Potential application of Air Cleaning devices and personal decontamination to manage transmission of COVID-19

SAGE-EMG 4th November 2020

Executive Summary

Application of air cleaning devices may be a useful strategy to reduce airborne transmission risks in poorly ventilated spaces (medium confidence). Air cleaning devices have limited benefit in spaces that are already adequately ventilated, and are not necessary for adequately ventilated buildings unless there are identified specific risks (medium confidence).

Air cleaning devices are not a substitute for ventilation, and should never be used as a reason to reduce ventilation; all occupied spaces must have some background ventilation to be suitable for human habitation and to comply with building and workplace regulations. Ventilation should be assessed, and if possible improved, first before considering whether there is a need to use an air cleaner (high confidence).

With respect to the candidate air cleaning technologies there is some evidence for effectiveness against other coronaviruses, but there is as yet little data that demonstrates the effectiveness of most candidate technologies against SARS-CoV-2. Advice in this paper is therefore based on potential effectiveness drawn from the known efficacy of devices against other viruses and the principles of virus transmission.

Air cleaning devices where the primary principle of operation is based on fibrous filtration or germicidal UV (UVC) are likely to be beneficial if deployed correctly (medium confidence). These devices are recommended for settings where the ventilation is poor and it is not possible to improve it by other means. The efficacy and safety of such devices should be evidenced by relevant test data.

Devices based on other technologies (ionisers, plasma, chemical oxidation, photocatalytic oxidation, electrostatic precipitation) have a limited evidence base that demonstrates effectiveness against SARS-CoV-2 and/or may generate undesirable secondary chemical products that could lead to health effects such as respiratory or skin irritation (medium confidence). These devices are therefore not recommended unless their safety and efficacy can be unequivocally and scientifically demonstrated by relevant test data.

The use of chemical sprays such as triethylene glycol to clean the air in an occupied space has a limited evidence base in being effective in reducing airborne virus transmission risks, and has potential health effects for those exposed over a long period of time (medium confidence). These approaches are not recommended without further evidence to support their safety and efficacy.

Spray booth type devices for decontaminating people are not recommended. They are unlikely to be effective against the virus and have serious health impact and safety concerns. SARS-CoV-2 transmission is usually through a result of exhaled virus or via the hands, so even where a person who is infected with COVID-19 has passed through a whole-body disinfection system/device, as soon as they breathe, speak, cough or sneeze they can still spread the virus to others (high confidence).

Effectiveness of air cleaning devices depends on multiple parameters including the underlying technology, the design of the device, the in-room location of the device, the environment that it

is used in and the maintenance of the device. The performance of most devices is based on data measured in idealised controlled environments, and is likely to be different and often lower in a real-world setting (high confidence). Caution should be used when considering idealised performance data stated by a manufacturer.

There may be unintended consequences from the application of air cleaning devices including emissions that could cause health effects, noise, changes in temperature and drafts. Further, it is clear there is a requirement for regular maintenance and consumable requirements for some devices. In selecting devices it is important to consider all aspects, not just the potential ability to remove or kill the virus (high confidence).

We are unaware of any evidence on how the use of air cleaners might affect people's confidence in and use of environments to mitigate risk of transmission of the virus or other behavioural responses that might undermine the effectiveness of air cleaners such as switching them off or blocking their use in any other way; it would be beneficial to conduct research to understand and anticipate behavioural responses to air cleaners.

The range of regulatory processes that may apply to air cleaning devices are complex and overlapping. Within a class of devices, some are high quality and likely to be effective while some use poor components and poor manufacturing and are ineffective. There are examples of devices which do not meet safety limits on emissions despite claims by the manufacturer. It is recommended that appropriate regulators consider whether there are suitable systems to assess all safety, efficacy and environmental impacts. This may need to be accompanied by action from trading standards, where justified, to remove unsafe or ineffective products.

There are a wide variety of devices available on the market with differences in specification and performance, and it is challenging even for those with expertise to select appropriate systems. A number of UK companies seeking to develop or improve upon air cleaning technologies are small, independently owned enterprises that are struggling to commission validation testing for their equipment. To use air cleaning devices effectively, urgent action is therefore needed to support industry and consumers in ensuring they are selecting and using devices safely and effectively. This includes:

- Further research on the efficacy of devices including evidence of the technology against SARS-CoV-2 virus (or a suitable viral surrogate) and other pathogens, performance of devices in real-world settings, and behavioural responses to the use of such devices.
- Appropriate advice to support the manufacturers of devices and impartial guidance for consumers to allow them to identify appropriate technologies and high quality products and cut through the marketing information on manufacturers websites.
- Guidance and training for facilities managers and building services practitioners on the selection, design, installation and maintenance of air cleaning devices.
- Standards for device testing and approved facilities where industry can access independent and verifiable testing. Alongside microbial testing, there needs to be a specific requirement to measure chemical emissions, by-products and the formation of secondary chemical pollutants, some of which have defined workplace exposure limits, and to demonstrate that these are within permitted levels where they have been identified as potentially harmful.
- Innovation funding to support the development, verification and deployment of high-quality systems. If well managed this could support UK jobs through growth of a well-regulated industry.

Evidence Review

Scope and Definitions

This paper considers the efficacy and safety of the following strategies for mitigating transmission risks:

- Portable and fixed room air cleaners designed to be used in occupied spaces: The primary focus is on devices and technologies that impact on the virus in the air. The potential benefit is therefore in the reduction of the risk of airborne transmission. A small number of technologies are also intended to impact on surface contamination and hence transmission via surface contacts. It is unlikely that any of the air cleaning devices considered in this paper would be effective at mitigating short range person-to-person transmission because they are generally designed to work in the background and not in close proximity to a person's breathing zone where droplet-based transmission occurs.
- Spray device technologies to decontaminate people in public spaces: These spray people's bodies, including clothing and hence are intended to target transmission via surface contact only. There will be no effect on airborne or short-range transmission and the disinfectant will have no effect on any virus within an infected person's body.
- The use of spray chemicals as a strategy for inactivating virus in the air of occupied rooms: This would primarily target airborne transmission but may also act as a surface disinfection method.

The following devices and strategies are out of scope:

- Devices within centralised building HVAC systems
- High energy UV devices (e.g. mobile carousel designs)/chemical airborne disinfection units designed for decontamination of un-occupied rooms
- Local surface cleaning devices such as hand held foggers and UV wands
- Personal air cleaning devices designed to be worn or carried by an individual

Within this report we refer to environmental systems as ***air cleaning devices***. Some research papers and device manufacturers use the terms air purification, air disinfection or air sterilisation. Some documents also refer to such devices as air scrubbers, particularly when used in a dental or healthcare setting. Air cleaning is considered to be a more appropriate descriptor as it recognises that these devices have the potential to reduce the bioburden in the air and hence the exposure to infectious virus, however these devices do not lead to sterile environments.

Part 1: Device technologies

What evidence is there that different device technologies may be effective against SARS-CoV-2 in terms of air cleaning?

Principles of air cleaning devices

Air-cleaning technology is being increasingly recommended as a means of improving air quality (Siegel, 2016). A recent online survey of 1,237 people showed that 8% of respondents have purchased a portable air cleaner, purifier or air disinfection device in recent months with the majority quoting COVID-19 as the main motivation for their purchase (OPSS, 2020). In-room air cleaning devices are designed as a local system to remove or inactivate contaminants in indoor air. In the context of this paper, the focus is on those devices which have the potential to reduce the concentration of airborne virus. A number of these devices may also remove other pollutants

such as non-biological particulates or volatile organic compounds (VOCs) depending on the technology. **It is important to recognise that an air cleaner is a recirculation system and does not introduce fresh air in to the treated space. As such it is not a substitute for ventilation and should never be used as a reason to reduce ventilation rates.** An air cleaner will also not remove other human bioeffluents such as exhaled carbon dioxide or many other indoor air pollutants. The US-EPA (2020) underlines this principle in their guidance, stating that, although portable air cleaners may be helpful when additional ventilation with outdoor air is not possible, the use of air cleaners alone cannot ensure adequate air quality, *particularly where significant pollutant sources are present and ventilation is insufficien*t.

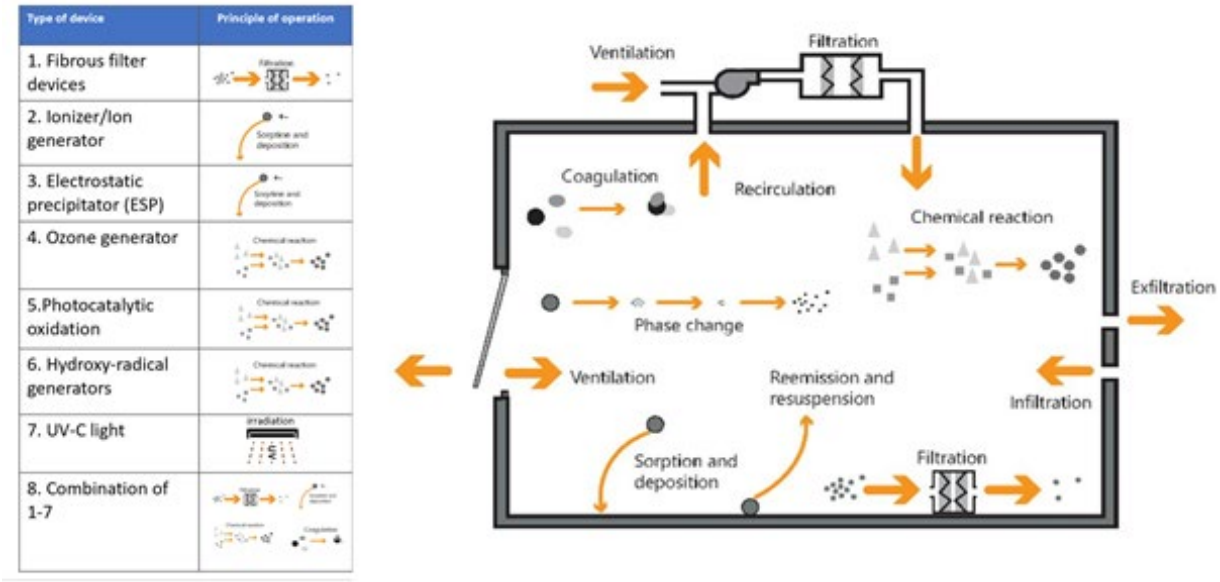

Figure 1. Principle of operation of air-cleaning devices in relation to key indoor mechanisms affecting indoor pollutant levels (CIBSE, 2020)

Air-cleaning devices adopt one or more of a number of different techniques (Figure 1): thermal- or photocatalytic oxidation, adsorption, filtration (of particles), UV germicidal irradiation, ion generation, and electrostatic precipitation (Zhang et al., 2011). However, a recent review of these technologies concluded that none of them removed all of the indoor air pollutants present and many generated undesirable secondary products (Zhang et al., 2011). Some operate by generating high concentrations of hydroxyl (OH) radicals, with the aim of removing biological pathogens. However, OH radicals are a reactive species and can initiate chemical oxidation indoors, leading to a wide variety of chemically complex products some of which are likely to be harmful to health (Waring and Wells, 2015). In the context of COVID-19, it is therefore important to understand the impacts of air cleaning device use, in order to make sure that their use does not inadvertently lead to replacing a biological hazard with a chemical hazard.

There are a vast array of devices and technologies on the market and it is not feasible for this paper to consider all of them. Air cleaning devices can range from small *portable* consumer units that can be located anywhere in a room and run from a standard power socket, through to larger *fixed* devices installed on a wall or ceiling that look similar to an air conditioning unit. Some suppliers provide a range of device sizes as part of a ‘family’ of systems and the size and installation of a device will depend on the type of setting where it is used and who the consumer is.

Annex 1 sets out the most frequent classes of technologies used, their principle of operation, the potential for them to be effective against SARS-CoV-2, and the considerations required, including usability and health and safety implications. Evidence to support the potential application of these devices is given in a number of sources including a previous EMG paper (Application of UV disinfection, visible light, local air filtration and fumigation technologies to microbial control, 18th May), a rapid review from NHS Scotland (supporting paper), a number of published research studies, experience of testing such devices by the authors, and an ASHRAE position statement (ASHRAE 2015).

