# COVID-19:
# Air cleaning technologies

Version 1

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# Contents

# 1 Summary

There are a vast number of different air cleaning devices marketed for the removal of SARS CoV-2. It is difficult for potential users or purchasers to choose one that reduces transmission risks effectively. Their interaction with the environment in which they are placed is extremely complex, and it is often difficult for non-experts to differentiate between them or evaluate manufacturer claims.

This guidance aims to help building practitioners and managers to assess whether an air cleaning device might be beneficial in indoor environments and to assess suitability, safety, effectiveness, and fitness for purpose.

# 2 Scope and purpose

This guidance gives a brief introduction to SARS-CoV-2 transmission pathways and removal mechanisms and provides links to sources that go into more detail.

It is not intended to be an in-depth academic assessment of the technologies, and largely relies on the judgement of expert sources who have undertaken such studies in making its recommendations.

It is accompanied by the *Relative Exposure Index Calculator* (CIBSE, 2021), a simple tool in Excel format that can be used to calculate the relative exposure risk for two scenarios, enabling the relative impact of introducing an air cleaner into a room to be assessed (see section 9 for further detail).

## 2.1 Who is this guide for?

The guide is divided into two parts. The first, covering sections one to seven, is intended for lay-readers. It summarises the existing guidance and makes general recommendations around the selection of air cleaning devices, including their performance, risks, and general maintenance.

The second part, from section eight onwards, goes into more detail – providing a background to air flow performance metrics, pollutant and viral decay, and tools for assessing the performance of air cleaners in context. This section is aimed at building services engineers, facilities managers, and other technical staff involved in the selection and specification of ventilation systems and air cleaning devices.

## 2.2 What buildings does this guide cover?

This guidance is aimed at most residential and commercial buildings. Its applicability is limited in healthcare settings where more specialised ventilation and filtration guidance should be followed.

# 3 Background and existing guidance

## 3.1 What are air cleaners?

Air cleaners, sometimes called 'air purifiers' or 'air disinfection devices', are devices that are intended to improve air quality by removing or inactivating contaminants in indoor air. Air cleaners generally target a wide range of indoor pollutants (particulate matter, dust, volatile organic compounds, viruses, bacteria) and whilst many of the technologies have been used for a number of years, interest in them has grown in light of the COVID-19 pandemic.

## 3.2 What types of air cleaners are there?

Air cleaners include a variety of technologies (some of which remove pathogens by filtration, whilst others render pathogens biologically inactive) and a single device could contain one or more of the technologies listed below:

- high-efficiency particulate air (HEPA) or other mechanical filters
- ultra-violet (UV) germicidal irradiation
- thermal or photocatalytic oxidation
- ion generation, or plasma devices
- electrostatic precipitation
- other 'novel' proprietary technologies.

The operating principle of each type of device has been described in detail in previous papers (e.g. (SAGE-EMG, 2020). These devices come in a variety of sizes, and can be free-standing or installed within fixed ventilation systems.

Air cleaning technologies can be installed as part of the fixed building services. The installation of HEPA filters in central air handling units (AHUs) will increase energy consumption and operational costs; these may impact noise levels, and filters will require regular maintenance.

Many existing systems may not be suitable for retrofitting with HEPA filters due to the large pressure drop or leakage around the filter they can induce in the system. This could lead to the ventilation rate decreasing if the system is improperly designed or poorly maintained.

Advice from a specialist engineer is therefore highly recommended before deciding on the replacement or upgrade of filters in an existing mechanical vent system. Air cleaning devices should therefore never be used as a replacement for the provision of outside air into buildings. They should only be used to supplement existing systems, or in areas where removal of pollutants is not possible by other means.

Devices based on widely tested UV-C technology are covered in more detail by REHVA (REHVA, n.d.), in the CIBSE guidance document *COVID-19: Ventilation* (CIBSE, 2021), and elsewhere (ASHRAE Epidemic Task Force, 2021), (IES, 2015). In the interest of brevity, the scope of this guidance excludes UV-C or upper-room UV disinfection technologies. A

thorough assessment evaluating both benefits and safety considerations should be undertaken when deciding whether to apply UV in buildings.

## 3.3 Which pollutants can they remove?

Concerns around air quality, particularly amid the COVID-19 pandemic, have stimulated interest from building owners and operators in the best ways to protect the health of building users. Some air cleaning devices could reduce indoor pollutants levels; however, epidemiological evidence on health impacts is limited and inconsistent (Cheek, et al., 2021).

The bulk of this guidance specifically focuses on air cleaning within the context of SARS-CoV-2 transmission; however, many of the devices and technologies discussed are marketed and used for removal of chemical, biological, and particulate indoor pollutants. Some of the high-level tools provided for assessing the suitability of an air cleaner (see sections 6 and 7) could be applied irrespective of the intended indoor pollutant target. A cautious approach to manufacturer claims is recommended, and if in doubt, consulting an accredited air quality expert is advisable.

# 4 Assessing the benefits of an air cleaning option for reducing SARS-CoV-2 transmission

Often the benefits of an air cleaning system are marketed in comparison to an equivalent scenario with no pollutant removal mechanisms. However, in reality, there will be some removal mechanisms present in every space regardless of the presence of either ventilation or air cleaning devices, and these will vary in magnitude from room to room. All spaces should be ventilated.

A preliminary review of any ventilation system by a specialist building services engineer is recommended to answer fundamental questions such as:

- Is there recirculation?
- What are the ventilation rates?
- Where are supply and extract grilles in relation to occupants, and how is that likely to impact on airflow patterns?

## 4.1 Removal mechanisms for SARS-CoV-2 laden aerosols

There are several mechanisms by which aerosols (some of which may contain viable SARS-CoV-2) can be removed from a space:

**Ventilation**: air in the space is exhausted and replaced with 'SARS-CoV-2 free' air from outside, mixing and diluting the concentration of the viral laden aerosols in the indoor space.

