (fungus)
- Aspergillus niger endospores (toxic black mold surrogate)

4.1 Real-World Results

ActivePure's high inactivation rates in controlled settings have been replicated in real-world studies, with measurements and analysis conducted through independent, FDA-compliant laboratories. In occupied buildings such as hospitals, schools, retail spaces, and assisted-living facilities, ActivePure has demonstrated its ability to reduce the number of pathogens, both in the air and on surfaces. Some typical examples include:

- ActivePure Units installed in an assisted-living facility reduced bacteria, molds (fungi), and particulate matter by 73%-93%, an effect equivalent to increasing the ventilation in the room by three to four-fold.[21]
- Portable units installed in multiple hospital ICUs reduced bacteria, fungi, MRSA, and Staphylococcus aureus by 73%-100%.[22]
- Units installed in another major hospital's operating room reduced airborne particulates by 90%, surface bacteria by 83%, and surface MRSA by 95%.[23]

5. SAFETY AND REGULATORY STATUS

5.1 FDA

On June 17, 2020, the ActivePure Medical Guardian with ActivePure technology received FDA Class II Medical Device Clearance with 501(k) Certificate Number K201220. This multi-year testing and clearance process included a full FDA review of the safety and efficacy of the device in occupied rooms. The device demonstrated a 99.99% to 99.9999% (4-6 log) rapid reduction against all tested pathogens, including gram positive and negative bacteria, fungal and bacterial spores, and DNA and RNA viruses (for which a 99.997% reduction was achieved). The technology passed all required safety testing, including being shown not to produce harmful levels of ozone or volatile organic compounds. The same ActivePure technology in the ActivePure Medical Guardian is used in all ActivePure devices.

Additionally, ActivePure technology has been shown by the University of Texas BSL3/4 medical laboratory, cited above, to meet the FDA's guidelines[24] for effectiveness at eliminating airborne SARS-CoV-2. (ActivePure is filing for clearance by the FDA in this case, but clearance has not yet been granted.) ActivePure also demonstrated a greater than 99.99% reduction of surrogate viruses that are harder to inactivate than SARS-CoV-2; and it is the only technology cleared by the FDA in a Medical Device proven to

inactivate high concentrations of SARS-CoV-2, achieving elimination from the air below detectable limits of 99.96% in under 3 minutes (inclusive of aerosols and droplets), and achieving a 99.98% reduction from surfaces.

5.1 Other Regulatory Bodies

- Manufactured in an EPA-registered facility (#95839-CHN-001) and in accordance with EPA guidance regarding air cleaning devices.[25]
- Tested for compliance by a facility designated a Nationally Recognized Testing Laboratory (NRTL) by the U.S. Occupational Safety and Health Administration (OSHA), approved to perform testing for ANSI/UL Standard 867 and UL507, UL1598, UL1995, UL2998 and applicable Canadian and EU/CE standards.
- Shown in tests at an FDA-compliant laboratory to emit VOC gases far below all OSHA 8-hour exposure limits.[12]
- CARB (California Air Resources Board)-certified on all products sold in California. All ActivePure products sold in California meet the state's requirements for ozone emissions.
- ActivePure complies with all Federal and state environmental and safety standards.

6. COMPARISONS WITH OTHER TECHNOLOGIES

6.1 Ventilation

Ventilation is meant to exchange outdoor air for indoor, in part to reduce the risk of disease transmission, but it is rarely possible to achieve enough ventilation to ensure proper safety.[26] Increased ventilation also comes with a direct tradeoff: Energy expenditure rises as the outdoor air must be pumped, heated or cooled, and humidified. In many climates, natural ventilation through opening windows is impossible for much of the year.