Air cleaning devices typically operate on one of two principles:

- **Enclosed devices:** These operate as a stand-alone unit that draw air into the device using a fan and treat the air while it is inside the device in some way before returning treated air to the room. Such devices could contain a range of different technologies such as germicidal ultraviolet (UVC) lamps which inactivate the virus, electrostatic technologies which precipitate particulates from the air, or filters which physically remove particles. If designed well these devices usually pose little hazard as the inactivation technology is enclosed and any treatment effects are therefore localised to the device. Their effectiveness will be dependent on the efficacy of removal/inactivation of virus passing through and the relationships between the flow rate, device positioning and room volume.
- **Open devices:** These use the room itself as the zone where the technology interacts with the virus. This may be through an open field UVC lamp or by emitting something into the room, such as a chemical, plasma or ions that can potentially inactivate the virus. As these devices are open or are emitting their treatment, they bring greater risks of health hazards than enclosed devices, through potential for exposure to UVC irradiation or to chemical by-products from the device. They may also cause damage to fixtures and fittings.

A number of devices use a combination of technologies which may combine open and enclosed approaches, for example a filter unit combined with an ioniser. When selecting a device it is important to consider all the technologies that it incorporates, and base the selection on the pros and cons of all the relevant technologies set out in Table 1. Currently there is little data available on the health risks of devices containing multiple technologies (ASHRAE 2015). However, if a device incorporates a technology that is known to pose a health risk that cannot be easily mitigated, the device should not be used regardless of the other technologies it incorporates unless its safety and efficacy can be unequivocally and scientifically demonstrated by relevant test data.

Potential effectiveness of different devices

In principle germicidal ultraviolet (UVC at a wavelength around 254 nm) is effective against human coronavirus SARS-CoV and SARS-CoV-2 and this has been demonstrated where irradiation is delivered at a distance of a few cm from the target microorganisms (Darnell *et al*, 2004; Heilingloh *et al*, 2020). However, these viral reduction tests have typically used exposed liquid viral samples, not bioaerosols. More recently, a review by Heßling *et al* (2020) concluded that, as coronaviruses do not vary structurally to any great extent, the SARS-CoV-2 virus, and its possible future mutations, will likely be highly UV sensitive.

Similarly, while there is no direct evidence that use of high efficiency particulate filters can reduce the transmission of SARS-CoV-2, it is widely accepted that the virus is contained within exhaled droplets and aerosols, with those in the 1-100 micrometer range likely to pose the highest risks. Devices incorporating HEPA filters or other high grades of filter (e.g. MERV 13 or higher) are therefore likely to be effective at removing a substantial proportion of airborne virus. HEPA filters are generally rated on their efficiency at the most penetrating particle size which is between 0.1 and 0.3 micrometers.

The evidence therefore suggests that devices based on high efficiency filtration and germicidal UVC technologies are likely to be effective against the SARS-CoV-2 virus**.** Well designed and appropriately installed devices based on these technologies are appropriate to use to supplement ventilation in some situations.

Devices based on far UV (222nm) were shown in the previous EMG paper to have potential but are very early stage in development and require more research evidence, including full-scale testing, before they can be recommended for mainstream application.

Technologies based on UVA/UVB, ionisation, plasma, electrostatic precipitation and oxidation methods have limited evidence of efficacy against the virus and/or significant concerns over toxicological risks during application. As such SAGE EMG does not recommend using these devices in occupied rooms against COVID-19 without further independent evidence to demonstrate their viability and safety in realistic settings.

Part 2: Effectiveness

What are the factors that determine the effectiveness of air cleaning devices?

Factors influencing performance

The performance of all air cleaning devices depends on the ventilation rate of the room, with the relative effectiveness significantly better at lower ventilation rates. This is illustrated in figure 2 for a typical enclosed device. Air cleaning devices are therefore only recommended as a control strategy for inadequately ventilated spaces (see EMG paper Role of Ventilation in Controlling SARS-CoV-2 Transmission), as the benefits are limited where ventilation is already good.

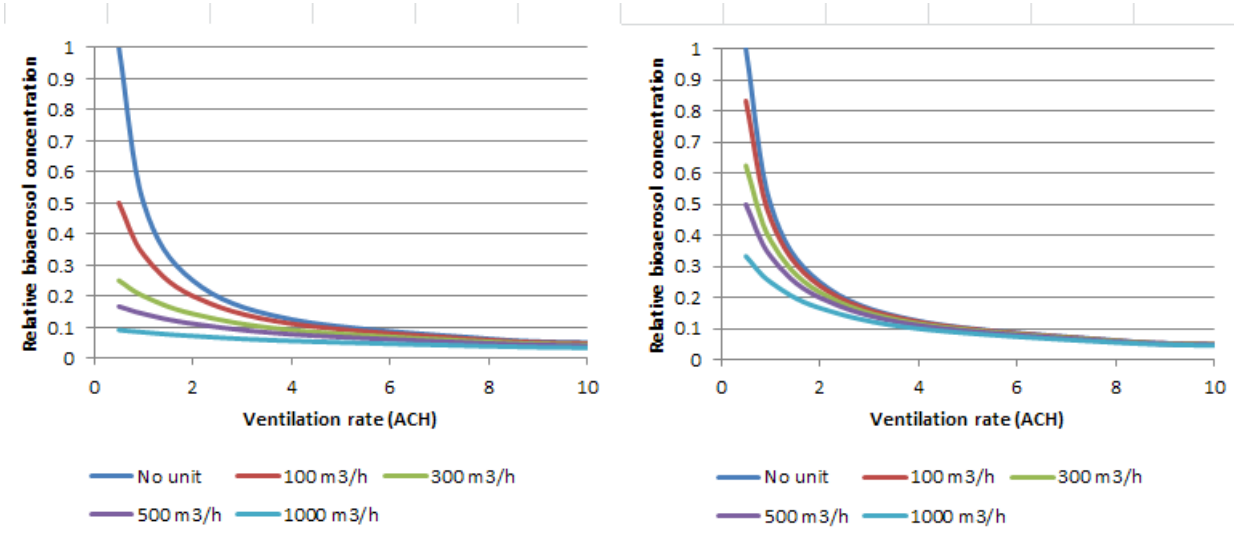

Figure 2: Modelled effectiveness of an enclosed air cleaning device with device and room ventilation rate for a 100 m^3 room (left) and a 500 m^3 room (right). Calculation of device effectiveness uses a simple zonal model and assumes 50% reduction in device effectiveness to account for incomplete mixing.

Effectiveness of an enclosed device depends on both the direct inactivation of virus within the unit, and how it operates when located within a real-room environment. The direct inactivation will be determined by the technology within the unit and the flow rate of air through the device. Manufacturers will often quote a single-pass effectiveness which expresses the reduction in virus concentration between the air that enters the device and that which leaves. The majority of systems on the market quote values of 99% single-pass effectiveness or greater. Testing of these devices shows that while this is correct for some, others may have much lower single pass effectiveness due to poor manufacturing or issues such as poorly fitting filters. Devices that are designed to remove particulates often quote a Clean Air Delivery Rate (CADR) which is an experimental test measure set by the USA Association of Home Appliance Manufacturers that expresses the equivalent amount of clean air that a device produces, usually in Cubic Feet Per Minute. For a filter-based device that incorporates at HEPA filter with 99% efficiency, the CADR is almost identical to the air flow rate through the device.

The single pass effectiveness or CADR does not express the performance in a real-world setting, which is determined by the flow rate of the device compared to the size of the room and the room ventilation rate. As illustrated in Figure 2, a single device that is effective in a small room, may have minimal effect in a large space. The effectiveness also depends on the airflow patterns within the room and the ability for the device to effectively mix the air in the room and draw air through it – a small device with a tiny fan may clean the air local to the device over and over, but have almost no effect on the air at the other side of the room. Most device testing is carried out in controlled chamber settings which don't reflect the variability of real occupied environments.

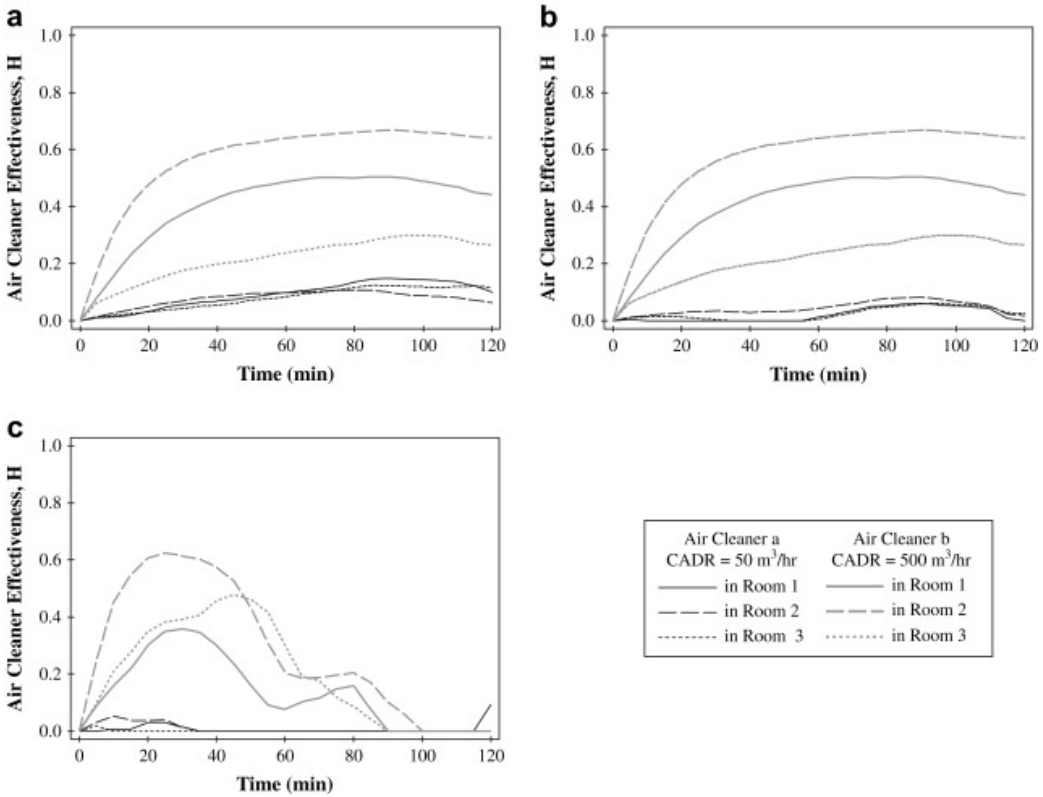

Figure 3. Air cleaner effectiveness, H, as a function of time for different CADRs and room placements for (a) 0.74 µm particles, (b) 3.2 µm particles, and (c) 10 µm particles. (Novoselac and Siegel, 2009). .

Positioning of the device as well as its airflow design and flow rate will therefore determine the performance as illustrated in Figure 3. Simulations of enclosed UVC air cleaning units suggest that positioning the device closest to the infectious source (if known) will provide the most benefit (King et al 2011)

Open devices are generally more effective at providing coverage across the whole of a room space, but are far more dependent on the specific design of the device and how it interacts with the room air flows. For example, an upper-room UV device will depend on the UVC lamp intensity, the specific design of the fitting to create a UV field, the ventilation rate and air mixing in the room that determines the interaction between virus in the air and the UV field. Computational modelling studies show that even something as simple as positioning the device on the opposite wall of the same room could reduce the UV dose received by the room air by up to 1.6 times due to the interaction between the UV irradiance field and the room airflow (Noakes et al 2006). Several studies also show that room airflow mixing is important for upper-room UV systems to perform effectively (Gilkeson and Noakes 2013), which can be enhanced in some settings using mixing fans (Zhu et al 2013)

The environmental conditions can also influence effectiveness for some systems; UVC performance is more effective at low humidity and higher temperature (Ko et al 2000, Lau et al 2009), while systems based on oxidation or ionisation principles will also be affected by the environmental conditions.

Testing methodologies to measure performance

Understanding the performance of a device can be difficult. There are standard test procedures in the US defined for devices that remove particles, including the CADR defined above. BS EN IEC 63086-1:2020 outlines a method for measuring the performance of electrical air cleaning devices based on a 30m^3 test chamber. The 63086-1:2020 method however only covers the technical specifications for the testing chamber itself, whilst the actual air cleaner performance standard (IEC-63086-2) is still under preparation. Table 1 gives a summary of these testing protocols.

There are no UK or international test standards for microbial inactivation and removal, and manufacturers tend to rely on university laboratories, a small amount of commercial work carried out by PHE and HSE or overseas testing laboratories. As such manufacturers report a very wide range of test results under different room scenarios, ventilation rates, test microorganisms and test conditions. In many cases the data reported lacks information on how the testing was carried out.

Single pass testing can often be carried out by a microbiology laboratory with appropriate biosafety cabinets, or else using bespoke bioaerosol delivery and sampling tunnels, where available. Room scale testing requires a very specialised bioaerosol chamber facility where microorganisms can be safely aerosolised in the presence of the device; there are very few of these facilities in the UK and worldwide. There are typically two approaches to chamber testing.