**Deposition**: aerosols will deposit onto surfaces either by eventually settling under gravity or hitting surfaces by momentum-induced deposition.

**Viral decay**: the SARS-CoV-2 virus requires a host cell to invade in order to replicate and survive. It cannot remain viable outside the host organism indefinitely. Various chemical and biological mechanisms render the virus inviable, removing its function of infectivity. The decay rate for a virus is known as a half-life; one half-life is the time taken for half of the virus to become unviable.

**Air cleaning devices**: sometimes called 'air purifiers' or 'air disinfection devices.' These are devices which are intended as a means of improving air quality, either through removing or inactivating contaminants in indoor air.

The underlying principles of the removal mechanisms shown in Figure 1, below, can be described as an equivalent ventilation flow rate and expressed in terms of litres per second; however it should be noted that there is still a high level of uncertainty around the mechanistic transmission of the virus.

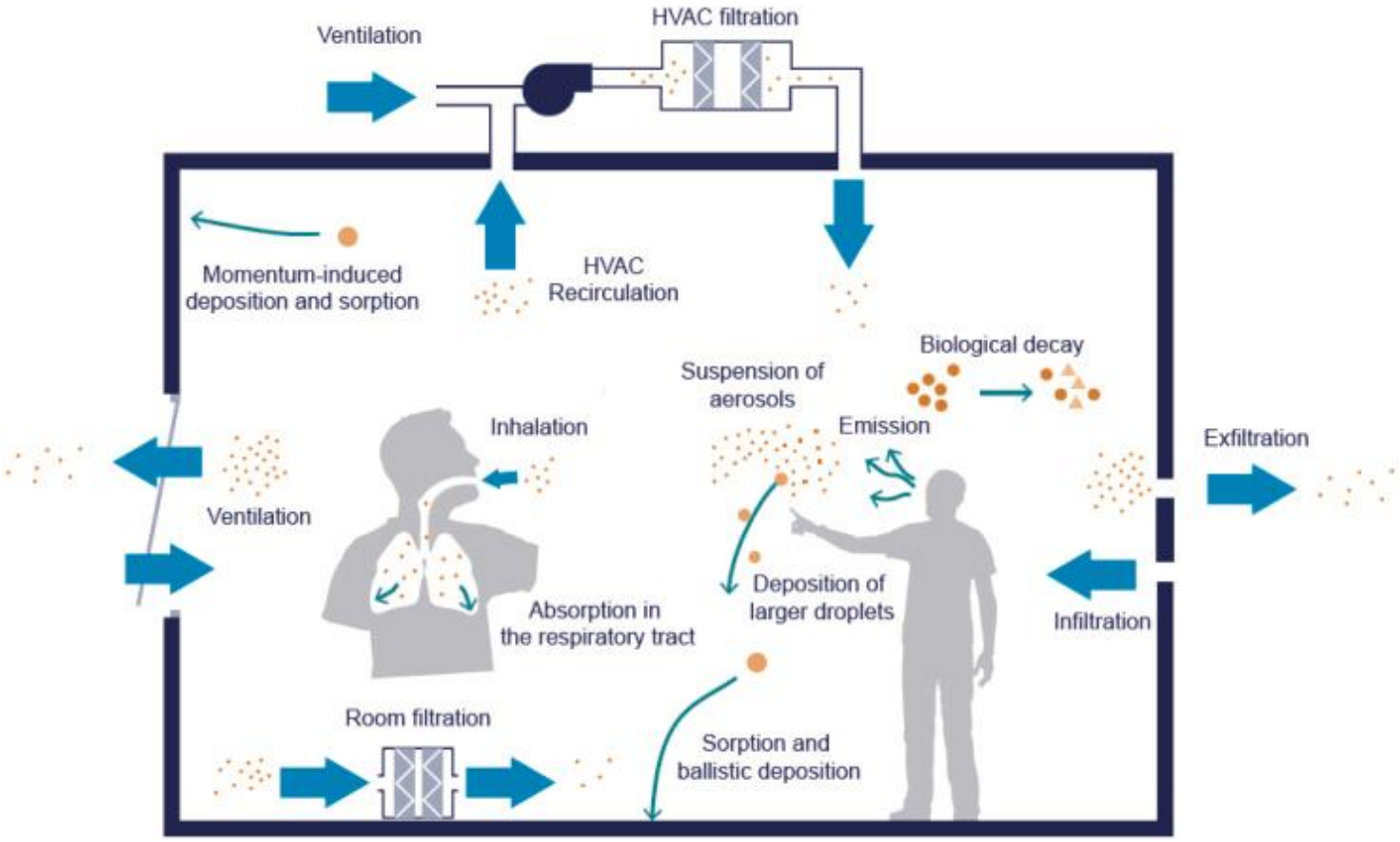


Figure 1 Single-zone mass-balance model of virus transport via exhaled aerosols (Jones, et al., 2021)

## 4.2 Air cleaning and COVID-19

The science of SARS-CoV-2 spread and transmission prevention is complex, as shown in Figure 2 (SAGE-EMG, 2020). It is clear, however, that there are no 'silver-bullet' solutions and a combination of measures is required to reduce the risks of infections indoors.

While Figure 2 outlines basic principles of infection control, every indoor environment offers a unique set of conditions (including building systems specifications and occupants), therefore assessing measures for individual buildings or rooms is the recommended strategy. We recommend that you review the UK government's Scientific Advisory Group for Emergencies Environmental Modelling Group (SAGE-EMG, 2020), Health and Safety Executive (HSE) (HSE, 2021), CIBSE (CIBSE, 2021), REHVA (REHVA, 2020), ASHRAE (ASHRAE, 2021), and the World Health Organisation (WHO) (WHO, 2021) guidance documents. These documents provide detailed guidance on which combination of measures would be most suitable to reduce the risk of infection from pathogens such as SARS-CoV-2.

