Application of UV disinfection, visible light, local air filtration and fumigation technologies to microbial control

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Overview

This paper summarises evidence for ultraviolet (UV) disinfection, visible light, local air filtration and fumigation technologies to be applied to control COVID-19 transmission. Key findings are:

- There is good evidence that germicidal UV (GUV) that uses UV-C light and fumigation approaches (particularly Hydrogen Peroxide Vapour (HPV)) are likely to be viable decontamination approaches against SARS-CoV-2 for unoccupied rooms. Both are widely available as commercial systems and are already used in many hospitals for terminal disinfection. UV-C is more challenging to apply well in a complex space with surfaces in shadow but 'shadowing' effects can also affect fumigation efficacy, with areas facing away from delivery equipment or positions on the underside of room surfaces the most challenging to reach.
- Both UV-C and fumigation decontamination require a sufficient duration of exposure to be effective. As such they are more likely to be effective as part of a terminal cleaning process rather than daily disinfection. This is particularly the case for fumigation which requires 30-90min cycle time, plus time for aeriation to remove of any excess fumigants. UV carousel devices are typically deployed for between 20 and 45 minutes, depending on the room to be treated, but may also require moving and repeat treatment to overcome shadowing effects.
- Removal of fumigant by aeration is a particular concern for fumigation approaches that should be considered particularly in environments with a high level of soft furnishings.
- There is good evidence that upper room GUV has good potential to be used effectively to reduce microbial load in the air in occupied rooms, although there is limited evidence for application against respiratory viruses in a real-world setting. The technology is only suitable in rooms with a high enough ceiling and is most effective in poorly ventilated spaces. It should not be seen as an alternative to ventilation but is likely to be beneficial where ventilation can't be improved. An upper room GUV system needs to be sized correctly for the size of the room and the microorganism, and needs to consider the interaction with the ventilation flow.
- Local air cleaning devices, including filter devices and UV-C devices – which may be found in combination - are unlikely to have significant benefit unless the airflow rate through the device is sufficient. There may be some poorly ventilated spaces where these may be useful.
- Far-UV technology is promising as a control but is far too early in development to be applied in real-world settings without significant further research.
- There is some evidence that visible light or blue/violet (HINS) light may be effective in reducing bacterial contamination in buildings, but there is very weak evidence for the effect on viruses. Enhancing natural light in buildings (e.g opening blinds) is a no cost precautionary measure where good light ingress already exists, but it is unlikely to have more than a marginal benefit. The benefits of HINS light are worthy of further research as this has been developed to a level that it has been applied in hospitals.

- Both UV-C and fumigation decontamination approaches have significant safety considerations and should only be carried out by trained staff with appropriate risk assessments and controls in place.
- Upper room GUV has significant safety considerations which must be taken into consideration in the design, installation and operation.
- We have not considered the cost-effectiveness of any of these approaches, This would need to be considered alongside enhancing conventional strategies such as improving ventilation and increasing standard cleaning approaches to determine whether there is additional benefit to be gained from applying disinfection technology.
- The approaches detailed in this paper should never be regarded as a substitute for good cleaning or good ventilation. They are technologies that could be used to supplement conventional methods but not to replace them. Importantly, chemical fumigation and UV based room treatments should be regarded as disinfection processes, not as sterilization, regardless of supplier claims.

Ultraviolet disinfection approaches

Germicidal Ultraviolet (GUV, also known as UVGI) uses ultraviolet light in the UV-C wavelength range (200nm to 280nm) to inactivate microorganisms. Most systems use low pressure mercury lamps which produce a peak emission around 254nm. The approach is well recognised as an inactivation technique with application to water treatment, room decontamination, ventilation/coiling coil treatment and in-room air disinfection.

UV-C for surface and air decontamination has to consider health and safety issues. Human exposure to UV-C can cause significant eye and skin damage and hence UV lamps must be located within enclosed or shielded devices, or operated when no occupants are present. In real use UVc light from these devices rarely passes through single layers of glass and double glazed units will usually inhibit its transmission, so most of the exposure risk is likely to be associated with exposure to the irradiation effects if resent in the room when a unit is switched on.

UV inactivation depends on microorganism species, whether the microorganism is in air, water or on a surface, and environmental conditions such as temperature and humidity. The majority of laboratory and control experimental studies focus on bacterial pathogens, however a number consider viruses. Under laboratory conditions GUV has been shown to be effective against bacteriophages on surfaces (Tseng and Li, 2007) and in air against influenza (McDevitt et al 2012), adenovirus serotype 2 and MHV coronavirus (Walker and Ko, 2007). Several studies show that activation reduces with increased humidity for both bacterial (Ko et al 2000) and viral aerosols (McDevitt et al 2012).

Walker's study calculated a UV susceptibility constant for MHV coronavirus of 0.37 m^2/J, which places it as one of the easier microorganisms to inactivate. Darnell *et al.* (2004) showed that SARS-CoV-1 could be inactivated by UV-C to enable safe working with virus containing materials. Bedell et al (2016) showed a UV-C decontamination device was able to inactivate MERS-CoV and MHV coronavirus at 1.22m, with almost a 6 log reduction for MERS-CoV in 5 minutes. There is no data yet for SARS-CoV-2, but the data for other coronaviruses suggest it is highly likely that it is susceptible to UV-C.

UV-C devices are widely used for room surface decontamination in healthcare settings. Such devices usually comprise multiple UV-C lamps located on a portable trolley, usually in a carousel formation to offer 360° delivery - that can be wheeled into a room and operated remotely to prevent occupant exposure. Several studies have evaluated these devices in hospital settings and shown they can inactivate a range of bacterial pathogens (Mahida et al 2013), (Beal *et al.*, 2016). Devices are shown to be easy to use and can rapidly disinfect rooms. A standard UV-C device showed 3 to 4 log reductions on petri-dish samples ((Mahida et al 2013) while a pulsed UV device was combined with cleaning of high touch sites to give an overall 90% reduction (Beal *et al.*, 2016). A study also showed that a UV-C device led to a 1.37 log reduction on textiles inoculated with *Enterococcus faecium* in a ward setting (Smolle *et al.*, 2018). Shadowing is however a concern and a study of ambulance decontamination indicated that some surfaces could be disinfected in seconds while others took over 15 hours as they didn't receive enough irradiation (Lindsley *et al.*, 2018). Several studies are currently exploring the use of UV-C as a viable approach to PPE decontamination.

Application of UV-C devices within building ventilation systems is widely advocated to both reduce contamination of cooling coils leading to energy efficiency benefits and to control infection transmission in ventilation systems with recirculation. This approach may have some benefit in commercial UK buildings, however UK hospital ventilation systems (with a small number of specific exceptions) are 100% fresh air and hence UV-C installation will have no benefit.