- A steady-state test compares the concentration of a test microorganism in the room air under continuous contamination conditions with and without the device in operation. The difference between the two conditions, gives the reduction in contamination due to the device and is indicative of performance in an occupied space with an infectious person present. Such data may be expressed in terms of percentage or log reduction over time with

the intervention in place, when compared to the process control (without the device in place).

- A decay test compares the rate at which a test microorganism is removed from the chamber with and without the device present after generation of the microorganism ceases. This test gives an indication of how quickly a device will clean the air in a room following contamination.

Both cases require carefully set up tests with multiple replicate samples to capture the variability that is inherently present in a biological system under real room scale. Decay measurements in chambers require careful analysis to avoid introducing error into the resulting decay rates (Parker et al. 2015).

Table 1. Review of testing protocols for air cleaning devices (Afshari et al., 2020)

Standard/Protocol (Ref.)	Country	Method	Challenge Particles	Measured Particle Size Range	Performance Index
Portable Air Cleaners					
ANSI/AHAM [17]	US	Pull-down	Environmental Tobacco Smoke Arizona Road Dust Paper Mulberry Pollen	0.1 to 1.0 µm 0.5 to 3.0 µm 5 to 11 µm	CADR [a]
GB/T-18801 [18]	China	Pull-down	Environmental Tobacco Smoke Arizona Road Dust Paper Mulberry Pollen	0.1 to 1.0 µm 0.5 to 3.0 µm 5 to 11 µm	CADR
NRC Protocol [27]	Canada	Pull-down	Polydisperse Potassium chloride (KCl)	50 nm to 5 µm	CADR
NCEMBT Procedure [28]	US	Pull-down	Polydisperse potassium chloride (KCl)	0.1 to 11.5 µm	CADR
Lucerne University (2012) [29]	Switzerland	Pull-down	ISO 12103-1 A1 Ultrafine test dust.	0.2 to 5 µm	
JIS C 9615 [30]	Japan	Single-pass	JIS Z 8901 standard dusts	…	Removal rate
XP B44-200 [31]	France	Single-pass	DEHS, cat allergens, *Staphylococcus epidermidis Aspergillus niger*	0.3 and 5 µm	SPE [b], CADR
In-duct air cleaners					
ANSI/AHRI 681 [32]	US	Single-pass	Polydisperse potassium chloride (KCl)	0.3 µm to 10 µm	SPE

Note: (a) CADR: clean air delivery rate; (b) SPE: single pass efficiency.

Device performance has been shown to be very variable and is dependent on the particular device rather than the class of device. Chamber testing at the University of Leeds and by HSE has shown that many devices do not perform as expected and in some cases the performance of the device is significantly reduced if filters are removed, suggesting that in many cases it is filters within devices rather than the other technology that is delivering most of the effect (Table 2). It should also be noted that chemical by-product formation is rarely considered in these tests, with the focus being on the bioserosol removal efficiency (Carslaw et al 2013, Carslaw et al 2017).

Table 2. Performance of two commercial air cleaning devices with and without HEPA filters. Testing carried out in a 32 m3 chamber at 1.5 ACH using S. aureus bacteria nebulised under steady-state conditions (unpublished test data, University of Leeds)

Device	Reduction (%)
Device 1 HEPA filter only, no ionisation	60.2
Device 1 HEPA filter plus ionisation	62.1
Device 1 Ionisation only, HEPA removed	25.2
Device 2 HEPA filter only, no ionisation	52.9
Device 2 HEPA filter plus ionisation	28.1
Device 2 Ionisation only, HEPA removed	1.6

How likely are air cleaners to be at reducing the risk of transmission under different ventilation conditions/different settings?

Epidemiological data

The majority of experimental and field data considers the reduction in microbial load in air, but does not relate the application of the device to the reduction in infection rates. This is primarily because it is exceptionally hard to measure the large-scale impact of this this type of intervention, requiring control and test study sites that have comparable and sufficient infection rates to get statistically reliable results. Several studies have measured the impact of upper-room UV devices in clinically relevant settings. Original studies by Wells and Riley (Riley et al 1962) demonstrated the airborne transmission of tuberculosis from people to guinea pigs and showed the installation of UV lamps in patient rooms reduced the risk of infection in guinea pigs. Wells et al (1942) also showed the effectiveness of upper-room UV against measles in a school environment. Modern day repeats of the TB study, with measurement of ventilation rates and genomics alongside infection rates demonstrated a 71% reduction in transmission in one 10 month trial Escome et al (2009), and an efficacy of 80% in another 7-month trial (Mphaphlele et al, 2015). The latter recommends UV devices with an upper room average irradiance of 5-7 μW/cm2. A study in a workplace setting has shown reduction in absenteeism (Menzies, 2002).

Evidence for other technologies is more limited. A short trial of ionisers in a UK hospital showed that *Acinetobacter* infections dropped to zero, but that surface contamination increased and there was no impact on *S. aureus* infections (Kerr et al 2006). This would suggest that the technology may lead to preferential deposition and is highly dependent on the circumstances and the pathogen. As detailed in the NHS Scotland Rapid Review, a small number of studies have shown that HEPA filter-based units can be effective at reducing the concentration of bacterial pathogens in air in real-world hospital settings. A number of studies have shown the positive impact of HEPA filter devices on fungal infections, with one showing the use of portable HEPA devices reduced the incidence rate from 34.61/100,000 patient-days to 17.51/100,000 patient-days (Salam et al 2010). There is very little data on viruses, however an animal study showed that HEPA filter-based systems can be effective against transmission of PRRSV by aerosol (Dee et al 2006). In a yet-to-be-peer-reviewed study, Curtius et al (2020) made experimental measurements of particle concentrations within class rooms with and without air cleaners. They observed a greater than 90% reduction in aerosol concentration and estimated a six fold reduction in risk from the use of air cleaners.

Modelled risk

Impact of air cleaning devices on transmission risks can be modelled using Wells-Riley or other aerosol models with a dose-response curve in a similar way to ventilation. In many cases it is

feasible to express the performance of an air cleaning device in terms of “equivalent air change rate” and use this value together with the room ventilation rate in a risk model.

Figure 4 illustrates the potential impact on infection rates resulting from different sizes of enclosed HEPA/UV devices in two different room configurations. In these estimates, flow rates through devices are reduced by 50% compared to the design flow rate quoted by the manufacturer. This is a precautionary approach to reflect that poor positioning of the device may cause local recirculation of air, but ineffective mixing across the whole space, and is based on ASHRAE recommendations for short circuiting flow. Results are consistent with those in figure 2 and illustrate the greater benefit of air cleaning devices in spaces which are smaller and have lower ventilation rates.

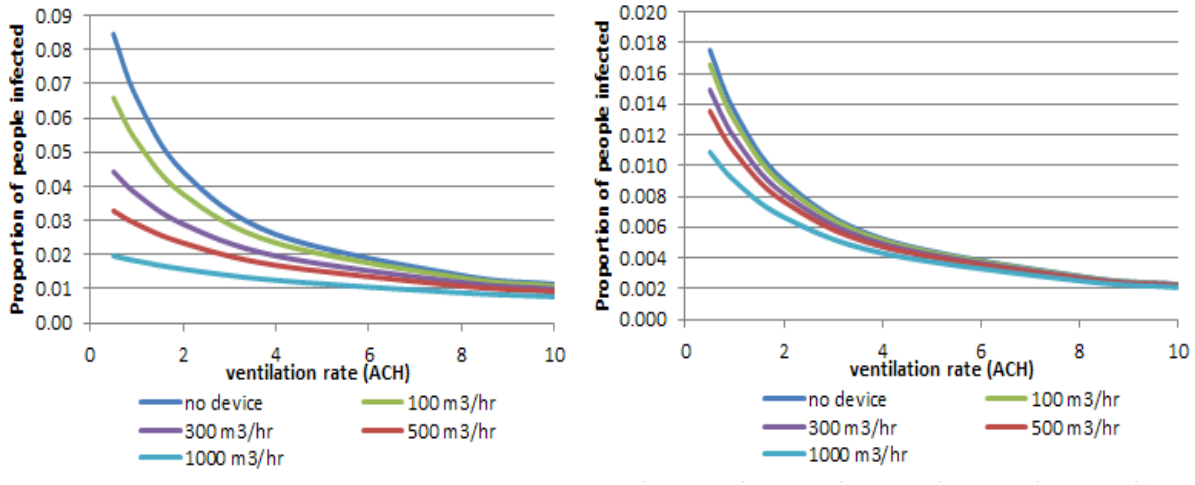

Figure 4: Simulation from Wells-Riley model for airborne transmission over a 2 hour period, , 10 quanta/hr and breathing rate of 10 l/min. Results for device flow rates between 100 and 1000 m3/hr in a 100 m3 room (left) and 500 m3 room (right).

Models of transmission risk for upper-room UV systems can be developed in a similar way, but need to consider the inter-zonal flow between the occupied zone of the room and the upper portion of the room where UV devices are located; this can be achieved through analytical models (Noakes et al 2015) or computational fluid dynamics (Noakes et al 2004, Gilkeson and Noakes 2013, Zhu et al 2013). Models show that with realistic installations, equivalent air change rates of 6-10 ACH can be readily achieved.

Implications for different scenarios

The following briefly sets out the types of systems and other considerations in a range of generic settings. There is considerable variability in these settings and this table should not be construed as a recommendation that devices are required in all of these locations. In all cases the ventilation should be assessed first, and air cleaning devices only considered where the ventilation is inadequate and cannot be easily improved. In all cases the application of an air cleaning device must take into consideration the specific setting including geometry, layout, occupancy, activity, ventilation strategy and risks.

Table 3: Potential application of air cleaning devices in different scenarios

Scenario	Considerations
Home	Unlikely to be needed in most settings, but small portable filter-based devices may be appropriate where it is difficult to ventilate due to poor outdoor air quality. Placement in highest risk room (visitors or room of a sick person)
Small office/meeting room with less than 10 people	A single small to medium sized filter or enclosed UV based device. Ideally positioned on ceiling/wall to provide effective air mixing, although portable devices may also be appropriate. An upper-room UV device could work if the ceiling is high enough.
Large office/education environment with 20-30 people	Larger enclosed devices or upper-room UV if the ceiling is high enough. Would need to consider noise of enclosed devices, and positioning to ensure sufficient coverage. Multiple devices are likely to be needed to provide effective coverage. Fixed devices are more appropriate than portable units.
Performance venue with 200+ people	Larger enclosed devices or upper-room UV may be effective if ventilation rates are insufficient. Would need to consider noise of enclosed devices. Devices need to be sized and positioned appropriately for the airflow. Additional consideration is needed where displacement ventilation is used as devices may disrupt the designed airflow. Multiple devices are likely to be needed to provide effective coverage. Fixed devices are more appropriate than portable units.
Large retail premises	Unlikely to be needed as ventilation is rarely low enough to merit installation.
Hospitality setting (bar or restaurant)	Several enclosed devices are likely to be needed depending on the size and shape of the venue. Upper-room UV devices may be viable in some settings if the ceilings are high enough, but may be harder to install in some settings, particularly if there are a lot of partitions/zones. Portable or fixed device may be appropriate depending on the venue
Gyms and indoor sports venues	Many venues have good ventilation and hence air cleaning would not be needed, however devices may be appropriate in settings with higher levels of aerobic activity that have lower ventilation rates. Fixed devices that are ceiling/high wall mounted are more appropriate to be away from activity.
Small business/smaller retail premises	May be appropriate for settings that rely on natural ventilation through opening doors. One or more enclosed devices, depending on the size and shape of the premises. Upper-room UV could be viable in some settings. Portable or fixed device may be appropriate depending on the venue.
Chilled food processing	May be beneficial in settings where there is a high degree of air recirculation to maintain temperatures. Upper room UVC or fixed ceiling mounted larger enclosed systems may be effective. Would be important to consider the influence of temperature and humidity on the effectiveness.

Large manufacturing environment	Unlikely to be needed as ventilation is rarely low enough to merit installation.
General hospital or care environment	Potentially beneficial in older settings and those that are naturally ventilated or are less able to guarantee airflow rates. Upper-room UV or enclosed devices could be used. Noise is a key consideration. Likely to require one device per bed/room, plus additional devices in communal spaces. A risk-based approach should be used to determined where devices are likely to be most effective.
Dentistry or healthcare aerosol generating procedure	High flow rate portable enclosed devices positioned to remove aerosol generation close to the source. Appropriate in poorly ventilated dental surgeries/treatment rooms, but not likely to be beneficial in spaces with high ventilation rates such as operating theatres.
Public transport	Benefits will depend on the ventilation rate – many vehicles have good fresh air flow rates. Not suitable for upper-room UV, but enclosed, fixed UV devices could be appropriate if they can be installed effectively and in a robust manner. HEPA filter devices are often unsuitable as the high level of particulates in the air on some transport routes means that filters need to be changed too often.