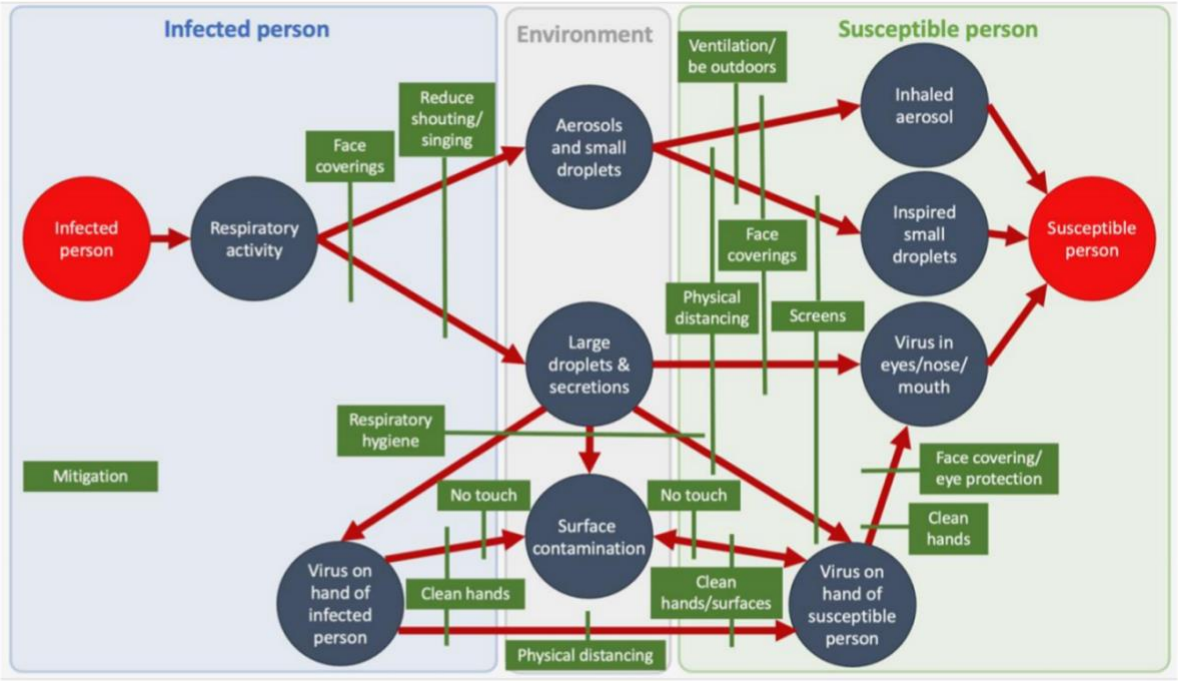


Figure 2 Schematic showing potential routes of transmission for all SARS-CoV-2 variants, together with ways in which personal, procedural and engineering mitigation measures can disrupt the transmission pathway (SAGE-EMG, 2020)

## 4.3 Are air cleaners an effective solution for reducing COVID-19 risks?

The scientific evidence suggests that air cleaners could be part of the solution in minimising risks in certain situations, but they are not a solution that reduces all risks. The primary building systems measure to reduce far field (> 2 m) airborne spread indoors is increased ventilation.

A review of air cleaners by SAGE-EMG (SAGE-EMG, 2020) outlined that they may be suitable for spaces where there is insufficient ventilation and where ventilation can't be improved. There is currently limited evidence that air cleaners are an effective control measure to prevent COVID-19 spread, however the principles of air cleaning suggest that they may be useful in some cases. Air cleaners that are based on filtration (with a HEPA filter) are most often recommended as likely to be effective (Lindsley, et al., 2021) and those that include ultraviolet lamps may also work (CIBSE, 2021).

The SAGE-EMG (SAGE-EMG, 2020) review of scientific evidence and others (ASHRAE, 2018) (EPA, 2021) caution against using devices that produce ozone, ions or other chemicals without independent evidence for their safety and efficacy, as the by-products created by these technologies may act as respiratory irritants.

## 4.4 What are the existing recommendations around air cleaning devices?

CIBSE (CIBSE, 2021), REHVA (REHVA, 2020), and SAGE (SAGE-EMG, 2020) outline that portable air cleaning devices based on mechanical filtration (such as HEPA filters or UV-C) are 'likely to be beneficial if deployed correctly' (SAGE-EMG, 2020). According to the World Health Organisation (WHO) and the Centers for Disease Control and Prevention (CDC), in situations where no other (short-term) strategies can be adopted, such as increasing ventilation rates, a stand-alone air cleaner with HEPA filters could be used (CDC, 2021) (WHO, 2021). The use of filtration-based devices may reduce aerosolised viruses that we can breathe in, such as SARS-CoV-2, and will almost certainly reduce concentrations of other harmful particulates such as $PM_{2.5}$ and $PM_{10}$ – depending on the filter efficacy.

However, it is important to understand that the effectiveness of air cleaning devices may be limited by how much air can pass through them and how people operate them (for example- which flow setting is used: low, medium, high) (Cooper, et al., 2021).

Some devices may generate unwanted chemical by-products through their operation. Exposure to pollutants such as ozone may be harmful for health (Bell, et al., 2006). Chemical exposure creates risks for a variety of symptoms and diseases related to the respiratory tract. Ozone has been shown to increase mortality and hospital admissions, therefore indoor concentrations should be reduced (COMEAP, 2015). Introducing air cleaners which emit ozone into a space, even at low levels, is not recommended.

SAGE-EMG's review of current scientific evidence demonstrated that devices whose operation relies on ionisers, plasma, chemical oxidation, photocatalytic oxidation or electrostatic precipitation may generate undesirable secondary chemical products that could lead to health effects such as respiratory or skin irritation (SAGE-EMG, 2020). Echoing SAGE-EMG advice and scientific evidence, devices relying on these technologies are not recommended unless their safety and efficacy is scientifically demonstrated by publicly-available relevant test data.