The majority of work on application of UV-C devices for airborne infection control focuses on upper-room GUV. These are shielded UV-C units that create a band of ultraviolet light above the heads of occupants. Airflow patterns within the room carry pathogens from the occupied zone though the upper-room UV zone providing on going disinfection while the room is occupied. The approach cannot achieve 100% disinfection; instead it acts in a similar way to increased ventilation by reducing the concentration of pathogens within the room air and hence reducing transmission risk. A key advantage of this type of system, compared with mobile UVc carousels, is that the treatment is designed so that the room can remain occupied.

There is good evidence from studies in TB hospitals that upper-room GUV is an effective control for tuberculosis. Escombe et al (2009) repeated classic experiments conducted by Wells and Riley in the 1950's and showed 77% reduction in human to guinea pig transmission. Chamber based studies show the effectiveness of GUV against a number of bacterial aerosols including Noakes et al 2004, Ko et al 2000, Kanaan *et al.*, 2015, Yang *et al.* (2012). There are several studies that have modelled upper-room GUV (Noakes et al 2004, Sung and Kato 2010, Gilkeson and Noakes 2013, Kanaan *et al.*, 2015, Yang *et al.* 2012)) and shown that the effectiveness depends on the placement of the lamps relative to the ventilation flow, and that the two need to be considered together when designing a system. Zhu *et al.* (2014) modelled the application of an upper-room GUV system combined with a ceiling fan to show that increased mixing in the room enhances the effectiveness of the GUV. Noakes, Khan and Gilkeson (2015) developed a zonal model coupled with the Wells-Riley infection model to show the potential impact of upper-room GUV on infection risk could be comparable to doubling the ventilation rate. Modelling studies also show that upper-room GUV is unlikely to significantly impact on the close range transmission risk within 1-2m of the infected source.

GUV can also be applied through enclosed systems located within a room. Larger systems are similar to a wall or ceiling mounted air conditioning unit, while smaller systems can be portable and plugged in at a convenient location. There are several such devices on the market and all show good single pass efficiency, however their effectiveness in a room is dependent on their flow rate relative to the room size; many devices have an insufficient air flow rate to be as effective in practice as claimed.

There is recent evidence to show that far-UV in the 200-222nm wavelength range may be effective at inactivating microorganisms without the risks to human health of conventional 254nm systems. Several papers show the effectiveness and lack of skin damage in laboratory studies (Buonanno *et al.*, 2017, Narita *et al.*, 2018, Welch *et al.*, 2018), however there is not yet any evidence of microbial inactivation from aerosol studies, chamber studies or real-world settings or any evidence for safety in real-world settings. This is a promising technology that could enable more effective disinfection than conventional UV-C, but needs substantially more research to prove it is effective in a real-world setting.

Guidelines on GUV systems are given by ASHRAE with some information provided in CIBSE Guide A. CIE (2020) have also produced a position statement on GUV which indicates that UV-C has significant potential but can be hazardous and therefore must be installed with care. They recommend only using properly constructed products which meet safety regulations and indicate that UV measurements to ensure human exposure limits are not exceeded are important for any systems that are not fully enclosed. It should also be noted that the effectiveness of GUV systems depends on the state of the lamps. The output of UV-C lamps degrades with time and is also affected by dirt on lamp surfaces. Good maintenance is important to ensure a GUV system operates correctly.

Approaches using other wavelengths of light

It is already known that SARS-CoV-2 decays rapidly in direct sunlight and hence there is a question as to whether simply increasing light levels within the built environment would be beneficial. Hobday and Dancer (2013) review the evidence for the effects of sunlight and natural ventilation (the “open air factor”) on microorganisms, including a number of historical studies. They cite several studies that show that bacteria exposed to direct sunlight, even through a window are inactivated however those exposed to diffuse light can survive for longer periods. Almost all the studies are from more than 40 years ago; there appears to be no modern work on this and no work on viruses. Despite this a review paper on buildings and COVID-19 suggests opening blinds to allow more light into buildings as a simple measure that may have an impact (Dietz et al 2020).

A number of studies have looked at High Intensity Narrow Spectrum (HINS) light as a potential approach for disinfection within occupied rooms. This is violet light from the visible spectrum with a wavelength of 405nm, that is less germicidal than GUV but has an antimicrobial effect. Health Protection Scotland (2019) carried out a systematic literature review to determine the evidence for using HINS in healthcare settings. They identified evidence from a number of laboratory studies that HINS can inactivate a wide range of bacterial pathogens, and indicated that there are three hospital based studies that showed it was effective at reducing environmental contamination in a burns unit isolation room and an ICU, although didn’t provide complete disinfection. There is evidence that HINS is safe for use in occupied spaces. We have identified one study (Tomb *et al.*, 2017) that used a feline

calicivirus in a laboratory setting that suggests that HINS may be effective against viruses. A review paper (Enwemeka et al 2020) focusing on COVID-19 also suggests that blue light could be effective but doesn't provide any strong evidence for effectiveness against viruses.

Fumigation approaches (including HPV)

A number of airborne disinfection chemicals, often called fumigants, have proven anti-microbial activity, including systems based on hydrogen peroxide, ozone and chlorine dioxide (Otter *et al*, 2013). Commercial systems for delivery of each are available and these three different chemical actives provide the major alternatives to formaldehyde vapour. Formaldehyde was used extensively for room and cabinet fumigation in the past but is now recognised as too toxic for use in all but laboratory and some veterinary settings, e.g. Chicken houses.

Hydrogen peroxide (H_2O_2), either as a thermally generated vapour or as a fine 'dry' mist, is probably the most commonly used chemical for modern fumigation and is certainly the most reported on. Its disinfectant properties have been recognised for decades and it has been described as 'nature's own disinfectant', as it protects mammalian cells from infection at the molecular level (Block 2001). H_2O_2 has a broad anti-microbial efficacy, is not affected by the antibiotic resistance of some bacteria and fungi and also offers virucidal activity due to its powerful oxidising activity; this is assumed to damage microbial proteins, lipids and nucleic acids.

H_2O_2 in airborne form is generated from aqueous source solutions that range from 7% to 35%, depending upon manufacturer and has applications as a room, cabinet or vehicle fumigant. It is compatible with most materials and is usually safe for use with electronic and electrical devices providing condensation is avoided and concentrated H_2O_2 solution does not deposit on surfaces as a consequence. This is important as although persistent residues are unlikely, H_2O_2 is toxic by inhalation, ingestion and by skin or eye contact and it has a low Workplace Exposure Limit (WEL) of 1ppm (8h TWA exposure) or 2ppm (15min exposure). Normal treatment concentrations may vary between 100 ppm and 800 ppm airborne concentrations so adequate removal off fumigant post-treatment is critical to avoid adverse health effects from those moving back in to treated areas. Complete decomposition should not be assumed at the end of treatment periods until adequate aeration has been undertaken. Once this is achieved the chemical leaves no harmful residues and decomposes to oxygen and water (Beswick et al, 2011).