:.

Part 3: Practical application

Are there any negative health/environmental effects of air cleaning devices?

Health Effects

Many air cleaning devices can have negative health impacts which most commonly relate to the significant effect on the indoor air chemistry that results when chemicals are emitted directly or formed from the resulting chemistry following their use. Ozone and hydroxyl radicals are generated by some of these devices. Once formed, these powerful oxidants can react with volatile organic species indoors that are generated when we using cleaning and personal care products (Carslaw et al., 2012). These reactions can then produce a range of secondary chemical species, some of which are themselves harmful to health, such as formaldehyde and ultra-fine and nano-particles. Health impacts will depend on the particular chemicals and particles that are produced.

There are complex interactions in indoor air, and numerous links between different chemical species in both the gas and particle phase, which is why care must be taken when attempting to ‘clean’ air. Removing a microorganism or a pollutant directly does not necessarily mean that the hazard will be eliminated, because it may be replaced via chemical reactions that lead to a new chemical hazard. Indeed, Carslaw et al. (2015) showed that removing particles from office inlet air using a filter led to higher than expected indoor Secondary Organic Aerosol (SOA) concentrations indoors. This observation was explained by a disruption of the equilibrium that exists between the gas- and particle-phases of potentially condensable species. In any air mass, this equilibrium will be defined by the concentration and relative molecular mass of the species, the partitioning coefficient and the temperature. If particles are removed from this air mass with a filter, equilibrium will be re-

established through the production of more particles. Changes in temperature between indoors and outdoors can also affect particle removal efficiencies by filters (Fisk, 2013).

Table 4: Potential health hazards associated with air cleaning devices

Hazard	Health impacts	Safe limit in indoor spaces
Ozone	Respiratory irritation, even at low levels	UK short term (15-minute) workplace exposure limit = 0.2 ppm (or 0.4 mg/m^3) (HSE, 2020b)
Formaldehyde	Respiratory irritation even at low levels, harmful to exposed mucous membranes. This chemical is carcinogenic.	UK short term (15-minute) and long term (8 hr TWA) workplace exposure limit both = 2 ppm (or 2.5 mg/m^3) (HSE, 2020b)
Nitrogen dioxide	Respiratory irritation, exacerbation of existing respiratory conditions	UK short term (15-minute) = 1 ppm (or 1.91 mg/m^3); long term (8 hr TWA) workplace exposure limit = 0.5 ppm (or 0.96 mg/m^3) (HSE, 2020b)
Ultrafine and nano-particles	Similar to inhalable vapours and dependent on the chemical residue involved. Particle ingestion and dermal exposure routes may also be relevant.	NISOH recommend for carbon nanomaterials: Recommended exposure limit = 1 $\mu g/m^3$
UVC	Ocular damage including photokeratitis (inflammation of the cornea) which may be evident several hours after exposure. Cutaneous damage leading to reddening of the skin similar to sunburn	NIOSH/CDC long term (8 hr) recommended exposure limit = 6 mJ/cm2

The health hazard posed by an air cleaner depends strongly on the technology. Some devices such as chemical oxidation devices deliberately produce compounds, such as ozone, to inactivate microorganisms. If the concentration is sufficient for the device to effectively disinfect the room, it is likely that the concentration will also exceed safe limits for human health. Some devices unintentionally produce secondary pollutants depending on the design and operation of the device. In many cases testing experience suggests this is a result of the device quality, with concentrations of by-products exceeding values stated by manufacturers. The most common by-product is ozone, which should remain below 0.2 ppm in an occupied space to avoid adverse health effects for those residing there.

Devices based on UVC at 254nm wavelength pose a particular risk to skin and eyes (ASHRAE 2019) if designed and installed poorly. Installation should ensure that occupants cannot be directly exposed to the UV light, and that the UV irradiance in the occupied zone of the room doesn't exceed the recommended limit values (see table 4). Some poorly designed UVC devices can also produce ozone. Both chemical by-products and UV light can potentially cause damage to materials and fixtures in a building (ASHRAE 2019). Far UV irradiation (222 nm) reportedly does not present the same hazard, but data for this technology remains limited (Buonanno et al, 2020).

Noise

Testing of air cleaning devices to determine their noise emissions is important because they are likely to be used in occupied indoor environments and must be designed with this in mind. It is a requirement for such devices to be assessed to determine that noise emissions are within acceptable levels under current standards, such as the Machinery Directive, for their intended indoor use.

To put daily noise levels in context, normal conversation typically produces around 60 dB(A). Any background noise above 60 dB(A) will result in people having to raise their voices, and a build-up effect can occur. For example, if people have to raise their voice to make themselves heard above the general background noise this creates a general level increases, which requires people to raise their voices further.

However, above 80 dB(A) daily exposure, for people at work, there ought to be noise risk assessment under the Control of Noise at Work Regulations (HSE, 2005). Typically, for the low range noise levels likely to be generated by in-room air cleaning devices, any usage restrictions are likely to to be based on noise nuisance, rather than risk. For devices generating less than 75 dB(A) at 1m, the issues to consider are therefore likely to include the following:

- how intrusive is the noise? This is only likely to be a major issue with blown air if small inlets or outlets or high-speed fans are in use.
- how close are the air cleaning systems to people? In practice it is the noise level at the nearest person that is important.
- how many air circulation devices are needed in a particular room space? If they are close together, every doubling of numbers will nominally add 3dB to the noise level.

The nature of the noise emissions is also important since there can be risks associated with stress and sleep disturbance from certain types of noise emission. All the devices of this type would be expected to produce non-hazardous broadband random noise with no distinctive tones or time variations.

Operating behaviour of air cleaners in 43 residential buildings in China demonstrated that only 5% of households were likely to operate their cleaning device at “High” air cleaning mode with noise cited as one of the main concerns (Pei, Dong and Liu, 2019). A comparison of noise levels of 6 HEPA air filters demonstrated noise levels of 27-35 dBA (at minimum flow rate) and 45-53 dBA (at maximum flow rate) (Peck et al., 2016). These levels exceed the noise level requirements for continuous ventilation systems in the Building Regulations Approved Document F which sets a limit of 30 dBA for living rooms and bedrooms in dwellings. A review of mechanical ventilation noise recommended a limit of is 30 dBA to avoid adverse effect on sleep (Harvie-Clark et al., 2019). The maximum flow rate noise levels from the Peck (2016) study also exceed the acoustic performance standards for UK schools (BB93, 2015), which range between 35 dBA- 45 dBA for most lecture rooms in both new and retrofitted schools.

It must be noted that Approved Document F however does not apply to portable air cleaners as it only covers “fixed building services”.

In an unpublished pilot study by Beswick *et al,* (2017) noise emissions were assessed by an acoustician for five commercially available air cleaning devices; four were floor standing and

one wall mounted and all devices contained fans and filtration elements. Noise levels were tested for each device during use at maximum air flow. Measurements were made of the LAeq (A-weighted time average sound level) with the air cleaning devices operating in a semi-anechoic chamber using a calibrated sound level meter. Noise emissions were taken with the devices standing on a hard concrete floor and repeat measurements were made with the devices on carpet. Noise readings were taken at a height of 1.3 m from the floor, to be representative of the ear height of a seated person. The horizontal distance from the device to the measurement point was 1 m, with repeat measurements at 2 m. This horizontal distance was measured from the front of the face that included the vent. Where measurements were made facing sides without a vent this distance was measured from the centre point. The assessment found that all devices worked at noise levels that fell below the threshold level of 75dBA that equates to 'no risk' in terms of a 24-hour daily noise exposure. Within the same study, the nature of the noise emissions was also assessed, since there can be risks associated with stress and sleep disturbance from certain types of noise emission. All the devices were found to produce non-hazardous broadband random noise with no distinctive tones or time variations.

All devices, with the exception of upper-room UV systems, incorporate fans to draw air through the device and/or blow the device output into the room. This airflow will influence the airflow patterns in the room. In many cases this will be a minor effect if the flow rate is small, and is likely to be beneficial in terms of promoting air mixing. However, devices with high airflow rates may create noticeable drafts and if positioned poorly could inadvertently distribute airborne virus between neighbouring spaces in a building. Use of a device in a room where there is a mechanical ventilation system based on displacement ventilation (these are common in theatres and auditoria) may disrupt the intended airflow patterns, however there is no evidence published currently to show the extent of this effect.

It is possible that use of air cleaning devices may impact on human behaviour. This could be beneficial through giving reassurance, however it is also possible that they could give people a false sense of security. There is a very small amount of evidence relating to consumer behaviour in selection of air cleaning devices to manage air quality, which suggests that awareness of risk, product knowledge and risk perception influence their likelihood to purchase an air cleaner (Wu et al 2017). OPSS data shows that air cleaner purchases have increased, and there are multiple media articles and public facing information (Which 2020). However there is no clear research evidence to our knowledge that relates to behaviour or risk perception relating to air cleaners for infection control

How should devices be safely deployed and what evidence is there to support servicing and maintenance?

Many devices contain internal components, such as high efficiency filters and UV lamps that are fragile if portable equipment is dropped or tripped over. If these components are dislodged or damaged then equipment performance may be affected. It is important to consider therefore whether portable or fixed devices are most appropriate for a setting.

Effective maintenance and safe use of any such device is also important to maintain system efficiency and functionality. It would be expected that any supplier would provide full instructions on the use of any purchased system(s). Key maintenance requirements will include electrical safety checks, changing filters, and in UVC based devices changing UV

lamps after a specified period of use. It is worth noting that there are growing numbers of low cost consumer devices, which may potentially be replaced rather than maintained. In a commercial or public environment it will be important to have clear responsibilities defined for maintenance of devices with appropriate schedules and checking processes.

Within the published domain, authoritative advice on safety in use and maintenance for air cleaning devices is sparse, but some examples do exist. A recent review of long-term portable air cleaner performance outlined that service life would vary between 1-37 months depending on the level of usage (1-12 hours per day) and outdoor air pollution levels (Pei et al., 2020). Dust and particle build up reduces the CADR of air cleaners (Zuraimi et al., 2017, Ju et al., 2019) due to both reduced filter performance and increased filter bypass. The typical operating life for UVC lamps is 9000h (ASHRAE 2019).

A detailed review on the use of air cleaning devices was undertaken by the Ontario Medical Advisory Secretariat (2005). The review was healthcare focussed and cites advice provided by ECRI, an independent organisation that conducts medical device evaluations. The user advice supported by both organisations included multiple maintenance and safety principles when using air cleaning devices, which are set out in **Annex 2**. Many of these usability and safety measures are also described in an earlier publication by Scott *et al*, (2002). In both cases these documents were prepared by healthcare experts with healthcare deployment in mind.

Relevant guidance on the application of air cleaning devices is given by a number of organisations. CIBSE Guide A (2015) has a short section on health and includes an overview of UV systems, while ASHRAE and CDC have detailed information on UV systems (ASHRAE 2019, CDC 2009) that includes safety, design, installation, commissioning, maintenance and disposal of lamps. The US EPA have guidance that is aimed at consumers looking to select air cleaners for home environments (US EPA 2018), as well as guidance that is specific to COVID-19 (US EPA 2020). There are also a number of academic and research groups offering guidance and calculation tools such as those provided by the Harvard Healthy Buildings Programme (Salimifard et al 2020).

What steps would need to be taken support the effective deployment of air cleaning/decontamination devices (research gaps, guidance, regulation)?

The range of regulatory processes that may apply to air cleaning devices are complex and overlapping. Regulations may differ depending on the size and design of devices, with portable consumer devices coming under different regulations than those that would be installed as part of the building services. There are existing regulations that set requirements for the supply and safe use of chemical products. This includes the use of disinfectants in both workplace and public settings. All devices must comply with existing regulations for product safety, however it is less clear how efficacy of devices can be compared and rated. Within a class of devices, some are high quality and likely to be effective while some use poor components and poor manufacturing and are ineffective. There are examples of devices which do not meet safety limits on emissions despite claims by the manufacturer. It is recommended that appropriate regulators and policy makers consider whether that there are suitable systems to assess all safety, efficacy and environmental impacts. This may need to be accompanied by action from trading standards, where justified, to remove unsafe or ineffective products.