## 4.5 Do I need an air cleaner?

In principle it is recommended that during the COVID-19 pandemic, outside air flow rates should be at least the minimum required by building regulations; and that this provision should be increased wherever it is reasonable to do so without causing undue thermal discomfort or a significant increase in energy usage. The flowchart below aims to provide a quick method for checking whether an air cleaner could be beneficial for reducing COVID-19 risks in an indoor environment. It is important to consider detailed scientific and technical evidence (CIBSE, 2021) (REHVA, 2020) (WHO, 2021) for selecting the appropriate COVID-19 mitigation strategies.

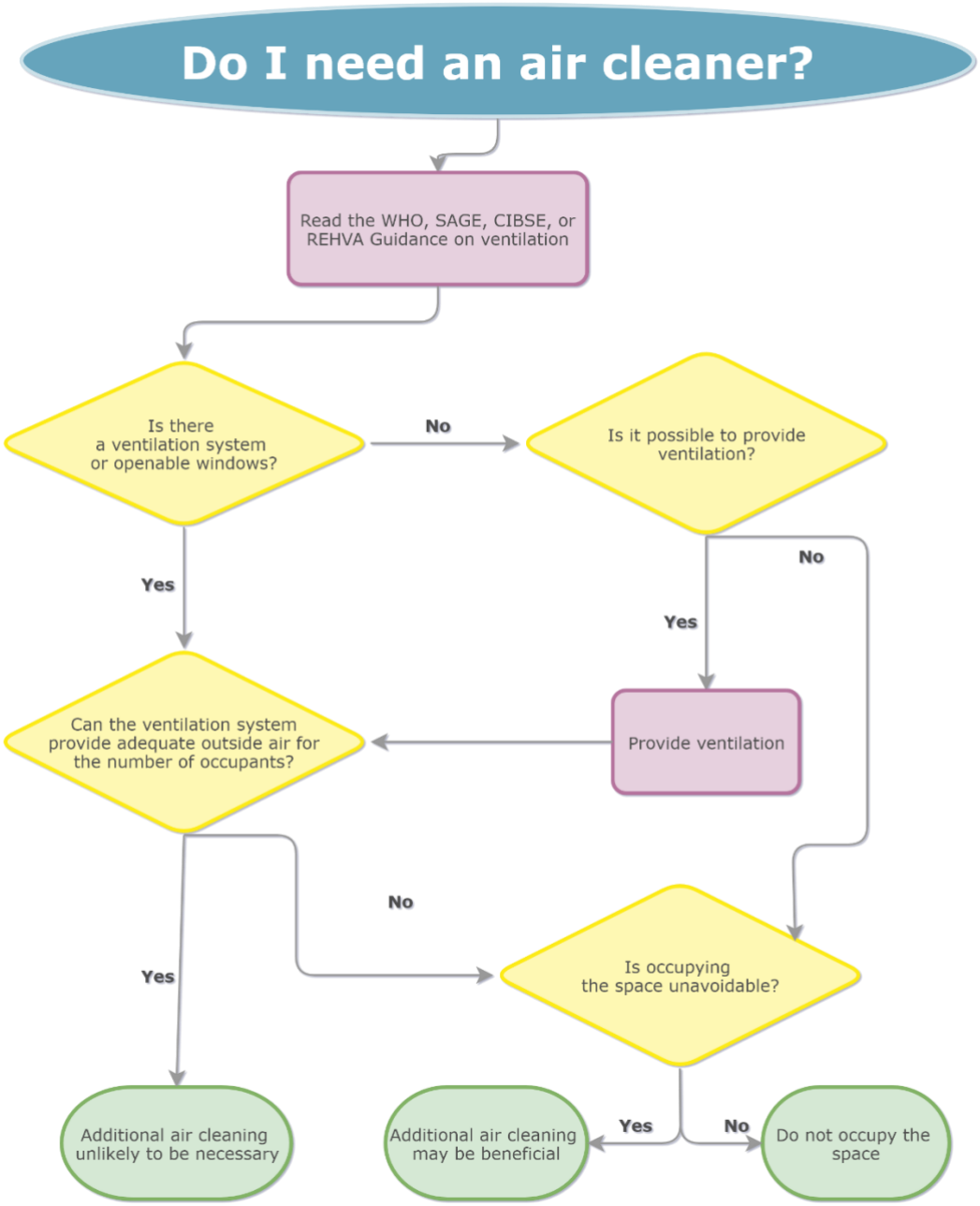


Figure 3 High level flowchart for assessing suitability of portable air cleaner as part of COVID-19 mitigation strategies

# 5 Performance and safety considerations

When considering air cleaning devices there are four main areas of performance that should be understood:

- the efficacy of the device
- the impact of the device on the situation in which it will be used
- the process or processes by which it works and the safety of those processes
- future operation and maintenance of the device.

When it comes to efficacy, whilst there are emerging international standards, they are often limited in scope (e.g. consider HEPA filters only). As a result, it is important for the specifier to carefully examine manufacturer claims and thoroughly examine the supporting technical, testing or scientific information (if any is available). If possible, ask the manufacturer to provide the clean air delivery rate (CADR) of the device; where this is not available, estimate the CADR from manufacturer data.

**See section 8.3 for a sample calculation to estimate the clean air delivery rate.**

Performance in a test lab does not necessarily mean that a device will be as effective in a real environment. As there is no internationally-agreed standard for testing air cleaners, results may not be representative of real-world performance. Different laboratories may also use different conditions when running tests, so the supporting test data must always be examined.

The test set-up, and how similar this is to the intended real-world environment, must also be considered. Independent, third-party testing by accredited experts or peer-reviewed research is preferable. The technical data for the device itself should be examined first, and then the applicability of this to the intended room or space should be considered.