H_2O_2 generating systems have been tested against various microorganisms over several decades, but mostly bacterial pathogens, including *Mycobacterial* species, Meticillin Resistant *Staphylococcus aureus, Clostridium difficile* and other spore forming bacteria (Hall *et al*., 2007, Kahnert *et al*, 2005; Shapey *et al*, 2008, Beswick *et al*, 2011). However, such treatments have also been evaluated using viruses, mostly within the laboratory and healthcare context. These studies do, however, provide useful read across for other types of H_2O_2 treatment and some information does exist about the treatment of other areas. These are considered below in chronological order and for the purposes of this summary the treatment of choice is generally referred to as hydrogen peroxide vapour (HPV) unless otherwise indicated. This acronym is usually linked to Bioquell fumigation systems to distinguish it from the Steris vapour hydrogen peroxide (VHP) systems, although these and other systems do all generate airborne forms of H_2O_2.

Examples of HPV or similar fumigation treatments assessing virucidal activity

Pottage *et al.* (2010) assessed two commercial gaseous disinfection systems against a resistant viral surrogate in the presence and absence of soiling. Suspensions of MS2 bacteriophage were dried on to stainless steel carriers and exposed to hydrogen peroxide vapour (HPV) and vapour hydrogen peroxide (VHP) gaseous disinfection systems. These systems use the same active (H_2O_2) but at different terminal humidity levels. The bacteriophages were also suspended and dried in 10% and 50% of horse blood to simulate the virus being present in a spill of blood/bodily fluids in a hospital ward environment. The effectiveness of both the HPV and VHP systems varied with the concentration of the bacteriophage with HPV resulting in a 6 $\log_{10}$ reduction in 10 min at the lowest viral concentration [10^7 plaque-forming units (pfu)/carrier] and requiring 45 min at the highest concentration (10^9 pfu/carrier). For the VHP system a 30 min exposure period was required to achieve a 6 $\log_{10}$ reduction at the lowest concentration and 60-90 min for the highest concentration. The addition of blood to the suspension greatly reduced the effectiveness of both disinfectants and the authors conclude that effective cleaning prior to gaseous disinfection, especially where high concentration agents are suspended in body fluids, to ensure effective decontamination.

Berrie *et al*, (2011) investigated the survival of a dried recombinant adenovirus – a genetically modified form of this respiratory virus - before and after HPV exposure to determine the efficacy of HPV at inactivating the virus. Adenovirus was dried down on stainless steel carriers prior to testing. A >8-log $TCID_{50}$ reduction resulted from 45-min exposure to HPV in a microbiological safety cabinet. The authors concluded that HPV may be useful for adenovirus decontamination in life science laboratories or in manufacturing facilities but also acknowledge the study was limited by its small scale and the use of only one recombinant adenovirus tested under unsoiled conditions.

Beswick *et al,* (2011) compared the performance of three different hydrogen peroxide-based fumigation systems (two vapour and one dry-mist methods), along with other systems employing ozone, formaldehyde and chlorine dioxide. A range of challenge microorganisms was used, including Vaccinia virus. Only chlorine dioxide and formaldehyde fumigants gave consistently high levels of antimicrobial efficacy across all test organisms, which included viral and bacterial challenges (typically greater than a 5-log reduction), with hydrogen peroxide systems giving grater variability but still capable of achieving 4-$\log_{10}$ to 6-$\log_{10}$ reductions. All systems performed similarly against Vaccinia virus, with total kill in all cases, equating to 3-$\log_{10}$ to 4-$\log_{10}$ reductions on steel carriers. The study revealed inconsistencies in system reliability and reproducibility, with all fumigant systems aborting mid-cycle on at least one occasion. All the fumigants tested have UK workplace exposure limits of 2 ppm or less, yet residual fumigant was detected for the formaldehyde and hydrogen peroxide systems following cycle completion, even after room aeration.

Bentley *et al,* (2012) investigated the use of hydrogen peroxide vapour to decontaminate a number of surfaces that had been artificially contaminated with feline calicivirus (FCV), a surrogate for norovirus. The surfaces tested were representative of those found in hospital wards. FCV was used to inoculate various surfaces, including stainless steel, glass, vinyl flooring, ceramic tile and PVC plastic cornering. The carriers were exposed to 30% (w/w) hydrogen peroxide vapour at 5-min intervals over 20 min, after which post-exposure viral titres were measured. HPV reduced viral titre by 4 $\log_{10}$ on all surfaces tested within 20 min

of exposure. This took longest to achieve on stainless steel (20 min), and was quickest on vinyl flooring (10 min). For glass, plastic and ceramic tile surfaces, the desired reduction was seen within 15 min of exposure. The authors conclude that HPV allows for large-scale decontamination of areas following outbreaks of infectious disease and may offer a suitable decontamination system for use during hospital outbreaks of norovirus.

Tuladhar *et al*, (2012) assessed the virucidal efficacy of HPV against respiratory and enteric viruses on materials representing those found in institutions and homes. The work included the use of poliovirus, norovirus surrogates, rotavirus, adenovirus and influenza A (H1N1) virus dried on to stainless steel, framing panel and gauze carriers, all exposed to 127 ppm of HPV for one hour in either a cabinet or room. Virucidal effect was measured by comparing recoverable viral titres against unexposed controls. HPV disinfection resulted in complete inactivation of all viruses tested, characterized by >4 $\log_{10}$ reduction in infectious particles for poliovirus, rotavirus, adenovirus and murine norovirus on stainless steel and framing panel carriers, and >2 $\log_{10}$ reduction for influenza A virus on stainless steel and framing panel carriers, and for all viruses on gauze carriers. The authors conclude that HPV could be an effective virucidal against enteric and respiratory viruses contaminating in-house environments.

Goyal *et al*, (2014) assessed HPV for the inactivation of a several distinct viruses of pathogenic relevance for healthcare, veterinary and public sectors. These were feline calicivirus (FCV, a norovirus surrogate); human adenovirus type 1; transmissible gastroenteritis coronavirus of pigs (TGEV, a *severe acute respiratory syndrome coronavirus [SARS-CoV] surrogate*); avian influenza virus (AIV); and swine influenza virus (SwIV). The viruses were dried on stainless steel discs in 20- or 40 µL aliquots and exposed to HPV (Bioquell) in a 0.2-m^3 environmental chamber. No viable viruses were identified after HPV exposure at any of the vaporized volumes tested. HPV was virucidal (>4-log reduction) against FCV, adenovirus, TGEV and AIV at the lowest vaporized volume tested (25 mL). For SwIV, due to low virus titre on the control discs, >3.8-log reduction was shown for the 25-mL vaporized volume and >4-log reduction was shown for the 27-mL and 33-mL vaporized volumes. The authors conclude that HPV was virucidal for several structurally distinct viruses dried on surfaces, suggesting that HPV can be considered for the disinfection of virus-contaminated surfaces.