There are already air cleaning devices on the market and some technologies are mature and available for deployment quickly. To support this, the following steps are recommended as immediate actions:

- Rapid research to evaluate likely consumer response to use of air cleaning technologies and understand their level of knowledge and potential behavioural actions.
- Development of impartial guidance for consumers to allow them to identify appropriate technologies that may be effective against SARS-CoV-2 and cut through the marketing information on manufacturers websites. This should explain the pros and cons of different approaches and indicate the key considerations for application including placement of the device and maintenance.
- Guidance and training for facilities managers and building services practitioners to enable them to select, design and install appropriate air cleaning systems and provide effective operational guidance to occupants and maintenance of devices. This could be developed in collaboration with expertise through the Royal Academy of Engineering, IMechE, CIBSE and other building services professional and training bodies.

Further steps are recommended to enable the longer term safe and effective deployment of devices, however the timescales for these are likely to be of the order of months or longer rather than immediate action:

- Further research is needed on the efficacy and usage of devices. This includes evidence of the technology against SARS-CoV-2 virus and other pathogens in very controlled settings, evidence of device efficacy against surrogate pathogens in controlled chamber studies, intervention type studies in real-world settings to determine impact on transmission and real-world studies to evaluate the wider impact of devices including impacts on other air quality parameters, maintenance requirements and frequency and user acceptability and behavioural response.
- Defined standards for device testing and approved facilities where industry can access independent and verifiable testing are both needed. An appropriate UK standard that sets out test conditions and microbial protocols would enable more consistent comparisons between devices and confidence in test data, particularly if it is provided in-house by a manufacturer. This should include testing against appropriate challenge microorganisms and specific requirements to measure any intended or unintended chemical emissions and evidence that these are below permitted human exposure limits. This is particularly important because most air cleaning devices are designed to be used in inhabited indoor spaces. Ideally this standard would also be developed in collaboration with international partners to ensure consistency between countries. Testing requires specialist bioaerosol chamber test facilities which have to be operated under tight protocols by highly trained scientists, due to the high risks associated with deliberately aerosolising microorganisms. This makes even basic testing expensive for those commissioning it (see below). Investment in facilities, either within academic or research organisations or as independent testing laboratories is necessary to enable appropriate and safe testing to be carried out.
- Innovation funding to support the development, verification and deployment of high-quality air cleaning systems. This could range from rapid review panels to identify potential good ideas for seed corn funding support, through to larger scale funding to support trials of devices in real-world settings. Many organisations who are developing

devices are SMEs with limited access to research organisations and funding to conduct studies. If well managed this could in the longer-term support UK jobs through growth of a well-regulated industry.

Part 4: Chemical Spray/Misting approaches for human body decontamination and air cleaning

What evidence are there for technologies being proposed for "decontaminating" people before they enter shared (entertainment) spaces being effective?

Principles of whole-body treatment

Walk-through, whole body decontamination technologies comprise cabinets, tunnels or other compartments that people must walk through while a fine disinfectant mist is delivered over their body surface. This includes the treatment of any clothing worn. Some suppliers of these technologies state that their systems do not act as spray systems, but rather as misting systems, claiming that the fine mist is non-wetting. The primary intention is to bring a fine disinfectant coverage in to contact with the body surface and clothing. There are also reported examples of UV being delivered to people in walk-through tunnel designs.

A small number of published papers appear to support or promote the use of these systems. These reports are typically written by engineers or designers who have developed spray systems. (Hussain *et al*, 2020); Maurya *et al*, 2020; Pham *et al,* 2020). In all cases the authors offer no public health or scientific insight to support the efficacy of their claims and fail to consider or understand the chemical exposure risks of the systems they are promoting.

Individuals infected with SARS-CoV-2 will harbour the virus within their bodies in the upper respiratory tract and delivering a disinfectant or UV treatment over the surface of a person's body, including clothing, will therefore have no effect on any virus within the infected person's body. These treatments, regardless of the chemical applied, will therefore do nothing to reduce the infectivity of those treated in this way (HSE, 2020; WHO, 2020; CDC Africa, 2020). As soon as an infected person breathes, speaks, coughs or sneezes they will produce infectious droplets and aerosols that may inadvertently contaminate others directly, or contaminated nearby surfaces. These infection routes will be unaffected by whole body spray treatment.

Health and safety concerns - whole-body walk-through treatment

Major concerns exist over the impact of such treatments on people's health and well-being and these are considered below. Within the UK, HSE-CRD is aware of a number of available body spray technologies intended to deliver chemical disinfectants such as Sodium Hypochlorite (bleach), Hypochlorous acid, Alkyl (C12-16) dimethylbenzyl ammonium chloride (ADBAC/BKC) and Didecyldimethylammonium chloride (DDAC). These chemicals, if used, would be delivered as a fine mist/spray using walk through equipment. Any non-viscous liquid disinfectant could, in theory, be delivered in this way and chlorinated products (bleach and related products) and alcoholic sprays have been reported in other countries (Rabby et al, 2020). These are potentially harmful to those exposed, with no certainty that they will eradicate microorganisms on clothes or exposed skin. If used in sufficient concentrations some may also have adverse effects on clothing materials, or pose a fire hazard. To support

system efficacy, some supplying companies cite disinfection test standards but these typically relate to suspension type tests performed with the same disinfectants applied to non-porous hard surfaces (usually steel carriers). These data therefore do not relate to or validate the spray application of the disinfectant on to clothing and body surfaces. There is no guarantee that the same disinfectant efficacy will be achieved when the product is sprayed as a fine mist on to clothing or other porous surfaces.

Scientific and medical evidence and advice - whole-body walk-through treatment
In recent months scientists and medical authorities internationally have voiced their concerns about the harm that whole body spray systems may do and their ineffectiveness. There is a consensus that currently no evidence exists that these systems work. In the US, the FDA states that, "*Surface disinfectants should **not** be used on people or animals. Disinfectant products, such as sprays, mists, wipes, or liquids are only to be used on hard, non-porous surfaces (materials that do not absorb liquids easily) such as floors and countertops, or on soft surfaces such as mattresses, sofas, and beds*." This stance is further supported in published scientific opinion statements from scientists and healthcare professionals in South Africa, Saudi Arabia and Bangladesh (Gray et al, 2020; Mallhi *et al,* 2020; Rabby *et al,* 2020). The publication of Gray *et al*, (2020) is particularly incisive in its statements about these technologies, describing, with additional supporting evidence, how:

- Chemicals, often of unknown quality and composition, can result in significant eye and skin irritation. Such chemicals are made for inanimate surfaces, not the human body.
- With inhalation, chemicals can irritate the respiratory system, and cause bronchospasm and asthma attacks. Resultant coughing and respiratory tract damage can actually increase the spread of the virus.
- Chemicals used for disinfection can irritate the digestive tract, causing nausea and/or vomiting.
- Frequent exposure may lead to long-term issues such as occupational lung disease or cancer.

CDC Africa (2020) provides a useful summary of chemicals that have been or could be delivered as whole-body sprays/misting devices in order to summarise the various health effects that can result from uncontrolled human exposure (see Table 5). This list includes UV treatment of people, which has been an additional walk-through treatment encountered in some countries.

Table 5. Health risks of dermal and inhalation exposure from common sprayed disinfectants (CDC Africa 2020).

Product	CAS reference number	Presentation	Indication of use	Health risks
Ozone	10028-15-6	Gas	Disinfectant of air and water	Inhalation at low concentrations may increase risk to health, accelerate viral or bacterial infections of the respiratory tract or exacerbate pre-existing chronic lung lesions
Hydrogen peroxide	7722-84-1	Liquid	Disinfectant, whitener	Eye, nasal, dermal, throat and respiratory irritation
Sodium hypochlorite	7681-52-9	Liquid, Granulated	Disinfectant for inanimate surfaces, terminal cleaning, water purification, bleaching	Eye irritation and dermal contact irritation Inflammation and erosion of mucous membranes if swallowed
Hypochlorous acid	7790-92-3	Liquid	Disinfectant	Potential dermal irritation from direct exposure Potential respiratory tract irritation and pulmonary oedema from vapour inhalation
Quaternary ammonium	Product mixes, varies by composition	Liquid surfactant	Disinfectant	Dermal irritation, shortness of breath, gastrointestinal injuries in case of ingestion
Isopropyl alcohol (not alcohol-based hand rub)	67-63-0	Liquid	Disinfectant	Eye, nose and throat irritation, second to direct exposure or contact with vapours
Ultraviolet rays		Light	Disinfectant of drinking water, air, titanium implants	UV-induced skin erythema and keratoconjunctivitis

In an assessment of the impact of whole body spraying of chlorinated disinfectant on a moderately large cohort, Mehtar *et al,* (2016) undertook a cross sectional survey by interviewing 1550 volunteers; 500 healthcare workers (HCW); 550 Ebola survivors (EVD); and 500 quarantined asymptomatic Ebola contacts (NEVD). This study has the advantage of being able to consider past treatments given to people during the outbreak. Demographics, frequency of exposure to chlorine, clinical condition after chlorine exposure particularly eye, respiratory and skin conditions were noted. The study found that 493/500 HCW, 550/550 EVD and 477/500 NEVD were sprayed at least once with 0.5 % chlorine. Following even a single exposure, an increase in the number of eye (all three groups) and respiratory symptoms (in HCW & EVD) was reported ($p < 0{\cdot}001$); after multiple exposure, respiratory

and skin symptoms increased. In HCW, multiple *vs* single exposure was associated with an increase in respiratory (OR = 32 (95 % CI 22 –49) p < 0.001), eyes (OR = 30 (95 % CI 21 – 43) p < 0.001) and skin conditions (OR = 22 (95 % CI 15–32) p < 0.001). The study found that any available personal protective equipment failed to prevent the adverse effects of chlorine. Mehtar *et al* (2016) conclude that despite a lack of evidence as a recognised outbreak control measure, deliberate exposure of humans to chlorine spray was widespread in Africa during the Ebola epidemic. This resulted in serious adverse health effects for those involved. This study conclusion strongly recommends that the practice of body spraying with chlorinated products be banned and that alternative safer methods be used.

A short evidence review by Gardezi *et al* (2020) identifies an important behavioural factor associated with whole-body spray device use – the false sense of security. The authors agree .that the efficacy of the devices for disinfection purpose is unproven and may depend on the circumstances of use. These include the type of active chemical in the disinfectant, its concentration, contact time, the spectrum of activity and manufacturer's instructions. These key elements determine the overall effectiveness of the disinfectant and if not met, the effectiveness of the disinfectant becomes doubtful and may result in a false sense of protection among users. The authors believe this may cause people to relax and fail to complete other infection control activities such as hand washing and safe distancing, which are known to be effective. Gardezi *et al* (2020) also highlight concern over washed-out fluid from the body spraying process; run off that is usually neglected. They describe how this is not only an environmental hazard, but also a nuisance for the public. Finally, this paper points out that some variants of sanitization walk through gates have UV lamps installed to offer the theoretical additional benefit of germicidal effect of UV light. The authors conclude that there is a concern that brief but repeated and uncontrolled UV exposure may cause skin and retinal damage resulting in more harm than good. As with the majority of informed commentators on this topic, this review recommends against the use of these commercial sanitization walk through and anti-viral gates, which the authors conclude have no scientific basis or medical research to support their use.

In a multi-national authored review Cariappa *et al,* (2020) describe how misting/fogging technologies have been widely evaluated for the treatment of certain environments and, *"These studies ensured the uniform spread of a high concentration of the disinfectant in the ambient atmosphere, kept the rooms seale*d f*or 25 min or more, and took measures to prevent contact of sensitive surfaces with the fog*". The authors present multiple reasons why spraying technologies of this kind should not be directed in to open spaces, where people may be exposed. The authors note that some countries have previously used spraying systems as part of organised Public health interventions (PHIs), and that that these measures were usually well meaning and intended to protect the health of communities and populations. However, a conclusion of Cariappa *et al,* (2020) is that unanticipated consequences can result if consideration is not given to the Principle of Harm, which determines when PHIs are ethically justifiable, and where there is no attempt to minimize harm in the face of uncertainty (the precautionary principle). The uncertainties around the spraying of people are presented, including potential toxicity and possibility that the products could do harm. The authors believe that spraying disinfectant over public spaces and onto people could backfire substantially, if real or perceived adverse effects appear.

The WHO (2020) effectively summarises current thinking, stating that the practice of spraying people or similarly treating them with whole-body walk-through systems etc. stating this "..*could be physically and psychologically harmful and would not reduce an infected person's ability to spread the virus through droplets or contact*". The WHO describes how even if someone who is infected with COVID-19 goes through a disinfection tunnel or chamber, as soon as they start speaking, coughing or sneezing they can still spread the virus. The WHO expert stance on human chemical exposure is consistent with the other organisations cited here, I.e. that the toxic effect of spraying with chemicals such as chlorine on individuals can lead to eye and skin irritation, bronchospasm due to inhalation, and potentially gastrointestinal effects such as nausea and vomiting.