Both filtration (see 6.2, below) and ventilation systems are measured in Air Changes per Hour (ACH), the number of times per hour that a volume of fresh air equal to the room volume is brought in.[27]

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) recommends that a typical home be designed to receive 0.35 ACH.[28] Schools are required to have 3 ACH, but even Energy Star and LEED buildings average closer to 2.[29] Office buildings are supposed to have 6-8 ACH, but a 2008 EPA analysis found that average levels are less than 2.[30]

These low ACH numbers would not be overly concerning if an "Air Change" meant that the room's air was entirely pristine afterward. That, however, is not what happens.

Passive systems, such as ventilation and filtration, are good at lowering initial contaminant levels, but not at eliminating them completely. They suffer from diminishing returns. Here is why:

As the fresh air comes in, it immediately begins to mix with contaminated air, diluting the entire mixture, including what leaves the room or passes through a filter. As a contaminant gets diluted, increasingly large amounts of air are required to pass through the filter or out the window in order to remove the same amount as before. According to the CDC's calculations, a room with 4 ACH will still take more than 3 hours to eliminate >99% of an initial concentration of contaminants,[31] and that is without a constant source, such as an infectious person, in the room. Consequently, in most buildings, even when HVAC systems are set to their maximum fresh-air settings, there may still be a high level of risk.

6.2 Filtration (MERV, HEPA)

Air filters such as HEPA (high-efficiency particulate air) filters, a technology developed more than 70 years ago, are designed to trap airborne particulates, either when the air is first pumped in from outside or recirculated between or within rooms. Pathogens that are continuously released in occupied rooms have plenty of time to spread and possibly infect people before finally being pulled through either a portable or duct-based filter.

This danger was clearly demonstrated in a study where filters in a hospital had little impact on

protecting construction personnel from airborne Aspergillus.[32] The CDC states that for a space treated with a portable HEPA filter that provides the recommended 2 ACH, it would take over *2* hours to eliminate 99% of an initial concentration of an airborne virus. This number becomes 6-10 hours when the air in the room is relatively stagnant, as in most classrooms, offices, and homes.[31]

Other limitations of filtration include:

- Filters have no effect on pathogens on surfaces.
- MERV filters (minimum efficiency reported value) rated 13 and below trap fewer than half of virus-sized particles.[33]
- The greater the filtration efficiency, the more stress is placed on the HVAC system. As a result, these systems need to be upgraded in size and power, at a high cost and producing damage to the environment.

6.3 Ionization

Ionizers use electricity to produce ions that impart an electrical charge to nearby particles. Over 90% of these ions cause particles to stick together and fall to the ground or other exposed surfaces, where the pathogens continue to live, rather than neutralizing them.[34–36] Only superoxide ions work to puncture the outer membranes of viruses like SARS-CoV-2, as well as fungi and bacteria, and inactivate them. But only a very small proportion of the ions produced by ionizers are superoxides.[35,37] ActivePure, by contrast to ionizers, uses a precise process to produce only the highly reactive compounds that will rapidly neutralize pathogens.[38] These are the same compounds used in the natural self-cleaning processes of the atmosphere.[2]

The large number of charged particles produced by ionizers has been linked to excessive sympathetic nervous system activation in humans (the "fight or flight" response) [39], a factor which has also been linked to "long-COVID".[40]

6.4 Ultraviolet Germicidal Irradiation (UVGI)

A dose of UV-C strong enough to neutralize SARS-CoV-2 viruses was shown to range from 3.7 mJ/cm^2 - 16.9 mJ/cm^2.[41] For a standard bulb with 245 µW/cm2, it would take more than 14 seconds of continuous and focused exposure to achieve the lowest range of this dose. However, UV-C is fundamentally limited when it comes to air purification, as it cannot be used in occupied spaces safely–except when hidden, which limits its efficiency. Instead it must be placed in the ducts, where air moves at speeds of hundreds of feet per minute, allowing only a fraction of a second of exposure time to the UV bulb and thus can only achieve an incomplete inactivation.[42]

UV-C light robots have become commonly used in hospitals, where they clean rooms between patient occupancy. These robots can operate only in unoccupied spaces because the light can cause irreparable damage to the retina. As a result, UV-C is only an episodic remedy and does nothing to address continuous risk arising from the reintroduction of pathogens into occupied spaces in between cleanings. In addition, UV-C light cannot reach pathogens in shadows.