Zonta *et al,* (2016) assessed the efficacy of a nebulization system that sprayed hydrogen peroxide on two main surrogates of Human norovirus, murine norovirus (MNV) and feline calicivirus (FCV). The viruses were dried on cover glasses and on stainless steel discs and exposed to nebulization. The number of infectious viral particles and genomic copies before and after the nebulization were compared. Efficacy in reducing infectivity of both surrogates was demonstrated. For the MNV and FCV a $\log_{10}$ reduction factor ≥4.84 and 4.85 was observed respectively after treatment, for tests on cover glasses and ≥3.90 and 5.30, respectively, for tests on stainless steel discs. Only low reductions in genomic copy numbers were observed for both surrogates. The nebulization of hydrogen peroxide showed a clear virucidal effect on both HuNoV surrogates, MNV and FCV, on two different carriers and the use of nebulization should be promoted in complementarity with conventional disinfection methods in healthcare settings and food processing facilities to reduce viral load and spread of contamination.

Stuart *et al*, (2020) compared vaporous formaldehyde and HPV fumigation using infectious bronchitis virus (IBV) as the biological target. The testing investigated the ability of both fumigants to permeate areas of a microbiological safety cabinet (MSC), including the workspace, under the work tray, and after the HEPA filters. The effect of organic soiling on efficacy was also assessed. Results showed that that formaldehyde fumigation could achieve a 6-log reduction of the virus throughout the cabinet, and high protein soiling in the presentation did not affect efficacy. Cycle conditions for the HPV system also gave a 6-log viral reduction within the cabinet workspace and overcame the presence of soiling. However, HPV treatment did not achieve an equal reduction above the cabinet's first HEPA filter using the cabinet workspace cycle, suggesting that fumigant penetration was not as effective as formaldehyde. The authors concluded that adjustment of the MSC air pulsing conditions might improve this result.

Note of caution – several of the papers summarised above have co-authorship from individuals who work for, or have worked for, one of the major HPV system suppliers; Bioquell. Whilst the publications have all been peer reviewed and are scientifically well presented it is worth noting that these authors are not completely independent of the devices they have tested and reported on.

Concise summary of retrieved evidence

Table 1. Summary of retrieved publications

Author and year	Test setting	Design	Result/comments
Pottage *et al.* (2010)	Exposure tests used MS2 bacteriophage surrogate positioned in a Class III microbiology safety cabinet	Bioquell HPV and Steris VHP systems positioned outside MSC and fumigant piped in via ports to treat surface based challenges.	HPV gave a 6 $\log_{10}$ reduction in 10 min at the lowest viral concentration [10^7 plaque-forming units (pfu)/carrier]; requiring 45 min at the highest concentration (10^9 pfu/carrier). VHP system needed a 30 min exposure period to achieve a 6 $\log_{10}$ reduction at the lowest concentration and 60-90 min for the highest concentration.
Berrie *et al*, (2011)	Looked at treatment of a dried recombinant adenovirus – a genetically modified form of this respiratory virus - before and after HPV exposure.	Bioquell HPV system used but delivery system small enough to fit inside MSC (Clarus S). Surface based challenges.	A >8-log $TCID_{50}$ reduction resulted from 45-min exposure to HPV in the MSC test environment.

	MSC again used for testing.		
Beswick *et al,* (2011)	Vaccinia virus one of several dried microbial residues used for surface challenge testing. . 34m^3 controlled atmospheric chamber and 150m^3 CL3 laboratory used.	Bioquell HPV, Steris VHP and Glossair dry mist H_2O_2 systems all tested as well as ozone and ClO_2 systems. Most fumigation systems located within these rooms. 750 µl wet volumes of challenges also used in addition to dried residues.	Best results obtained from Chlorine dioxide (ClO_2) and formaldehyde fumigants; each gave consistently high levels of antimicrobial efficacy, typically greater than a 5-log reduction for bacteria and total kill for virus. HPV, VHP and dry mist hydrogen peroxide systems gave greater variability, achieving 4-log_{10} to 6-log_{10} reductions. All systems performed similarly against Vaccinia virus, with total kill in all cases, equating to total kill, i.e. 3-log_{10} to 4-log_{10} reductions on steel carriers. Lowest bacterial kill generally associated with liquid challenges but all virus killed.
Bentley *et al,* (2012)	Used HPV to decontaminate a number of test surfaces. Class II MSC used for tests.	Bioquell HPV system located outside of MSC with fumigant piped in. Feline calicivirus (FCV) used as a surrogate for human norovirus.	HPV reduced viral titres by 4 log_{10} on all surfaces tested within 20 min of exposure. This took longest to achieve on stainless steel (20 min), and was quickest on vinyl flooring (10 min). For glass, plastic and ceramic tile surfaces, the desired reduction was seen within 15 min of exposure.
Tuladhar *et al*, (2012)	Assessed virucidal efficacy of HPV	Virus dried on to stainless steel,	HPV treatment gave complete

	against respiratory and enteric viruses on materials representing those found in institutions and homes. Tests conducted in an MSC or room and H_2O_2 generator was positioned inside both.	framing panel and gauze carriers using Poliovirus, norovirus surrogates, rotavirus, adenovirus and influenza A (H1N1)	inactivation of all viruses tested, characterized by >4 log_{10} reduction in infectious particles for poliovirus, rotavirus, adenovirus and murine norovirus on stainless steel and framing panel carriers, and >2 log_{10} reduction for influenza A virus on stainless steel and framing panel carriers, and for all viruses on gauze carriers.
Goyal *et al*, (2014)	Assessed HPV treatment of a several distinct viruses of pathogenic relevance for healthcare, veterinary and public sectors	Viruses used were feline calicivirus (FCV, a norovirus surrogate); human adenovirus type 1; transmissible gastroenteritis coronavirus of pigs (TGEV, a **severe acute respiratory syndrome coronavirus [SARS-CoV] surrogate**); avian influenza virus (AIV); and swine influenza virus (SwIV). All dried on to steel discs or used in small volume suspension within a 0.2-m^3 environmental chamber with Bioquell HPV system located outside.	No viable viruses were identified after HPV exposure at any of the vaporized volumes tested. HPV was virucidal (>4-log reduction) against FCV, adenovirus, TGEV and AIV at the lowest vaporized volume tested (25 mL). For SwIV, due to low virus titre on the control discs, >3.8-log reduction was shown for the 25-mL vaporized volume and >4-log reduction was shown for 27-mL and 33-mL vaporized volumes.
Zonta *et al,* (2016)	The study assessed the efficacy of a nebuliser system that sprayed hydrogen peroxide on to the test viruses.	Human norovirus, murine norovirus (MNV) and feline calicivirus (FCV viruses were dried on cover glasses and stainless steel discs and exposed to nebulized	For the MNV and FCV a log_{10} reduction factor ≥4.84 and 4.85 was observed, respectively, for tests on cover glasses and ≥3.90 and 5.30,