What is the evidence that triethylene glycol or other similar chemicals can be used for air disinfection for infection control purposes in occupied rooms?

There is currently no strong evidence that using a continuous spray chemical in the air will be an effective control against SARS-CoV-2 transmission. While there is some evidence to suggest that such compounds are virucidal, and may be useful for surface disinfection and room decontamination, there is no precedent for such an approach to be used as a continuous spray in an occupied space for infection control. Cleaning the air by spraying it with a chemical is a misnomer – it is simply swapping one contaminant for another. Although the health effects of triethylene glycol and other similar chemicals are lower than for many of the other compounds in this report, there is concern that continuous exposure could have more significant health consequences.

Use of spray chemicals for air cleaning is not recommended by SAGE EMG; the improvement of ventilation systems or application of filter-based or UVC air cleaning devices is a more appropriate solution.

Evidence for virucidal effects

There is no direct evidence that triethylene glycol (TEG), or other glycols are effective against coronaviruses. The US EPA List N Disinfectants for COVID-19 reports one product containing both triethylene glycol and quaternary ammonium that is effective as a liquid surface disinfectant. Ballantyne and Snellings (2007) provide a comprehensive scientific summary of the uses and toxicology of TEG. The authors describe how this chemical has been used for natural gas dehydration, as a solvent, a chemical intermediate in the synthesis of resins, plasticizers, lubricants as well as for other applications. The authors also describe how more than 50 years ago, TEG vapour or mist was introduced for disinfection purposes, notably in barracks and hospital wards (Wolman *et al.*, 1947). Ballantyne and Snellings (2007) report that several earlier studies have shown TEG to be bactericidal for haemolytic streptococci, pneumococci and staphylococci (Bigg *et al*., 1945; Hamburger *et al.*, 1945; Robertson and Lester, 1951). It is also reported by Ballantyne and Snellings (2007) that more limited data have suggested TEG is not effective in the control of respiratory infections (Krugman and Ward, 1951; Naval Medical Research Unit, 1952). It is important in considering these applications, the fact that war time and post-war authors would not have had access to much of the toxicological and health data now available for this chemical. Rudnick et al (2009) report that surfaces contaminated with influenza virus can be disinfected using TEG-saturated air containing 2 ppm of TEG. We have not identified any reports showing a virucidal effect in air.

Methods of airborne delivery for TEG

In a detailed review of the health effects for a range of glycols, Magari and Wesley (2017) describe the use of TEG and other similar chemicals for use as 'fogs' in theatre productions. Their report is focused on adult employee exposures and its conclusions may therefore not be applicable to child actors and audience members. The authors describe how theatre fogging machines work by either condensing vapour generated by heating liquid fogging fluid, or by mechanically generating aerosols directly from liquids. The fog consists of small liquid aerosols suspended in air, which include the same constituents as the fluids used in the machines. The authors emphasise that the fog is not real smoke or soot and is not generated by thermal decomposition or burning of fluid ingredients. However, a small amount of thermal decomposition by-products may be produced during the process of heating the fluid prior to condensation.

Potential health impacts of TEG

Triethylene glycol is typically a viscous liquid in stock, concentrated form (98-99% purity). For hazard characterisation purposes toxicological tests have shown a number of potential acute health effects. There is less evidence about the adverse effects of TEG at the concentrations being proposed for use in fogging devices. At high concentration the potential acute health effects (Fisher Scientific, 2007) include: being very hazardous in case of eye contact (irritant), causing gastrointestinal irritation with nausea, vomiting and diarrhoea if ingested. TEG may also cause respiratory tract irritation in case of inhalation. Inflammation of the eye is characterized by redness, watering, and itching. Ballantyne and Snellings' (2007) review of the toxicology of triethylene glycol considered all aspects of exposure. The authors describe how, under normal occupational situations, exposure to the liquid form is typically via skin and eye contact. Under these conditions local and systemic adverse health effects by cutaneous exposure are reportedly not likely to occur, although eye contact will produce transient irritation without corneal injury. However, when discussing exposure via the airborne route, as would be the case for exposures related to fogging type delivery, the authors state that, "....*repeated exposures to a TEG aerosol may result in respiratory tract irritation, with cough, shortness of breath and tightness of the chest. Recommended protective and precautionary measures include protective gloves, goggles or safety glasses and mechanical room ventilation*". Such effects would likely be dose dependent and also subject to individual exposure sensitivities.

In an earlier study by the same research group, Ballantyne et al (2006) conducted a 9-day aerosol study using nose-only exposure of rats for 6 h day^{-1} to TEG aerosol concentrations of 0, 102, 517 and 1036 mg/m^3. The study indicated that there were no clinical signs, no effects on food and water consumption, and no biochemical or histological evidence of hepatorenal (liver/kidney) dysfunction. By the end of the exposure period, the authors found that male and female rats of the 1036 mg/m^3 group had body weights lower than those of the controls, but not with statistical significance, thus it was concluded that 1036 mg/m^3 is considered to be a threshold for toxicity by nose-only exposure to TEG aerosol. The findings indicate that exposure to a respirable aerosol is not acutely harmful, but may cause sensory irritant effects. However, Ballantyne et al (2006) believed that repeated exposure to high concentrations of TEG aerosols may be harmful, particularly if there are contributions from additional routes of exposure.

A study on propylene glycol (PG) exposed volunteers to a PG aerosol for 4 hrs at 20 and 100 mg/m3 and 30 min at 200 mg/m3 and reported some changes to symptom reporting, but

no significant respiratory impacts or ocular irritation (Dalton et al 2018). A study of 101 theatre employees at 19 sites showed that exposure to glycol-based fogs were associated with chronic work-related wheezing and chest tightness, acute cough and dry throat and increased acute upper airway symptoms. They reported that lung function was significantly lower among those working closest to the fog source (Varughese et al 2005). A NIOSH study also considered theatrical smoke and found that there is no evidence that the levels found in the theatre cause occupational asthma, but that some of the constituents such as aerosolised glycols could cause respiratory irritation in some individuals (Burr et al 1994).

In a more recent review, Magari and Wesley (2017) report that for six glycols and glycerol, where these chemicals were being considered for use by the stage/theatre sector, all are known to exhibit low acute and sub-acute toxicity in animal models and are generally characterised as mucous membrane irritants. This review presents recommendations for airborne exposure limits for a number of related glycol products, with specific recommendations for TEG as follows: Triethylene Glycol (CAS 112-27-6) - 8-Hour Time Weighted Average (mg/m^3) – 10, Peak (mg/m^3) - 40

Annex 1: Summary of Air Cleaning Technologies and their potential application

Technology	Principle of operation	Pollutants removed	Potential to be effective against SARS-CoV-2	Benefits	Issues
Fibrous filter based devices	Filter fibres capture particles either using mechanical media filter (MMF) or electrostatic charge via electret media filters (EMF) Typically uses a high grade filter such as a HEPA filter. Micro-organisms likely to be inactivated by dessication on filter surface (Mittal et al 2011)	Device will remove all particulate based contaminants down to ~0.3 micron including dust, soot and microorganisms including in respiratory aerosols. Doesn't remove any gaseous pollutants	SARs-CoV-2 is carried in respiratory droplets and aerosols which are typically 0.5-100 micron. HEPA filter based devices will remove this size of particles.	If rated high efficiency, very good at removing particles (high single-pass efficiency) Enclosed system poses low risks, and device is likely to be safe in operation MMF have improved efficiency with loading No emissions associated with the device	Effectiveness depends on device flow rate, design, quality and positioning. Noise may be a concern with higher flow rate devices. Filters need regular replacement, especially in dirty environments. Poorly maintained filters may produce sensory irritation EMF have reduced efficiency with loading Higher energy use than some other systems due to pressure drop over filter. HEPA filter needs to be correctly mounted to avoid bypass
Enclosed UV-C	Uses germicidal UV lamps (usually 254nm UV-C) to inactivate microorganisms by damaging DNA/RNA. Fan within the unit draws air over the UV lamps exposing the microorganisms.	Inactivates but doesn't physically remove microorganisms. Photoreactivation can occur for bacteria.	Evidence that UVC inactivates other corona viruses in air (Walker and Ko 2007). Some laboratory data shows inactivation of SARS-CoV-2 in liquid suspension (Heilingloh et al 2020). Data for air is not yet available, but it is very likely that	Enclosed system poses low risks, and device is likely to be safe in operation. Potentially quieter than filter based devices. No hazards from filter changes	Enclosed system and hence depends on device flow rate, contact time with UV lamps, design and positioning. Fan noise may be a concern with higher flow rate devices. Device is likely to be safe in operation. Maintenance will focus on cleaning and lamp changes. Devices should have a lamp fail warning to prevent

			inactivation will occur at a similar rate to other coronaviruses.		ineffective operation. Effectiveness may depend on UV lamp quality.
Upper room UV-C	Uses germicidal UV lamps (usually 254nm UV-C) to inactivate microorganisms. Lamps are located within louvred fittings mounted on ceilings or high on walls to create an open UV field above the heads of occupants. Bioaerosols are inactivated as they pass through the field. Systems are widely used for TB control and have been shown to be effective against measles, TB and in room scale laboratory tests	As above	Evidence as above. CDC (CDC 2009) recommend an upper-room UV fluence rate of 30-50 μW/cm2 for inactivating mycobacteria, which have a UV susceptibility of a similar order of magnitude to the coronavirus measured by Walker and Ko (2007)	Open system where effectiveness depends on UV field irradiance and room airflows. Silent operation and no use of built in fans to create drafts Potentially more energy efficient than increasing ventilation flow (Noakes et al 2015) Can provide good reductions with equivalent air change rates of over 6 ACH reported in modelling and chamber studies Performance may be enhanced by using mixing fans (CDC 2009, Zhu 2013)	Design and installation requires specialist input to ensure positioning for appropriate room coverage and safety in the lower room. UVC has significant safety concerns so irradiance in occupied zone should not exceed safety threshold, and this must be checked on installation.. Must be located above head height and out of reach for safety and not suitable for low ceiling rooms. Maintenance will focus on cleaning and lamp changes. Devices should have a lamp fail warning to prevent ineffective operation. Effectiveness may depend on UV lamp quality.
Far UV	UVC at 222nm wavelength. Has a similar mechanism as 254nm UVC.	As above		Similar benefits to UVC, however it is likely that the health impacts are significantly lower and hence can be applied more readily as an open field	Promising, but very early stage development

				device.	
Ionizers	Use a high voltage to electrically charge air molecules, which are blown into the room using a fan. Most generate negative ions, but some produce positive and others both.	Ions charge particles in the air causing preferential deposition onto surfaces depending on the charge. There are some studies that suggest there could be a biocidal effect too, but this is uncertain (Fletcher et al 2007).	No evidence specifically against SARS-CoV-2 or other viruses. Evidence for other microorganisms is mixed. A UK healthcare study showed benefits for Acinetobacter infection, but no impact on MRSA (Kerr et al 2006) and a trial on TB transmission was inconclusive (Escombe et al 2009).	Low power; quiet, low maintenance	Widely available as consumer devices, but most products have little good evidence to support their effectiveness. Some devices may produce ozone, which has a low workplace exposure limit of 0.2 ppm and may cause respiratory irritation at higher levels (HSE, EH40, 2020). As an open device, ions have the potential to interact in the whole room. Charged particles can settle on room surfaces rather than being removed, potentially increasing surface contamination
Chemical oxidation, which generate ozone or hydroxy radicals	Ozone is generated via an ozonizer device and released into the room, or is mixed with chemicals such as terpenes/alkenes to produce hydroxy radicals, which are then emitted into the room.	Can remove VOCs and some devices have a biocidal effect	.	Can enhance catalytic oxidation for VOC removal	Ozone is a well recognised respiratory pollutant and is harmful to health at high concentrations (see also above). The hydroxy radical can react with numerous indoor air species (particularly hydrocarbons which are typically 10x higher in concentration indoors than outdoors) to produce potentially harmful species such as formaldehyde and ultrafine particles.