**To check what impact the device could have on relative risk of exposure, use the Relative Exposure Index calculation in section 8.4.**

The chemistry of indoor air is extremely complex, and the specifier should consider the potential indirect impacts on health of any device. Devices that rely on ‘novel’ methods (ionisers, plasma, chemical oxidation, photocatalytic oxidation, electrostatic precipitation and others) may remove some pollutants, but their use indoors may unintentionally generate

by-products that may be harmful (Carslaw, et al., 2017). In some cases, they may also have little to no effect on pollutants (Zeng, et al., 2021).

These by-products may not occur at all in laboratory conditions where filtered air is supplied in testing chambers, as they could be a result of the device's interaction with indoor air. The by-products are also often difficult or costly to detect, and are thus overlooked by manufacturers.

It is essential that specifiers ask for independent test results and supporting literature describing the device's air cleaning process, rather than rely on advertising claims; in particular, independent test data showing that the device does not and cannot produce harmful chemical by-products (including but not limited to ozone) at levels which are harmful to human health.

This recommendation echoes the SAGE review of the scientific research associated with alternative devices (SAGE-EMG, 2020).

If in any doubt, it would be sensible to consult an accredited air quality expert for advice.

# 6 Maintenance, commissioning, and long-term performance of air cleaning devices

The majority of available test data on air cleaning devices represents new devices that have been correctly installed and commissioned. The testing data also assumes that devices are operated correctly or at optimal conditions (such as highest flow rate). The effectiveness of devices can degrade over time, and regular replacement of filters or operating parts is needed to ensure devices operate as intended.

Care should be taken to ensure that maintenance and operation is well understood, and that equipment is well-maintained. A recent study found that the way people used portable air cleaners in homes was linked more closely with thermal comfort rather than perceived air quality (Cooper, et al., 2021). It is important that end-users of the devices are considered, and operational advice is considered and tailored for non-technical audiences. If users are impacted by noise, for example, they may reduce the flow rate or turn off the device completely. Even if the device is proven by independent data to be effective, improper usage could eliminate the benefit of having it in the first place. Specifiers should identify who will be responsible for maintenance and ongoing inspection of the device to ensure continued performance.

ASHRAE's *Position Document on Filtration and Air Cleaning* (ASHRAE, 2018) summarises the state of the research on lifetime performance:

'In actual installations, there could be air and contaminant bypass around air cleaning devices (Ward and Siegel 2005), degradation in the performance of some technologies over time (Lehtimäki et al. 2002), and potential for the emission of primary and/or secondary by-products (Zhao et al. 2007; Rim et al. 2013). Commissioning, active maintenance, and monitoring of filtration and air-cleaning devices are needed to ensure design performance. Information on these aspects is nearly non-existent, and there are nearly no documents regulating and necessitating examination of long-term performance of filtration and air cleaning devices.'

# 7 How do I choose an air cleaner?

The flowchart below aims to provide a process map for how to select a suitable device and what technical information to request, consider and assess during the selection process. It is important to review appropriate scientific and technical advice in order to ensure that if a device is specified, it is commissioned, used and maintained appropriately.