		hydrogen peroxide vapour. Number of infectious virus and genomic copies before and after the nebulization was compared.	respectively, for tests on stainless steel discs. Only low reductions in genomic copy numbers were observed for both surrogates. The nebulization of hydrogen peroxide showed a clear virucidal effect on both HuNoV surrogates, MNV and FCV, on two different carriers
Stuart *et al*, (2020)	Compared vaporous formaldehyde and HPV fumigation. The discs were Placed within an MSC for treatment.	Used infectious bronchitis virus (IBV) as the biological target. The effect of organic soiling on efficacy was also assessed. Stainless steel discs 2 cm in diameter were placed centrally within the cabinet workspace.	Formaldehyde achieved a 6-log reduction of the virus throughout the cabinet, and high protein soiling in the presentation did not affect efficacy. Cycle conditions for the HPV system also gave a 6-log viral reduction within the cabinet workspace and overcame the presence of soiling. However, HPV treatment did not achieve an equal reduction above the cabinet's first HEPA filter using the cabinet workspace cycle, suggesting that fumigant penetration was not as effective as formaldehyde and would require further optimisation.
Andersen *et al*, (2005)	Uses a Sterinis fumigation device generating a dry mist from 5% source H_2O_2 disinfectant. The test included treatment of rooms, ambulances and various medical	Three cycles performed with increasing contact times using *Bacillus atrophaeus* spores as test challenge. Spore strips were placed in various positions in rooms,	In the ambulances, the penetration of H_2O_2 into equipment, devices, glove boxes, under mattresses, and the drivers' cabins was 100% (60/60 tests) when using three

	equipment.	ambulances, and inside and outside the items of medical kit.	cycles, but was less effective when using one or two cycles. Decontamination was effective in 87% of 146 spore tests in closed test rooms and in 100% of 48 tests in a surgical department when using three cycles.
Tucker (2015)	Describes the developed of fumigation technologies to decontaminate complex interior spaces. Bespoke cabin style test chamber used for testing purposes.	The assessment considered various forms of H_2O_2 product delivery, including electrostatic, ultrasonic and nebulizing spray technologies. The test used low hazard *Bacillus* test spore strips	Observed up to 6.5 to 7.0 log_{10} reductions in spore levels in test spaces using a rotary atomizer system for delivering a fine mist from 3.5% aqueous H_2O_2. Some of the best results were achieved when a germination primary step was used to weaken spores prior to fumigation.
Alvarez-Aldana *et al*, (2018)	**WET DISINFECTION STUDY OF AMBULANCES (NOT FUMIGATION):** evaluated the cleaning and disinfection procedures in six ambulances from three different locations	The three different wet disinfection products used at three separate ambulance stations; The presence /absence of contamination was calculated from data obtained during bacterial growth assessments carried out before and after cleaning.	The most frequently isolated contaminants in the study were Gram-positive bacteria (*Staphylococcus aureus*), which also remained in the greatest proportion after disinfection. By implementing cleaning microbiological isolates were eliminated by 33.3% overall, with the door of the ambulance area showing the greatest decrease (50.0%). Although a decrease in microorganisms was achieved, these were not eliminated. Authors conclude that different approaches must be considered in order to improve cleaning

			efficacy.

Health and safety considerations: Fumigant aeration and off gassing

Materials used for most healthcare and laboratory environments are designed to be impervious and easy to keep clean. In addition, laboratory spaces that may require fumigation are not supposed to contain absorbent materials such as cardboard storage boxes or textile seat covers. Yet even in such areas fumigant may take long periods of time to clear following a period of fumigant treatment. This may even be the case where mechanical ventilation is available to aerate the room and clear the air (Beswick et al, 2011).

In areas where softer furnishings such as carpet and seat coverings are permitted these materials can act as a 'sink', absorbing fumigant (any fumigant) during treatment and then releasing it long after treatment completion. Observations following fumigation tests conducted at HSE's Science and Research Centre in Buxton, on behalf of the Home Office, Government Decontamination Service (Defra), Department of Health and other organisations, has shown that the off-gassing process can sometimes occur for hours after the main treatment aeration has ended. Room air may appear to be clear upon initial inspection but upon closer examination using a handheld fumigant monitor may demonstrate persistent localised emissions of fumigant around textiles etc. that may exceed the workplace exposure limits. This possibility must be considered if fumigating any room or vehicle with H_2O_2 or any other effective fumigant, since their persistence in the air can at the least cause respiratory discomfort and at wort may cause more serious ill-health effects.

In view of the above, the amount of fumigant delivered to an area, the amount of absorbent material present and the required aeration time and best mechanism for aeration must all be carefully considered prior to treatment. For vehicles, if at all possible treatment in the outdoor air or a large well ventilated space such as a large bus garage would be preferable, with doors/windows opened by a suitably protected operator at the end of treatment, to allow good aeration of the residual fumigant. The required period of aeration will vary subject to the variables above.

Before H2O2 systems are used, extensive testing to ensure H2O2 can be distributed through the area, biological efficacy, material compatibility (especially for vehicles), reproducibility and safety would be required for any new applications.

Examples of UK available commercial fumigation systems that use hydrogen peroxide:

Bioquell: https://www.bioquell.com/life-sciences/systems-and-services/decontamination/?lang=en-uk

Steris: https://www.sterislifesciences.com/products/equipment/vhp-sterilization-and-biodecontamination

Phileas: https://www.tecomak.com/phileas-genius/

Halo-fogger: https://icsolutions247.com/products/

Nebulair: http://www.nebulairtechnologies.com/

Hygiene Solutions: https://www.hygiene-solutions.co.uk/deprox-product-infection-control

Air cleaning devices

Mobile (non-ducted) air purification devices, have been used across many UK sectors for years, but particularly in healthcare and sanitation. Many such devices are available, with most claiming to remove airborne dust, microorganisms, other allergens and odour. Some system suppliers claim to reduce surface microbiological contamination, for example by the generation of reactive oxygen species, such as the hydroxyl free radical (OH- ions). These are reportedly harmless to people residing in the rooms. Some studies describe the use of these devices to create negative pressure isolation rooms, where the flow rate is high and filtered air can be released outdoors. This may be beneficial for some healthcare requirements.

Unlike chemical fumigation systems (foggers) air purification devices are typically designed to work in the background while the treated room(s) remain occupied. To this end some have been evaluated for the removal of allergens to aid asthma sufferers. The devices are usually left running for long periods, even permanently, to maintain or improve air quality. The devices of interest usually have the capacity to treat large air volumes using coarse and/or high efficiency filtration steps, or by combining filtration with either electrostatic precipitation (based on particle charge) and high energy disruption of entrained contaminants. Many of the available systems are scalable, with flow rates and equipment size dependent on the intended use. Some manufacturers also provide versions of their systems that can be inserted in to existing ventilation ductwork where efficient filtration might not otherwise exist. There are a limited number of published studies for these devices and the higher quality papers are mainly healthcare related, although some data are available for other settings, such as domestic dwellings. A selection of papers is presented below, with relevant data summarised where possible. It has not been possible to undertake an exhaustive literature search in the time available but a good representation of available studies is presented.