6.5 PCO Cleaners

Many other PCO-type cleaners are based on early versions of the technology. They have a simple titanium dioxide catalyst and an inefficient UV reactor resulting in significantly reduced reaction rates, limiting their effectiveness. These cleaners use a fan to pull pathogens into a reaction chamber where inactivation is designed to take place, making them little better than any other passive filtration technology.[43] The fifth-generation ActivePure technology has solved these limitations with a new photocatalyst formula and patented reactor, resulting in an FDA-cleared, PCO-originated technology qualitatively different from any other version of PCO. ActivePure creates submicroscopic molecules that are propelled from the reaction chamber, and move through the air in a room at high speeds inactivating pathogens in the air and on surfaces throughout the treated area.

It is important to note that early-generation PCO-type air cleaners create ozone and dangerous Volatile Organic Compounds (VOCs). These deficiencies preclude their use in occupied settings, such as hospitals and schools. It was precisely these limitations that led to the creation of today's ActivePure technology, used today by governments, educators, retailers, and consumers.

4. CONCLUSION

The COVID-19 pandemic has highlighted the need for advanced strategies to combat not just the current widespread virus, but tomorrow's pathogens as well. Public health experts have urged a greater understanding of the danger of airborne spread of the SARS-CoV-2 virus in both droplets and tinier aerosols and of the relationship between viral load and disease severity.[44]

It has become clear that the world needs layered defense strategies that combine vaccination, distancing, masking, and environmental controls. While the first two mitigations are dependent on individual behavior and will become less commonplace as the COVID-19 vaccination rollout progresses, the third can be implemented *en masse* and maintained indefinitely.

As schools and businesses continue to plan for their reopening, increasing attention has been given to the importance of HVAC systems, air filtration, and surface disinfection. Much of this focus has been misplaced. MERV 13 filters and UVGI applications must wait for airborne virus particles to come to them before being partially filtered or inactivated. Surface disinfection technologies are partially useful, but are limited by infrequent application, high costs, and the health concerns posed by toxic chemicals.

By contrast, an active purification technology such as ActivePure that can continuously and safely inactivate virus particles and other pathogens both in the air and on surfaces will have an immediate impact on limiting transmission in occupied public spaces.

We conclude that ActivePure technology provides a safe, effective and essential layer of protection against the risks of community acquired infections, including places where masks cannot always be worn – for example, hospitals, schools, breakrooms, dentist offices, and restaurants. Even after the majority of the population has been vaccinated, the possibilities of imperfect vaccine efficacy, waning of immunity, and emerging variants, will create an environmental risk of persistent community transmission requiring mitigation that a technology like ActivePure provides. Perhaps more importantly, a technology like ActivePure allows us to prepare a defense against other airborne pathogens, including the flu and viruses to come.

REFERENCES

1. Shao, L. *et al.* The role of airborne particles and environmental considerations in the transmission of SARS-CoV-2. *Geosci. Front.* **12**, 101189 (2021).
2. Lelieveld, J., Dentener, F. J., Peters, W. & Krol, M. C. On the role of hydroxyl radicals in the self-cleansing capacity of the troposphere. *Atmospheric Chem. Phys.* **4**, 2337–2344 (2004).
3. Gilraine, M. *Air Filters, Pollution and Student Achievement*. *EdWorkingPapers.com* https://www.edworkingpapers.com/ai20-188 (2020).
4. Wargocki, P. Productivity and Health Effects of High Indoor Air Quality☆. in *Encyclopedia of Environmental Health (Second Edition)* (ed. Nriagu, J.) 382–388 (Elsevier, 2019). doi:10.1016/B978-0-12-409548-9.01993-X.
5. Harvard Research into Indoor Air Quality and Workplace Productivity. *Aeramax Professional* https://aeramaxpro.com/harvard-research-indoor-air-quality-workplace-productivity/ (2016).
6. Arakaki, T. *et al.* A General Scavenging Rate Constant for Reaction of Hydroxyl Radical with Organic Carbon in Atmospheric Waters. *Environ. Sci. Technol.* **47**, 8196–8203 (2013).
7. He, S. Z. *et al.* Measurement of atmospheric hydrogen peroxide and organic peroxides in Beijing before and during the 2008 Olympic Games: Chemical and physical factors influencing their concentrations. *J. Geophys. Res. Atmospheres* **115**, (2010).