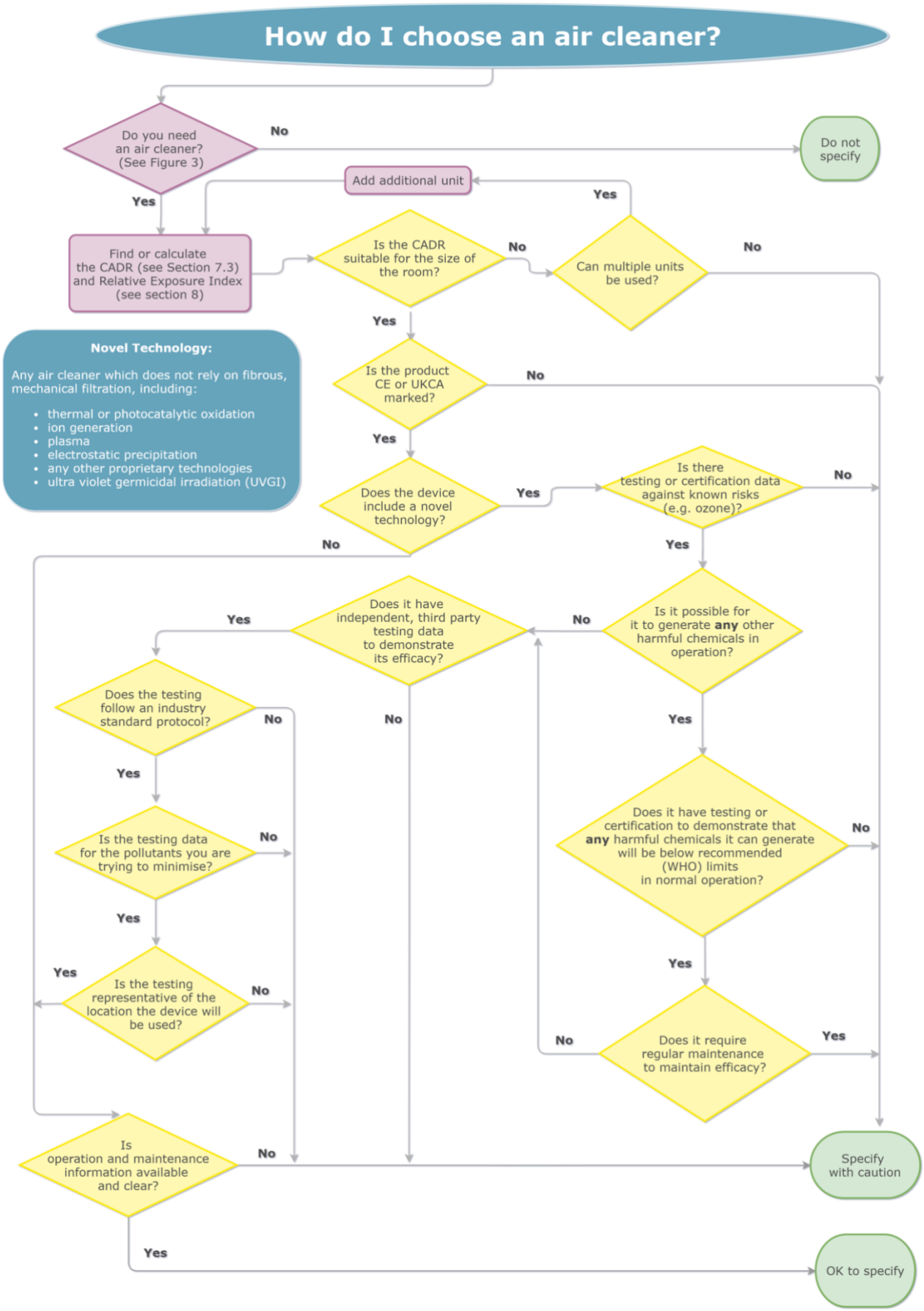


Figure 4 Detailed flowchart for selection of air cleaning devices

# 8 Ventilation performance metrics

## 8.1 Airflow quantification

Two metrics are used to quantify airflows: a volume flow rate (l/s or $m^3/s$), or an air change rate ($h^{-1}$). When a pollutant is continuously released into a space, its concentration eventually plateaus and reaches a steady state, and each airflow metrics reveals different characteristics.

Consider a tracer gas whose sole removal mechanism is ventilation. It is released at a constant rate into two offices: one office has twice the volume of the other, and both are ventilated with outside air containing no tracer gas. If each office receives the same **constant volume flow rate**, the concentration of the tracer gas will reach the same steady state value in both rooms irrespective of their volume. However, the number of molecules of the tracer gas (or the volume of the tracer gas) is greater in the larger space (see Figure 5).

Alternatively, if each office is ventilated at a **constant air change rate,** the steady state concentration of the tracer gas is lower in the larger space but the number of molecules in each office is the same (see Figure 6).

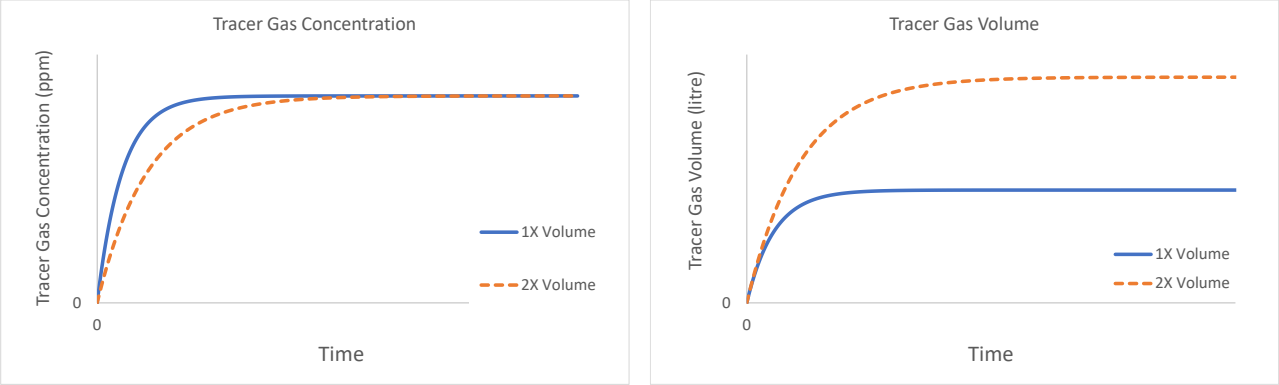


Figure 5 Two offices of different volumes ventilated with the same constant volume flow rate: (left) concentration of tracer gas in the space; and (right) volume of tracer gas in the space

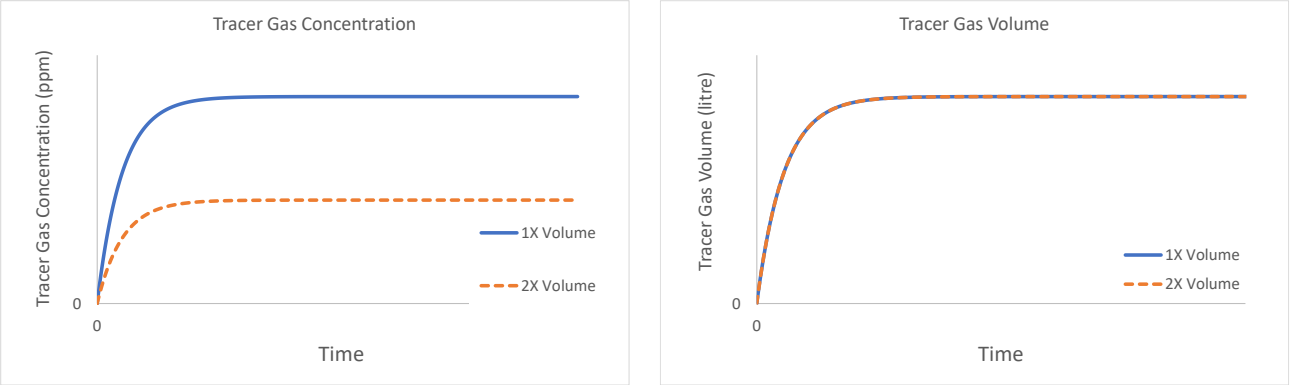


Figure 6 Two offices of different volumes ventilated with the same constant air change rate: (left) concentration of tracer gas in the space; and (right) volume of tracer gas in the space

By considering these principles we can begin to explore the risk of far field (> 2 m ) SARS-CoV-2 transmission via virus laden aerosols in indoor spaces.