Author/Year	Type of study	Study population and/or exposure context	Main findings/conclusions
Rao *et al*, (2020)	Healthcare – prospective study of paediatric unit care rooms	273 control patients and 289 in intervention group where room filtration was used.	Authors are medical professionals but are also involved in the development of the technology being assessed. They conclude that air purification on test may reduce hospital length of stay, rates of intubation, and need for non-invasive intervention and nebulizers for paediatric patients with respiratory distress. Non-invasive ventilation use was 77% in the pre-intervention

Author/Year	Type of study	Study population and/or exposure context	Main findings/conclusions
			period and decreased to 23% in the post-intervention period. The rate of nebulizer use was 59% in the pre-intervention period and 41% in the post-intervention period. The rate of intubation was 57.1% in the pre-intervention period and 43% in the post-intervention period
Blake & Yaneer, (2020)	Healthcare – speculative paper – editorial in nature	Related to healthcare worker exposures and staff using closed vehicles for healthcare activities	Authors propose that portable air filtering devices could reduce viral load in the environment leading to substantial decrease of the severity of individual disease. Future research suggested for hospital treatments areas, closed transit vehicles and using air filtration devices to augment PPE use.
Verhougstraete & Reynolds, (2016)	Healthcare – scientific intervention study, small scale	Multiple assessments of two unused ICU type rooms in a hospital	In both health care study rooms, no statistically significant difference was detected using the portable air disinfecting system and the natural HVAC system that was already in place. Authors concluded environments with reduced air exchange rates may benefit most from combining portable air filtration devices with natural HVAC conditions may help to further reduce aerosolized virus loads.
The Ontario Medical Health Secretariat, (2005)	Healthcare – structured review of literature	NA	In-room air cleaners suggested as alternative technology for increasing room ventilation when this cannot be achieved by the building's HVAC system, with preference given to fixed recirculating systems over portable ones. They may be deployed in situations with a novel/emerging infectious agent whose epidemiology is not yet defined and where airborne transmission is suspected.
Scott *et al*, (2002)	Healthcare – US state guidance note	provision of negative pressure isolation facilities	The authors describe how device can be used to create a negative pressure room facility if filtered outlet air can be discharged directly to the outside. Important conditions of use are emphasised, including the use of RPE/PPE when filters are changed,

Author/Year	Type of study	Study population and/or exposure context	Main findings/conclusions
			carrying our maintenance away from clinical areas, following manufacturer's instructions in relation to filter/UV lamp replacement and any periodic internal cleaning of the unit.
Offerman *et al,* (1985)	Non-healthcare – engineering testing paper	Cigarette smoke removal from residential rooms; testing using multiple types of filtration device	Air cleaning rates for particles were found to be negligible for several small panel filter devices, a residential-sized ion-generator and a pair of mixing fans. Air cleaning rates for particles were based on removal rates observed for 0.45 μm size particles. This was found to be negligible for several small panel filter devices, a residential-sized ion-generator and a pair of mixing fans. Effective cleaning (air flow) rates ranged from 0 m^3 h^{-1} for panel filters to 306 m^3 h^{-1} for the HEPA type filter unit. Electrostatic precipitators and extended surface (HEPA) filters removed particles at substantial rates (up to 58% and 86% efficient resp.), with the HEPA-type filter the most efficient air cleaner studied.
Myatt *et al*, (2008)	Non-healthcare – predictive modelling study based on real home observation and published data	Domestic air quality and related pollutants in the home over a year long period	Published data in the scientific literature were used to support a predictive model approach (CONTAM). Authors used an influenza virus exposure scenario. The predicted risk of influenza infection was found to be approximately 16% with conventional filtration as part of ducted ventilation, 5% for the configurations with a portable air cleaner in a bedroom and 0.6% with the high efficiency filtration.
Du *et al*, (2011)	Non-healthcare – randomized control study	126 US households recruited to assess the effects of indoor pollutant levels on childhood asthma	Before filter installation, particulate matter concentrations averaged 28 mg m^{-3} room air, number concentrations averaged 70,777 and 1471 L^{-1} in 0.3-1.0 and 1-5 μm size ranges, respectively. Filter use reduced PM concentrations by an average of 69-80%. Simulation models representing location

Author/Year	Type of study	Study population and/or exposure context	Main findings/conclusions
			conditions show that filter air flow, room volume and air exchange rates (AERs) are key parameters affecting PM removal.
Zuraimi *et al,* (2011)	Non-healthcare – laboratory simulated residential room study	Four portable air cleaning devices tested in two different room use scenarios.	The observed clean air delivery (flow) rates for the tested devices ranged from 45 m^3 to 800 m^3 h^{-1}. Modelling analysis demonstrated that the use of these devices can mitigate the risks of influenza infection via airborne route for a caregiver or a spouse sharing the same room. Specifically, after a coughing event, fine particles concentrations dropped below 25% of initial levels within 10 min and below 2% after 30 min. Particle exposures were near zero after 40 min.
Sublett, (2011)	Non-healthcare – literature review	Considers technologies that can be used to purify residential room air to help reduce allergen levels.	Concludes that the use of portable air cleaning devices trends toward clinical benefit, with effectiveness limited to a single room and not the entire dwelling (in the home setting). Several - placed in various rooms - are needed to match the effectiveness of whole house filtration systems. The author states that Ionic electrostatic room air cleaners provide little or no benefit compared with ducted systems or portable filtration devices and that ionic appliances can also produce ozone, a respiratory irritant.
Barn *et al*, (2016)	Non-healthcare – part literature review/data presentation	HEPA filter and electrostatic precipitator use in the domestic setting to lower indoor concentrations of fine particulate matter from wildfire smoke	Among homes affected a lower mean infiltration of smoke (± standard deviation) was found for filtration periods (19% ± 20%) compared with control when filtration was not in place (61% ± 27%). The authors cite other international studies related to smoke particle removal to further support their argument that these devices should be a fundamental response to particulate removal in homes.

Applications of air purification devices

Healthcare

A healthcare study by Rao et al, (2020) assessed the use of a portable air filtration device in hospital paediatric treatment areas. This prospective study evaluated the use of a system with photo-electrochemical oxidation (PECO) technology (see Annex, Figure 1). The historical control group comprised matched patients; 273 were admitted in the pre-intervention phase (control group) and 289 in the post-intervention phase (where air purification was used). The mean length of ICU stay was 0.7 days in the pre-intervention period and decreased to 0.4 days post-intervention (those in rooms treated with air purifier). The mean length of overall hospitalization reduced by 0.3 days. The rate of non-invasive ventilation use was 77% in the pre-intervention period and decreased to 23% in the post-intervention period. The rate of nebulizer use was 59% in the pre-intervention period and 41% in the post-intervention period. The rate of intubation was 57.1% in the pre-intervention period and 43% in the post-intervention period. The authors concluded that portable PECO air purification may reduce hospital length of stay, rates of intubation, and the need for non-invasive intervention and nebulizers for paediatric patients admitted with respiratory distress.