Catalytic oxidation	Commonly photolytically using TiO2 with a UV or visible light source to oxidise pollutants in air. Devices aimed at microorganism removal usually use UVC as the light source, and hence act as a UVC device	Aldehydes, aromatics, alkanes, olefins, halogenated VOCs, odour compounds, NO, microorganisms when with UVC	Potentially effective if using UVC lamps	Good at removing single compounds with efficiency ranges from 16-90%. Can be combined with adsorbent media to increase efficiency	Catalytic oxidation is a surface effect and hence the inactivation needs to take place inside the device. Competitive adsorption effect by contaminants and water vapour can affect oxidation rate; not as good with mixtures; catalyst has finite lifespan. Can form secondary pollutants including Ozone, HCHO and CH3CHO and other aldehydes, NO2 and CO2 as by-products, depending on target compounds. Unlikely to have benefits over UVC unless there is a requirement to remove other pollutants at the same time.
Plasma	corona discharge with alternating current, direct current and dielectric barrier discharge to ionise pollutants	Particles; can be combined with catalytic technology to remove some VOCs	Some early evidence of a device acting against SARS-CoV-2 RNA, but no data on live virus (Bisag et al 2020)		Not good at removing gas-phase pollutants. May produce NOX and O3, both of which are chemical categories that have existing workplace exposure limits due to their potential for respiratory irritation (HSE, EH40, 2020)
Electrostatic precipitation	Corona discharge wire charge incoming particles which are collected on oppositely charged plates within the device.	Removes particulates, more effective at larger sizes and with high particle loading	No evidence of effectiveness against SARS-CoV-2. May have an impact	High collection efficiency (60-95%); no pressure drops, low maintenance Potentially lower noise than filter based devices	Process can generate NOX and O3 high energy requirements efficiency decreases with loading plates need cleaning efficiency varies with particle composition
UVA/UVB	Exposure to sunlight inactivates virus	Potential benefits for a	Evidence from laboratory studies	No emissions, may be quiet	Devices available unlikely to have any measurable impact on

		range of microbial pathogens	under simulated sunlight shows rapid inactivation. However it is not feasible to achieve these light levels through UVA/UVB lamps in indoor settings and hence the impact will be minimal		transmission risks. Potential risks from exposure (high intensity tanning lights)
Chemical spray	Use of disinfection compounds including bleach based, alcohol based and glycol based substances dispersed into the air through the ventilation system or a stand alone unit.	Potential inactivation of virus and bacteria	Many substances show inactivation of pathogens. Some data for certain compounds against SARS-CoV-2 in lab settings, but no data explicitly on virus in air	Potential to inactivate virus on surfaces as well as in air	Concerns that many of the potential compounds have health impacts and should not be used in occupied spaces for long durations.

Annex 2: Principles for safety and maintenance of air cleaning devices adapted from Ontario Medical Advisory Secretariat (2005)

Overall safety and operational principles for all air cleaners

- The device should not allow access to energised or moving parts.
- Mechanisms to prevent unauthorized or inadvertent adjustment of controls should be incorporated into the design of the air cleaner.
- The unit should have visible warning signs to prevent the obstruction of the intake or exhaust ducts.
- The unit should conform to appropriate electrical safety requirements and should be certified to demonstrate this
- Portable devices should be physically stable during movement or when stationary and easy to transport otherwise.
- The user may have to consider other factors such as electrical load, additional electrical connection point, tip hazards etc.
- In-room air cleaners should be used and maintained by competent people knowledgeable about this technology.
- In a healthcare setting, maintenance, physical plant, or biomedical engineering staff should be instructed in the use of the in-room air cleaner and about infection-control precautions to be used when servicing the device.

Safety and maintenance for filter-based devices

- The HEPA filters within the unit should be individually tested and certified as true HEPA filters.
- There should be no leaks around the filter.
- The filter should be “pushed” on to the filter housing by the pressure of the air flow
- The filter should be inserted in the correct orientation.
- The need for filter changes should be clearly indicated on the unit, and filter maintenance should be easy to perform.
- The exhaust blowers should be positioned downstream (after) the HEPA filter to minimize the possibility of exposure to infectious particles.
- The HEPA filter should be adequately sealed within the in-room air cleaner and periodically inspected for damage and particle loading.
- A safe filter changing and disposal protocol is required.

Safety and maintenance for UVC based devices

- In-room air cleaners that use UVGI lights should not expose people to harmful UV radiation, and UVGI lights should shut off automatically when the access door is opened.
- When UVGI lights are incorporated into in-room air cleaners, the manufacturer should be consulted regarding the possibility that the device will produce ozone when first used.
- In-room air cleaners with UVGI lights consume more power than will those without. Additional expense will therefore be incurred to maintain UVGI lights in the device.

- It has been suggested that adding UVGI technology to an in-room air cleaner with a HEPA filter may be advantageous in 3 ways: the UVGI will sterilize the air that passes by it as well as the inside of the unit; it will serve as a backup air cleaning technology to the HEPA filter should the filter become damaged (leak) or fail; and the UVGI acts to protect the filter maintenance staff from exposure to infectious microorganisms by inactivating microorganisms within the system.
- If the UVGI lamps are upstream to (before) the HEPA filter, such that air passes first by the UVGI lights and then to the HEPA filter, this may help to prolong the life of the filter.
- Dust build-up on UVGI lights will reduce their effectiveness; periodic cleaning is required.
- UVGI may effectively treat the interior surfaces of an in-room air cleaner that are directly exposed to it but not unexposed or shadowed areas. Because of this, the shadowed areas within the cabinetry of the air cleaner may still contain viable infectious pathogens to which maintenance personnel could be exposed. Thus, when changing filters or lamps, proper isolation precautions should be used by maintenance personnel, regardless if UVGI lights are incorporated within the system.
- Regardless of the use of UVGI, lights within the in-room air cleaner system and any contaminated filters should be treated as infectious material and disposed of according to local institutional policy for the management of biohazardous waste.

References

Africa Centres for Disease Control. (2020) Position statement: The use of disinfection tunnels or disinfectant spraying of humans. https://africacdc.org/pillar/infection-prevention-and-control/.

Afshari A et al (2020) Electrostatic Precipitators as an Indoor Air Cleaner—A Literature Review, Sustainability 12, 8774

ASHRAE 2015 Position Document on Filtration and Air Cleaning https://www.ashrae.org/file%20library/about/position%20documents/filtration-and-air-cleaning-pd.pdf

ASHRAE 2019 Handbook Chapter 62, Ultraviolet air and Surface Treatment https://www.ashrae.org/file%20library/technical%20resources/covid-19/i-p_a19_ch62_uvairandsurfacetreatment.pdf

Ballantyne B, Snellings WM and Norris JC. (2006). Respiratory peripheral chemosensory irritation, acute and repeated exposure toxicity studies with aerosols of triethylene glycol. Journal of Applied Toxicology. **26**(5); 387-396. At: https://onlinelibrary.wiley.com/doi/abs/10.1002/jat.1160

Ballantyne B and Snellings WM. (2007). Triethylene glycol HO(CH2CH2O)3H. Journal of Applied Toxicology. **27**(3); 291-299. At: https://onlinelibrary.wiley.com/doi/abs/10.1002/jat.1220

BB93 (2015): acoustic design of schools - performance standards https://www.gov.uk/government/publications/bb93-acoustic-design-of-schools-performance-standards

Beswick A, Bailey C, Farrant J *et al*. (2017). An Independent Assessment of Five Mobile Air Purification Devices. HSL report: CBRU/2016/090 (unpublished pilot study).

Bigg E, Jennings BH, Olsen FCW. (1945). Observations on the use of glycol vapors for air sterilization. Am. J. Public Health 35: 788. At: https://ajph.aphapublications.org/doi/pdf/10.2105/AJPH.35.8.788

Bisag A et al (2020) Cold atmospheric plasma inactivation of aerosolized microdroplets containing bacteria and purified SARS-CoV-2 RNA to contrast airborne indoor transmission, Plasma process and polymers https://doi.org/10.1002/ppap.202000154

Buonanno, M., Welch, D., Shuryak, I. *et al.* (2020). Far-UVC light (222 nm) efficiently and safely inactivates airborne human coronaviruses. *Sci Rep* **10,** 10285. https://doi.org/10.1038/s41598-020-67211-2

Burr G.A., Van Gilder T.J., Trout D.B., Wilcox T.G., Driscoll R.M. National Institute of Occupational Health and Safety; Cincinnati, OH: 1994. Health hazard evaluation. Report HETA 90-0355-2449

Cariappa M, Bavdeka RD, Kumar, N *et al*. (2020). To Spray and Pray? The "Disinfectant Spray" Conundrum. Medical Journal of Dr D Y Patil Vidyapeeth. **13:** 427-430. At: https://www.researchgate.net/publication/344337989_To_Spray_and_Pray_The_Disinfectant_Spray_Conundrum

Carslaw, N., A. Hathaway, L. Fletcher, J. Hamilton, T. Ingham, C. Noakes, Chemical versus biological contamination indoors: trade-offs versus win-win opportunities for improving indoor air quality, Indoor Air, 23, 2013, 173-4.

Carslaw, N., L. Fletcher, D.E Heard, T. Ingham, H. Walker, Significant OH production under surface cleaning and air cleaning conditions: impact on indoor air quality, Indoor Air, 27, 2017, 1091-1100

Carslaw, N., T. Mota, M.E. Jenkin, M. H. Barley and G. McFiggans, A significant role for nitrate and peroxide groups on indoor secondary organic aerosol, Environmental Science & Technology, 46, 2012, 9290-9298

Carslaw, N., A.C. Terry, M.A. Ashmore, D.C. Carslaw, Crucial role for biogenic chemistry outdoors for indoor secondary organic aerosol formation. Environ. Sci. Technol., 49, 2015, 11011-11018.

CDC (2009) Environmental Control for Tuberculosis: Basic Upper-Room Ultraviolet Germicidal Irradiation Guidelines for Healthcare Settings https://www.cdc.gov/niosh/docs/2009-105/pdfs/2009-105.pdf

CIBSE (2015) Guide A: Environmental Design

CIBSE(2020) TM61: Operational performance of buildings

Curtius J, Granzin M, Schrod J (2020) Testing mobile air purifiers in a school classroom: Reducing the airborne transmission risk for SARS-CoV-2, under peer review https://www.medrxiv.org/content/10.1101/2020.10.02.20205633v2

Dalton P et al (2018) Lack of respiratory and ocular effects following acute propylene glycol exposure in healthy humans Inhal Toxicol, 30(3):124-132

Darnell, ME, Subbarao K, Feinstone SM et al. (2004). Inactivation of the coronavirus that induces severe acute respiratory syndrome SARS-CoV J. Virol. Methods, **121**: pp. 85-91. At: https://www.researchgate.net/publication/8362562_Inactivation_of_the_coronavirus_that_induces_severe_acute_respiratory_syndrome_SARS-CoV

Dee, SA et al (2006) Further evaluation of alternative air-filtration systems for reducing the transmission of Porcine reproductive and respiratory syndrome virus by aerosol, Canadian Journal of Veterinary Research, 70: 169-175

Escombe, A.R., R.H. Gilman, M. Navincopa, E. Ticona, B. Mitchell, C. Noakes, C. Martínez, P. Sheen, R. Ramirez, W. Quino, A. Gonzalez, J.S. Friedland, and C.A. Evans. 2009. Upper-room ultraviolet light and negative air ionization to prevent tuberculosis transmission. PLoS Med 17(6)

Fisk, W. J. (2013) 'Health benefits of particle filtration', *Indoor Air*, 23(5), pp. 357–368. doi: 10.1111/ina.12036

Fisher Scientific. (2007). Material safety data sheet for high purity triethylene glycol. At: https://fscimage.fishersci.com/msds/01653.htm

Fletcher, L.A.; Gaunt, L.F.; Beggs, C.B.; Shepherd, S.J.; Sleigh, P.A.; Noakes, C.J.; Kerr, K.G. (2007) Bactericidal action of positive and negative ions in air. *BMC Microbiology*, 7(1), pp.32

Gardezi A, Rathore FA and Farooq F. (2020). Sanitization Walk-Through Gates During COVID-19 Pandemic: Effective or A False Sense of Protection? Annals of King Edward Medical University. 26: 259-261. At: https://www.annalskemu.org/journal/index.php/annals/article/view/3649

Gilkeson CA, Noakes CJ (2013) Application of CFD Simulation to Predicting Upper-Room UVGI Effectiveness Photochemistry and Photobiology, 89(4):799-810

Gray CL & van Niekerk A. (2020). The use of disinfection tunnels or disinfectant spraying of humans as a measure to reduce the spread of the SARS-CoV-2 virus. *SAMJ: South African Medical Journal*, *110*(8), 751-752. https://dx.doi.org/10.7196/SAMJ.2020.v110i8.14995

Hamburger M Jr, Puck TT, Robertson OH. (1945). The effect of triethylene glycol vapor on air-borne beta hemolytic streptococci in hospital wards. J. Infect. Dis. 76: 208. At: https://www.jstor.org/stable/30089351?seq=1

Harvie-Clark J et al (2019) How loud is too loud? noise from domestic mechanical ventilation systems, International Journal of Ventilation, 18(4)

Heßling, M., Hönes, K., Vatter, P., & Lingenfelder, C. (2020). Ultraviolet irradiation doses for coronavirus inactivation - review and analysis of coronavirus photoinactivation studies. *GMS hygiene and infection control*, *15*, Doc08. https://doi.org/10.3205/dgkh000343