### 8.1.1 Viable virus steady state concentration

The SARS-CoV-2 virus is encapsulated in aerosols and is a biological organism; there are removal mechanisms that work differently to ventilation. The effects of these can be expressed as an *equivalent* air change rate:

**Ventilation rate (ψ):** the air change rate is a function of the ventilation rate and the space volume ($V$)

**Biological decay rate (λ):** a function of the half-life of the virus, the time for half of all viruses present in a space to become unviable when outside a host cell, and the rate of biological inactivation by *air cleaning devices* such as UV

**Respiratory tract absorption (ζ):** a small number of viruses might be inhaled by occupants of a space. Some will be exhaled, some may deposit in the respiratory tract; this will be proportional to the concentration of viable virus in the air and the breathing rate of occupants.

**Surface deposition rate (γ):** the rate at which aerosols containing virus deposit on surfaces via ballistic deposition and momentum deposition; a function of surface area.

**Filtration rate (ω):** the rate at which aerosol-borne virus is filtered from the air by a mechanical device.

The risk of a susceptible occupant becoming infected is related to the number of viable viruses absorbed into their respiratory tract and the dose required before infection occurs. The higher the concentration of viable viruses in a space, the more viable virus are inhaled, increasing the risk of an infective dose. The steady-state quantity of any pollutant (number of molecules of a gas or number of viable virus) in a space ($n_{ss}$) is proportional to the quotient of the emission rate ($G$) and the total removal rate ($\phi$), also known as the *equivalent* air change rate, expressed per unit time (e.g. $h^{-1}$).

$$n_{ss} \propto \frac{G}{\phi} \tag{1}$$

The total removal rate is the sum of all individual removal mechanisms

$$\phi = \psi + \gamma + \lambda + \xi + \omega \tag{2}$$

The pollutant concentration ($\frac{n_{ss}}{V}$) is dependent on the space volume and is given by

$$\frac{n_{ss}}{V} \propto \frac{G}{\phi V} \tag{3}$$

In the case of a tracer gas for which the only removal mechanism is ventilation, $\phi=\psi$.

However in the case of the SARS-CoV-2 virus, the contribution of the other removal mechanisms can be significant.

To compare the **concentration** of viable virus in each space, the equivalent air change rate must be converted to an *equivalent* volume flow rate, which **is space dependent.**

### 8.1.2 The reservoir effect affects exposure

An indoor space can act as a fresh-air reservoir, which is useful for absorbing the impact of pollution emissions. The greater the volume of the space, the greater the effect. This reservoir effect means that the time taken to reach the steady state is longer in larger-volume spaces than in smaller-volume spaces. In larger-volume spaces, because there is a reservoir of fresh air already stored in the room, susceptible occupants are exposed to the steady state concentration of viable virus for less time. This reduces the risk of infection. CIBSE's AM10, *Natural ventilation in non-domestic buildings* (CIBSE, 2005) and the AIVC's A *Guide to Energy Efficient Ventilation* (Liddament, 1996) both outline calculations to determine the reservoir effect.

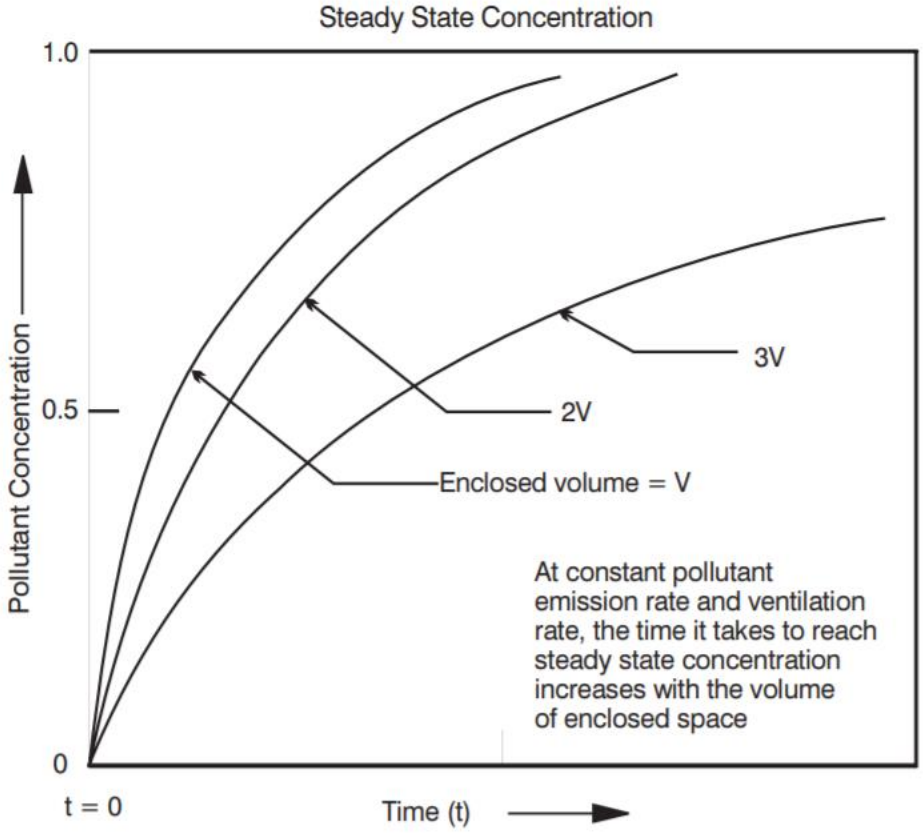


Figure 7 The building as a fresh air reservoir (reproduced with permission from *A Guide to Energy Efficient Ventilation* (Liddament, 1996))

## 8.2 Equivalent ventilation rate of air cleaning devices (eqACH)

An equivalent ventilation rate is a metric for evaluating the effectiveness of a removal mechanism acting on air in a room, given as an equivalent outdoor airflow (e.g. l/s, ACH, $m^3/s$). This can be expressed as:

$$\dot{Q_{eqv}} = \eta_f \times \dot{Q}$$

Where $\eta_f$ is the fractional removal efficiency of particles that pass through the device, and $\dot{Q}$ is the volume flow rate of air through the device.