Blake & Yaneer, (2020) considered healthcare and closed vehicle environments in a speculative review that suggests using portable air filtering near a coronavirus patient may reduce the Covid19 viral load in the environment. They propose that this may in turn decrease the probability of health care worker infection through flaws in Personal Protective Equipment (PPE). The authors also suggest that a significant mode of disease progression occurs through lung tissue re-infection through air circulation in the environment of the patient. This paper proposes that it may be possible to reduce viral load in the environment leading to substantial decrease of the severity of individual disease. Rapid action is advised on evaluating the validity of these ideas and the authors suggest a number of topic areas where attention might be focused, including hospital treatments areas, closed transit vehicles and using air filtration devices to augment PPE use.

Verhougstraete & Reynolds (2016) investigated the removal of a viral surrogate- coliphage - from two intensive care hospital rooms using a portable air device. The two unused rooms were seeded with airborne coliphage ThiX 174 using a nebuliser over a 15 minute period to create a measurable bioaerosol. Air samples were taken with and without the intervention of a T1 Air Disinfector-Recirculator, which had coarse, medium and HEPA filtration as well as biocidal UV incorporated. In both health care study rooms, no statistically significant difference was detected using the portable air disinfecting system and the natural HVAC system that was already in place. There were differences in the HVAC performance in each of the two rooms that was thought to be related to air exchange rate, with a reduction of 1.76 log of coliphage with air exchange of 12.4 air changed h^{-1} compared with a 2.46 log reduction where the air changes were 37 h^{-1}. The authors concluded that environments with reduced air exchange rates may benefit most from portable air filtration and that combining portable air filtration devices with natural HVAC conditions may help to further reduce aerosolized virus loads.

The Ontario Medical Health Secretariat (2005) assessed the potential for using air cleaning technologies. Whilst acknowledging that many such technologies are portable the authors also state that fixed devices can be attached to either a wall or ceiling and are preferred (in

their opinion) over portable units because they have a greater degree of reliability (if installed properly) for achieving adequate room air mixing and airflow patterns; both important for optimal effectiveness. The authors comment on the importance of equipment placement and how this should be done in discussion with suppliers/engineers in order to maximise the performance of the chosen system. The effectiveness of an air filtration unit that is not in-built ventilation is dependent on filtration efficiency and the rate of air filters over time. This paper summarises US data that shows how they have been estimated to be between 12% and 99% effective, depending on how the systems are engineered. Although their effectiveness is acknowledged as variable, the United States Centers for Disease Control and Prevention (CDC) has acknowledged in-room air cleaners as alternative technology for increasing room ventilation when this cannot be achieved by the building's HVAC system, with preference given to fixed recirculating systems over portable ones. With relevance to viral transmission this review concludes that since influenza is primarily acquired by large droplets and direct and indirect contact with an infectious person, any in-room air cleaner will have little benefit in controlling and preventing its spread. Importantly though, the review concludes that in-room air cleaners may be used to protect health care staff from air borne infectious pathogens such as tuberculosis, chicken pox, etc. and although not effective at preventing the spread of droplet-transmitted diseases (e.g. influenza and SARS), they may be deployed in situations with a novel/emerging infectious agent whose epidemiology is not yet defined and where airborne transmission is suspected.

Scott et al (2002) present a Michigan state guidance note consider the provision of negative pressure isolation facilities and the related use of portable air filtration units. The authors emphasise that device will not create a negative pressure room unless it can be discharged directly to the outside. Recommendations are made about where the unit should be placed, i.e. as close to the expected source of the contamination as possible to increase effective capture of the infectious/hazardous agents. The authors describe how droplet capture decreases with the square of the distance from the intake, so the distance from the patient has an impact on the ability to filter out droplet nuclei. For rooms where there is a risk of infectious transmission the paper recommends 12 air changes per hour, but states that this may be more easily achieved in smaller rooms and that variable airflow on the purification device should be adjusted accordingly, rather than just set to maximum flow. Important on going usage conditions are described by Scott et al, (2002), including the use of RPE/PPE when filters are changed, carrying our maintenance away from clinical areas, following manufacturer's instructions in relation to filter/UV lamp replacement and any periodic internal cleaning of the unit.

Non-healthcare environments

As long ago as 1985 Offerman et al. tested 11 air purifiers of different designs for the removal of respirable cigarette smoke particulates. The size of the tobacco smoke particles was of median diameter of 0.15 μm. Air cleaning rates for particles were based on removal rates observed for 0.45 μm size particles. This was found to be negligible for several small panel filter devices, a residential-sized ion-generator and a pair of mixing fans. Air flow rates Effective cleaning rates ranged from 0 m3 h-1 for PFI panel filters to 306 m^3 h^{-1} for the HEPA type filter unit. Electrostatic precipitators and extended surface (HEPA) filters removed particles at substantial rates (up to 58% and 86% efficient resp.), with the HEPA-type filter the most efficient air cleaner studied.

Myatt et al (2008) used an indoor air quality modelling system (CONTAM) to study common airborne contaminants, including microorganisms, present in indoor air over a year as a function of natural ventilation, portable air cleaners, and forced air ventilation (conventional and high efficiency filtration systems). Published data in the scientific literature were used in the predictive models, including a viral exposure scenario based on a carer spending 12 hours in a bedroom adjacent to a second bedroom occupied by an individual infected with influenza. The risk of influenza infection was found to be approximately 16% with conventional filtration as part of ducted ventilation, 5% for the configurations with a portable air cleaner in the bedroom and 0.6% with the high efficiency filtration. Overall, the results indicated that the use of high efficiency in-duct air cleaners provide the most effective means of controlling airborne contaminant levels not only in a single room, as with a portable air cleaner, but for the whole house.

Du et al, (2011) assessed the effectiveness of filters on pollutant exposures of children with asthma; 126 US households were recruited and randomized into control or treatment groups. The latter received a free-standing high efficiency air filter placed in the child's bedroom. Before filter installation, particulate matter (PM) concentrations averaged 28 mg m^{-3} room air, number concentrations averaged 70,777 and 1471 L-1 in 0.3-1.0 and 1-5 μm size ranges, respectively. Filter use reduced PM concentrations by an average of 69-80%. Simulation models representing location conditions show that filter air flow, room volume and air exchange rates (AERs) are the key parameters affecting PM removal, however, filters could achieve substantial removal in even "worst" case applications. The study concluded that PM levels can be dramatically reduced in homes using filters.