Heilingloh CS, Aufderhorst UW, Schipper L *et al.* (2020). Susceptibility of SARS-CoV-2 to UV irradiation. American Journal of Infection Control 48 (2020) 1273−1275. https://doi.org/10.1016/j.ajic.2020.07.031

HSE. (2020). Disinfecting premises using fog, mist, vapour or ultraviolet (UV) systems during the coronavirus pandemic. At: https://www.hse.gov.uk/coronavirus/disinfecting-premises-during-coronavirus-outbreak.htm#donotspray

HSE. (2020b). EH40/2005 Workplace exposure limits, 4th edition. At: https://www.hse.gov.uk/pubns/books/eh40.htm

HSE. (2005). Noise at Work Regulations. At: https://www.hse.gov.uk/noise/regulations.htm

Hussain S, Jehanzeb CM, Saad M et al, (2020). Proposed Design of Walk-Through Gate (WTG): Mitigating the Effect of COVID-19. Applied System Innovation. **3**. 1-7.At: https://www.researchgate.net/publication/344328623_Proposed_Design_of_Walk-Through_Gate_WTG_Mitigating_the_Effect_of_COVID-19

Ji L, Pei J, Liu W (2019) Long-term performance of fibrous ventilation/air-cleaner filters for particle removal, Building and Environment, 160: 106222

Kerr KG, Beggs CB, Dean SG, et al. Air ionisation and colonisation/infection with methicillin-resistant Staphylococcus aureus and Acinetobacter species in an intensive care unit. *Intensive Care Medicine* 2006; 32: 315-317

King MF, Pickin L, Noakes C, Fletcher L, Gilkeson C and Sleigh PA (2011) 'The effectiveness of in-room UVGI disinfection devices at providing local control of airborne infection transmission' Proc. Conf. Indoor Air 2011, Austin TX, 4–10 June 2011

Krugman S, Ward R. 1951. Air sterilization in an infant's ward. Effect of triethylene glycol vapor and dust suppressive measures on the respiratory cross infection rate. J. Am. Med. Assoc. 145: 775–780. At: https://jamanetwork.com/journals/jama/article-abstract/309736

Ko, G., M.W. First, and H.A. Burge. 2000. Influence of relative humidity on particle size and UV sensitivity of Serratia marcescens and Mycobacterium bovis BCG aerosols. Tubercle and Lung Disease 80(4-5):217-228

Lau J, Bahnfleth W, Freihaut J (2009) Estimating the effects of ambient conditions on the performance of UVGI air cleaners, Building and Environment, 44: 1362-1370

Magari SR and Wesley (2017). Theatrical Fog Exposure Assessment Methods, Exposure Limits, and Health Effects – Literature Review. Prepared by Colden-Phylmar for the Contract Services Administration Trust Fund (CSATF). At: https://tsp.esta.org/tsp/working_groups/FS/docs/Colden-Phylmar_Theatrical%20Fog%20Review%20Final%20Report_for_CSATF.pdf

Mallhi TH, Khan YH,, Alotaibi NH. (2020). Walkthrough Sanitization Gates for COVID-19: A Preventive Measure or Public Health Concern? The American Journal of Tropical Medicine and Hygiene. 103(2). At: https://www.ajtmh.org/content/journals/10.4269/ajtmh.20-0533#html_fulltext

Maurya., Gohil MK., Sonawane, U. *et al.* (2020). Development of Autonomous Advanced Disinfection Tunnel to Tackle External Surface Disinfection of COVID-19 Virus in Public Places. *Trans Indian Natl. Acad. Eng.* **5,** 281–287. https://doi.org/10.1007/s41403-020-00141-7

Menzies D, Popa J, Hanley JA, Rand T, Milton DK. Effect of ultraviolet germicidal lights installed in office ventilation systems on workers' health and wellbeing: double-blind multiple crossover trial. Lancet. 2003;362:1785–91

Mehtar, S., Bulabula, A.N.H., Nyandemoh, H. *et al.* (2016) Deliberate exposure of humans to chlorine-the aftermath of Ebola in West Africa. *Antimicrob Resist Infect Control* **5,** 45. https://doi.org/10.1186/s13756-016-0144-1

Mittal, H., Parks, S. R., Pottage, T., Walker, J. T., & Bennett, A. M. (2011). Survival of microorganisms on HEPA filters. Applied Biosafety, 16(3), 163-166

Morawskaa L, Tangb JW, Bahnflethc W, et al. (2020). How can airborne transmission of COVID-19 indoors be minimised? Environment International. Vol.142. At: https://www.sciencedirect.com/science/article/pii/S0160412020317876?via%3Dihub

Mphaphlele, M., A.S. Dharnadhikari, P.A. Jensen, S.N. Rudnick, T.H van Reenen, M.A. Pagano, W. Leuschner, T.A. Sears, S.P. Milonova, M. van der Walt, A.C. Stoltz, K. Weyer, and E.A. Nardell. 2015. Controlled trial of upper room ultraviolet air disinfection: A basis for new dosing guidelines. American Journal of Respiratory and Critical Care Medicine 192(4):477-484

Naval Medical Research Unit. 1952. The use of triethylene glycol vapor for control of acute respiratory diseases in naval recruits. II. Effect on acute respiratory disease. Am. J. Hyg. 55: 215–229. At: https://www.deepdyve.com/lp/ou_press/the-use-of-triethylene-glycol-vapor-for-control-of-acute-respiratory-KJ0qlEov8c

Noakes, C.J., Beggs, C.B. and Sleigh, P.A. (2004) Modelling the Performance of Upper Room Ultraviolet Germicidal Irradiation Devices in Ventilated Rooms: Comparison of Analytical and CFD Methods, Indoor and Built Environment, 13(6), 477-488

Noakes, C.J., Sleigh, P.A., Fletcher, L.A., Beggs, C.B. (2006) Use of CFD modelling in optimising the design of upper-room UVGI disinfection systems for ventilated rooms. Indoor and Built Environment, 15(1), 347-356.

Noakes CJ, Khan MAI, Gilkeson CA (2015) Modelling Infection Risk and Energy Use of Upper-Room UVGI Systems in Multi-Room Environments. Science and Technology for the Built Environment 21(1):99-111

Novoselac A, Siegel JA (2009) Impact of placement of portable air cleaning devices in multizone residential environments, Building and Environment, 44: 2348-2356

Ontario Medical Advisory Secretariat (2005) Air Cleaning Technologies: An Evidence-Based Analysis; Ontario Health Technology Assessment Series 2005. **5**(17). At: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3382390/

OPSS 2020 https://www.gov.uk/government/publications/opss-covid-19-consumer-survey

Parker, S.T., Nasir, Z.A. and Campos, L.C. (2015). Estimating Exponential Concentration Decay Rates Using Time-Integrated Aerosol Sampling of Variable Duration. Aerosol Air Qual. Res. 15: 1160-1165. https://doi.org/10.4209/aaqr.2014.10.0265

Peck RL, Grinshpun SA et al (2016) Efficiency of portable HEPA air purifiers against traffic related combustion particles, Building and Environment, 98: 21-29

Pei J, Dong C, Liu J (2019) Operating behavior and corresponding performance of portable air cleaners in residential buildings, China, Building and Environment, 147: 473-481

Pei J, Dai W, Li H, Liu J (2020) Laboratory and field investigation of portable air cleaners' long-term performance for particle removal, Building and environment, 181: 107100

Pham TT, Nguyen MH, Nguyen NS. (2020). The Disinfectant Solution System Preventing SARSCOV-2 Epidemic. International Journal of Scientific Engineering and Science. **4(**6): 11-14. At: http://ijses.com/wp-content/uploads/2020/06/61-IJSES-V4N5.pdf

Rabby, MII, Hossain, F. Akter, F. *et al.* (2020). Disinfection booth: blessing or curse for spreading of COVID-19 in Bangladesh. *Can J Public Health* **111,** 660–662. At: https://doi.org/10.17269/s41997-020-00402-6

Riley RL, Mills CC, O'Grady F, Sultan LU, Wittstadt F, Shivpuri DN [1962]. Infectiousness of air from a tuberculosis ward—ultraviolet irradiation of infected air: comparative infectiousness of different patients. Am Rev Respir Dis 85(4):511–525

Robertson OH, Lester W Jr. 1951. The lethal effect of triethylene glycol vapor on dried air-borne bacteria. Am. J. Hyg. 53: 69–79. At: https://europepmc.org/abstract/med/14810698

Rudnick, SN, McDevitt JJ, First MW, Spengler JD (2009) Inactivating influenza viruses on surfaces using hydrogen peroxide or triethylene glycol at low vapor concentrations Am J Infect Control. 2009 Dec; 37(10): 813–819

Salam Z-H A, Karlin RB, Ling ML, Yang KS (2010) The impact of portable high-efficiency particulate air filters on the incidence of invasive aspergillosis in a large acute tertiary-care hospital Am J Infect Control 38(4):e1-7. doi: 10.1016/j.ajic.2009.09.014

Salimifard P, Jones E, Allen J (2020) Portable Air Cleaners: Selection and Application Considerations for COVID-19 Risk Reduction https://schools.forhealth.org/wp-content/uploads/sites/19/2020/08/Harvard-Healthy-Buildings-Program-Portable-Air-Cleaners.pdf

Scott, J and Zanoni, PG. (2002). Michigan Department of Licensing & Regulatory Affairs (LARA) - Guidelines for use of Portable Air Filtration Systems in Health Care Facilities. At: https://www.michigan.gov/documents/mdch/bhs_hepa_337337_7.pdf

Siegel, J. A. (2016) 'Primary and secondary consequences of indoor air cleaners', Indoor Air, 26(1), pp. 88–96. doi: 10.1111/ina.12194

US-EPA. (2020). Air Cleaners, HVAC Filters, and Coronavirus (COVID-19). Accessed 28.10.20 at: https://www.epa.gov/coronavirus/air-cleaners-hvac-filters-and-coronavirus-covid-19

US EPA (2018) 'Indoor Air Quality (IAQ) 3rd Edition Portable Air Cleaners Furnace and HVAC Filters (EPA 402-F-09-002)', (July), p. 74. Available at: www.epa.gov/iaq

Varughese S, et al (2005) Effects of theatrical smokes and fogs on respiratory health in the entertainment industry Am J Ind Med, 47(5):411-8.

Walker, C. M. and Ko, G. (2007) 'Effect of ultraviolet germicidal irradiation on viral aerosols', Environmental Science and Technology, 41(15), pp. 5460–5465. doi: 10.1021/es070056u.

Waring, M. S. and Wells, J. R. (2015) 'Volatile organic compound conversion by ozone, hydroxyl radicals, and nitrate radicals in residential indoor air: Magnitudes and impacts of oxidant sources', *Atmospheric Environment*. Elsevier Ltd, 106(3), pp. 382–391. doi: 10.1016/j.atmosenv.2014.06.062.

Wells WF, Wells MW, Wilder TS. The environmental control of epidemic contagion I: an epidemiologic study of radiant disinfection of air in day schools. Am J Hyg 1942;35:97-121

Which 2020 https://www.which.co.uk/news/2020/03/coronavirus-can-an-air-purifier-protect-you/

Wolman A, Fair GM, Hardenbergh WA et al. (1947). Recent studies on disinfection of air in military establishments. Am. J. Public Health 37: 189–198. At: https://ajph.aphapublications.org/doi/10.2105/AJPH.37.2.189

World Health Organization (2020). Coronavirus disease (COVID-19) Situation Report – 115. Available at: https://www.who.int/docs/default-source/coronaviruse/situation-reports/20200514-covid-19-sitrep-115.pdf?sfvrsn=3fce8d3c_6

Wu X, Qi W, Marinova D, Shi X (2018) Risk knowledge, product knowledge, and brand benefits for purchase intentions: Experiences with air purifiers against city smog in China, Human and Ecological Risk Assessement, 24(7)

Zhang, Y. *et al.* (2011) 'Can commonly-used fan-driven air cleaning technologies improve indoor air quality? A literature review', *Atmospheric Environment*. Elsevier Ltd, 45(26), pp. 4329–4343. doi: 10.1016/j.atmosenv.2011.05.041

Zhu, S., J. Srebric, S.N. Rudnick, R.L. Vincent, and E.A. Nardell. 2013. Numerical investigation of upper-room UVGI disinfection efficacy in an environmental chamber with a ceiling fan. Photochemistry and Photobiology 89:782-791. hdx.doi.org/10.1111/php.12039

Zuraimi MS et al (2017) Impact of dust loading on long term portable air cleaner performance, Building and Environment, 112: 261-269