8. Kellogg, E. W., Yost, M. G., Barthakur, N. & Kreuger, A. P. Superoxide involvement in the bactericidal effects of negative air ions on Staphylococcus albus. *Nature* **281**, 400–401 (1979).
9. Kröling, P. Part C Natural and artificially produced air ions — A biologically relevant climate factor? *Int. J. Biometeorol.* **29**, 233–242 (1985).
10. Maness, P.-C. *et al.* Bactericidal Activity of Photocatalytic TiO2 Reaction: toward an Understanding of Its Killing Mechanism. *Appl. Environ. Microbiol.* **65**, 4094–4098 (1999).
11. Sutherland, M. W. & Gebicki, J. M. A reaction between the superoxide free radical and lipid hydroperoxide in sodium linoleate micelles. *Arch. Biochem. Biophys.* **214**, 1–11 (1982).
12. Permissible Exposure Limits – OSHA Annotated Table Z-1 | Occupational Safety and Health Administration. https://www.osha.gov/annotated-pels/table-z-1.
13. Huang, Y. *et al.* Removal of Indoor Volatile Organic Compounds via Photocatalytic Oxidation: A Short Review and Prospect. *Molecules* **21**, (2016).
14. MRIGlobal. Verification of the Effectiveness of ActivePure® Technology in Decontamination of SARS-CoV-2. (2020).
15. William Lawrence. Airborne Inactivation of the Novel Coronavirus SARS-CoV-2 by Aerus Technology. (2020).
16. FDA Grants Class II Medical Device Clearance for Aerus Medical Guardian with ActivePure Technology. *Bloomberg.com* (2020).
17. Sattar, S. A. Hierarchy of Susceptibility of Viruses to Environmental Surface Disinfectants: A Predictor of Activity Against New and Emerging Viral Pathogens. *J. AOAC Int.* **90**, 1655–1658 (2007).
18. Greenberg, D. L., Busch, J. D., Keim, P. & Wagner, D. M. Identifying experimental surrogates for Bacillus anthracis spores: a review. *Investig. Genet.* **1**, 4 (2010).
19. Sapiña, M., Jimenez-Relinque, E., Nevshupa, R., Roman, E. & Castellote, M. Degradation of pollen on nanofunctionalized photocatalytic materials. *J. Chem. Technol. Biotechnol.* **92**, 210–216 (2017).
20. Bogdan, J., Zarzyńska, J. & Pławińska-Czarnak, J. Comparison of Infectious Agents Susceptibility to Photocatalytic Effects of Nanosized Titanium and Zinc Oxides: A Practical Approach. *Nanoscale Res. Lett.* **10**, (2015).
21. NessAiver, A. The Impact of Portable Air Purification Units on Airborne Pathogens in an Assisted Living Facility: A Case Study. (2021).
22. Eide, A. Efficacy of Beyond Medical Guardian Air with Aerus Activepure Technology in Canadian Medical ICU Settings. (2019).
23. Eide, A. Reduction of Airborne and Surface Pathogens in a Major Hospital Operating Room Through the Installation of Portable Air Purification Units: A Case Report. (2015).
24. FDA-2020-D-1138. Enforcement Policy for Sterilizers, Disinfectant Devices, and Air Purifiers During the Coronavirus Disease 2019 (COVID-19) Public Health Emergency. *U.S. Food and Drug Administration* https://www.fda.gov/regulatory-information/search-fda-guidance-documents/enforcement-policy-sterilizers-disinfectant-devices-and-air-purifiers-during-coronavirus-disease (2020).
25. US EPA, O. Pesticide Registration Manual: Chapter 13 - Devices. *US EPA* https://www.epa.gov/pesticide-registration/pesticide-registration-manual-chapter-13-devices (2013).