Zuraime et al, (2011) used an airborne microbiological surrogate (NaCl particulate) to simulate influenza virus particles and to assess their removal from a controlled atmospheric chamber by four portable air cleaner technologies. Particle counting and sizing equipment was used to assess the decay of particles over time and to account for any loss of the aerosol to surfaces, since this fraction was predicted to be larger than the particulates that would be removed by air filtration. The authors also modelled the predicted release of sneeze droplets based on 'typical' room conditions for a Quebec residential room. This allowed them to model the extent to which the risk of influenza via the airborne route is modified by the use of four different portable air cleaning (PAC) technologies for two scenarios: (1) a healthy individual such as a caregiver, spends an hour in the model room; and (2) a healthy individual such as a spouse, spends 8 h in the model room of an infectious individual. The clean air delivery rates for the tested devices ranged from 45 m^3 to 800 m^3 h^{-1}. The study found that particle exposures released during a cough or sneeze event in a residential room in Canada could be reduced using HEPA, electrostatic precipitation and electret filtration PACs when compared with a situation where no PAC is being used. Modelling analysis demonstrated that the use of these devices can mitigate the risks of influenza infection via airborne route for a caregiver or a spouse sharing the same room. Specifically, after a coughing event, fine particles concentrations dropped below 25% of initial levels within 10 min and below 2% after 30 min. Particle exposures were near zero after 40 min. Coarse particles were approximately 1% of the initial levels after 20 min, and close to zero by 30 min. The implications of the study were deemed significant considering low ventilation rates of Quebec City residences.

Sublett (2011) reviewed various technologies that can be used to purify residential room air to help reduce allergen levels, including the use of domestic air conditioning, specialist

bedroom air purification equipment for the alleviation of asthma and standalone filtration devices that can be used anywhere in the home. The choice of device is particularly relevant for the US, where 75% of housing units have ducted forced air heat, while 63% have ducted central air conditioning; so a quite different situation to most UK domestic dwellings where a 2008 report found that only 0.5% of UK homes had air conditioning of any kind. The author presents findings from long term studies of asthma sufferers where primary end points (bronchial reactivity and treatment requirements) were statistically improved in the treatment group over the controls. Secondary end points of lung function and allergen levels improved but this was not statistically significant. Sublett (2011) also cites further data that supports the use of portable air cleaning devices to reduce exposure of particulates associated with the exacerbation of asthma and other respiratory symptoms, but concluded that further research was necessary to determine whether such filters improve respiratory health. A large number of supporting papers are cited and the author concludes that the use of portable air cleaning devices trended toward clinical benefit, with effectiveness is limited to a single room and not the entire dwelling (in the home setting). Several - placed in various rooms - are needed to match the effectiveness of whole house filtration systems. The author concludes that Ionic electrostatic room air cleaners provide little or no benefit compared with ducted systems or portable filtration devices and that ionic appliances can also produce ozone, a respiratory irritant.

Barn et al, (2016) make the case for using HEPA filters and electrostatic precipitators in the domestic setting to lower indoor concentrations of fine particulate matter and so improve respiratory and cardiovascular outcomes. The authors argue that portable air cleaning devices should be at the forefront of the public health response to landscape fire smoke events. This has relevance for other exposure prone situations where small airborne particles are implicated because of the high levels of small particles (PM2.5) involved. This paper reflects on other studies but also reports from the authors' own research. Assessing thirteen randomly chosen residences home affected by wildfire smoke over or residential wood burning a HEPA filtration device was left in place during one 24-h period and removed (control period) during a second 24-h period. Among homes affected a lower mean infiltration of smoke (± standard deviation) was found for filtration periods (19% ± 20%) compared with control when filtration was not in place (61% ± 27%). Barn et al (2016) cite other international studies related to smoke particle removal to further support their argument that these devices should be a fundamental response to particulate removal in homes.

Duchaine, (2016) examined evidence for a number of air cleaning technologies including those using plasma discharge, which has been tested for the microbiologic decontamination of air and has been shown to be efficient against filamentous fungi. The plasma works by charging the particles, making them more prone to capture by electrical filtration. The author describes how other systems have been shown to destroy airborne particles in ambient air by denaturing organic compounds by means of UV light and titanium dioxide photocatalysis. Photocatalysis effectively destroys a wide range of bacteria and fungi, algae, protozoa, and viruses. Duchaine, (2016) also reports that several patented devices and technologies claim air decontamination by combining filtration and chemical treatment of air (eg, filter exposure to UV radiation on both the upstream and downstream sides and permeation of filters, in situ, with ozone).

Examples of commercial systems available in the UK and sources of information

Airora: air purification systems that includes generation of oxygen free radicals and contains an essential oil mix. Claims to clean the whole room because of this feature (not just the air). Room and personal devices available but flow rate not clearly indicated. Company claims no filters are used (or need replacing). https://www.airora.com/

Electromedia model 35F: HEPA standard air purification system with high energy field incorporated. Various sizes of device available and the device is claimed to treat 8.5m3 min-1. http://clean-air-healthcare.co.uk/index2.html.

Filtaire Solutions Ltd: Compact, simply designed filters and housings that can be mounted on walls, panels etc. Scalable technology based around high efficiency filtration. Airflow up to 600m³ h-1. http://www.filtaire.com/.

Healthway systems: HEPA level air filtration system – various scales of device available depending on environment to be treated. Flow rate for medium sized device up to 200 ft3 min-1. https://www.healthway.com/

Odorox: Air filtration but also claims the generation oxygen free radicals to aid room sanitation, including odour and microbiological contaminants. Various sizes of device available and airflow of a medium standalone unit is 140 ft3 min-1. https://odorox.com/.

Quest International AirManager: High efficiency, high airflow 3M filtration system with at least some models containing 'molecular disruption' technology based on high voltage energy field. Various sizes of device available and claims to be the only air sterilization and filtration system certified to provide clean air to in excess of operating theatre standards (minimum ISO 6 guaranteed). Airflow specifications could not be found but other relevant information is available here: https://www.flightglobal.com/bae-and-quest-introduce-new-cabin-air-management-system/89041.article and here: https://www.theengineer.co.uk/airmanager-cleans-cabin-air/

Other Considerations

An additional concern related to air filtration devices is the noise they may emit. HSE's Science Division laboratory (Buxton, Derbyshire) has previously tested four such devices for their noise emissions. All worked at noise levels that were considered to be of no long term risk to hearing for an eight hour exposure, i.e. operating at below 80dBA. In addition, all fell below the threshold level of 75dBA that equates to 'no risk' when the daily exposure is all day, i.e. 24 hours. 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.

A number of devices can produce emissions that can potentially be harmful as discussed by Siegel 2016. In some cases this is direct emission that may be due to a badly manufactured device or a device that should not be used in an occupied space. In other cases this may be an unintentional by-product, for example some ionisers or UV lamps in PCO systems have been shown to produce ozone (Siegel 2016). It is also possible that secondary emissions

can arise from the reactions between the air cleaner by-products or interactions with contaminants that are removed to the air cleaner.

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