26. Agarwal, N. *et al.* Indoor air quality improvement in COVID-19 pandemic: Review. *Sustain. Cities Soc.* **70**, 102942 (2021).
27. ASHRAE. Method of testing general ventilation air-cleaning devices for... https://iifiir.org/en/fridoc/4431.
28. Read-Only Versions of ASHRAE Standards. https://www.ashrae.org/technical-resources/standards-and-guidelines/read-only-versions-of-ashrae-standards.
29. Batterman, S. *et al.* Ventilation rates in recently constructed U.S. school classrooms. *Indoor Air* **27**, 880–890 (2017).
30. Persily, A. & Gorfain, J. Analysis of ventilation data from the U.S. Environmental Protection Agency Building Assessment Survey and Evaluation (BASE) study. 126.
31. Air | Appendix | Environmental Guidelines | Guidelines Library | Infection Control | CDC. https://www.cdc.gov/infectioncontrol/guidelines/environmental/appendix/air.html (2019).
32. Cornet, M. *et al.* Efficacy of Prevention by High-Efficiency Particulate Air Filtration or Laminar Airflow Against Aspergillus Airborne Contamination During Hospital Renovation. *Infect. Control Hosp. Epidemiol.* **20**, 508–513 (1999).
33. Kowalski, W. & Bahnfleth, W. Airborne-microbe filtration in indoor environments. *HPAC Heat. Pip. AirConditioning Eng.* **74**, 57–69 (2002).
34. Meschke, S. *et al.* The effect of surface charge, negative and bipolar ionization on the deposition of airborne bacteria. *J. Appl. Microbiol.* **106**, 1133–1139 (2009).
35. Jiang, S.-Y., Ma, A. & Ramachandran, S. Negative Air Ions and Their Effects on Human Health and Air Quality Improvement. *Int. J. Mol. Sci.* **19**, 2966 (2018).
36. Lin, H.-F. & Lin, J.-M. Generation and Determination of Negative Air Ions. *J. Anal. Test.* **1**, 6 (2017).
37. Shahin, M. M. Nature of charge carriers in negative coronas. *Appl. Opt.* **8 Suppl 1**, 106–110 (1969).
38. Foster, H. A., Ditta, I. B., Varghese, S. & Steele, A. Photocatalytic disinfection using titanium dioxide: spectrum and mechanism of antimicrobial activity. *Appl. Microbiol. Biotechnol.* **90**, 1847–1868 (2011).
39. Wallner, P., Kundi, M., Panny, M., Tappler, P. & Hutter, H.-P. Exposure to Air Ions in Indoor Environments: Experimental Study with Healthy Adults. *Int. J. Environ. Res. Public. Health* **12**, 14301–14311 (2015).
40. Dani, M. *et al.* Autonomic dysfunction in 'long COVID': rationale, physiology and management strategies. *Clin. Med.* **21**, e63–e67 (2021).
41. Bianco, A. *et al.* UV-C irradiation is highly effective in inactivating and inhibiting SARS-CoV-2 replication. *medRxiv* 2020.06.05.20123463 (2020) doi:10.1101/2020.06.05.20123463.
42. EPA. Critical Assessment of Building Air Cleaner Technologies. https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=198703&Lab=NHSRC (2008).
43. Sultan, Z. M., Nilsson, G. J. & Magee, R. J. Removal of ultrafine particles in indoor air: Performance of various portable air cleaner technologies. *HVACR Res.* **17**, 513–525 (2011).
44. Pujadas, E. *et al.* SARS-CoV-2 viral load predicts COVID-19 mortality. *Lancet Respir. Med.* **0**, (2020).