For example, an air cleaning device containing an 80% efficient filter with a volume flow rate of 360 l/s has the following equivalent ventilation rate:

$$\dot{Q_{eqv}} = 0.8 \times 360 \ = 288 \ (l/s)$$

## 8.3 Clean air delivery rate

The clean air delivery rate (CADR) is a commonly used metric that can be useful both for comparing devices and for comparing the impact of dilution through ventilation. The CADR should be established through testing to the ANSI/AHAM AC-1-2015 standard (ANSI/AHAM, 2015). In the absence of this test-derived data, the CADR can be estimated from product data sheets in a process analogous to the equivalent ventilation rate:

$$CADR = \eta_f \times \dot{Q}$$

where $\eta_f$ is the fractional removal efficiency of particles that pass through the device and $\dot{Q}$ is the volumetric flow rate of air through the device (e.g. $m^3/hr$).

An air cleaner may be highly efficient (with a high value for f) but it will be ineffective at removing particles from the air if $\dot{Q}$ is very small. This can easily be converted to an equivalent air change:

$$\boldsymbol{\dot{Q_{eqv}}\ (ACH) = \frac{CADR}{room\ floor\ area\ \times\ room\ height}}$$

For example: if a room has a floor area of 55 $m^2$ and ceiling height of 3.3 m, a portable air cleaner with CADR = 6 $m^3$/min gives: EqACH = 6 x 60 / (55 x 3.3) = 2 ACH.

$$\boldsymbol{\dot{Q_{eqv}}\ (ACH) = \frac{(6\ (m^3/min) \times 60\ (min))}{(55\ (m^2) \times\ 3.3(m))} = 1.98\ (ACH)}$$

The EqACH can be used in the Relative Exposure Index Calculator (CIBSE, 2021) to establish the anticipated reduction in relative far field viral transmission risk (see Section xx). Note that this is an **approximate and heavily simplified method** that assumes air is well-mixed and does not consider location of the unit, entrainment of the air, or many other complexities, but does provide a simple way of comparing devices.

## 8.4 Relative Exposure Index

The Relative Exposure Index (REI) (Jones, et al., 2021) is a methodology to compare indoor scenarios with a defined reference case scenario and determine the relative far field (> 2 m) transmission risk in comparison to that reference scenario. It does not consider the risk of transmission by other mechanisms nor calculate the absolute infection risk.

One of the greatest uncertainties in assessing the risk of far field (> 2 m) airborne transmission of SARS-CoV-2 is that the amount of virus being released into a space is unknown. It is unknown how many infectors are in a given space, or how much virus they are releasing encapsulated in aerosols. The viral load, or amount of measurable virus in a standard volume of air, produced by an infector – a person who is already infected – can vary over several orders of magnitude; it also varies between individuals, and with respect to how many days since the infector was infected. This means that some individuals will shed much more virus than others. Some spaces may have zero infectors, whilst others may have several. Using the REI enables these uncertainties to be cancelled out by assessing the relative risk.

Although the REI does not give an absolute risk value for a scenario, it does enable the assessment of the risk level of one scenario in comparison with another. If an infector is present and releases sufficient virus to cause secondary infections via far field transmission, we would expect a greater proportion of the occupants to become infected in the scenarios with higher REI values.

The reference case is a typical classroom and results in a REI of approximately 1.

Table 1 A reference case for use of the REI method

| Space Volume | Number of occupants | Breathing rate | Respiratory activity | Occupation time | Air change rate |
|---|---|---|---|---|---|
| **148.5 m$^3$** | 32 | Children seated | Breathing: talking<br>= 75:25 | 7 hours | 5 l/s/person<br>(160 l/s total) |

This method is therefore useful in assessing the risk reduction that various interventions can provide in a scenario – for example, the effect of reducing the exposure time (spending less time in the indoor environment), increasing the ventilation flow rate, using an air cleaning device, etc. (Jones, et al., 2021).

The Relative Exposure Index Calculator (CIBSE, 2021) enables a scenario to be compared to the reference case.

# 9 The Relative Exposure Index Calculator

This Excel tool allows users to assess relative risk of exposure to COVID-19 in a given space by changing values for dimensions, number of occupants, breathing rate, respiratory activity occupation time and ventilation provision. Users can thus describe a space scenario in which the improvements of an air cleaner can be assessed.

The ventilation equivalent flow of the proposed air cleaner system can then be entered, and the median improvement on exposure risk is calculated.

As with all assumptions used in models, there are uncertainties around absolute values. For example, values for viral decay have a range that are distributed around a mean value. These uncertainties can be modelled and shown in the box whisker plots, as below.

The central line in the box represents the median expected REI value; the box represents the 50% confidence limits; and the whiskers represent the 95% confidence limits.

The uncertainties are calculated by modelling 10,000 occurrences using a Monte Carlo simulation, hence there will be slight changes in absolute value of REI each time the model is used.

Comparison of REI in two scenarios enables an assessment of the impact of mitigation measures in reducing the relative risk of secondary transmissions.

## 9.1 Worked example

Consider a typical UK classroom with ventilation of 5 l/s/person. Adding an air cleaner that can provide the equivalent of 1 ACH (calculated using the method in section 8.2) will reduce the median Relative Exposure Index by 18%, as shown below:

| | Without Air Cleaner | With Air Cleaner |
|---|---|---|
| Room width (m) | 7.42 | 7.42 |
| Room length (m) | 7.42 | 7.42 |
| Room height (m) | 2.7 | 2.7 |
| Number of occupants | 32 | 32 |
| Breathing rate | Children sitting | Children sitting |
| Respiratory activity: Breathing | 75 | 75 |
| Respiratory activity: Talking | 25 | 25 |
| Respiratory activity: Vocalising | | |
| Occupation time (hours) | 7 | 7 |
| Air change rate (ach) | | |
| Ventilation rate (l/s/person) | 5 | 5 |
| Ventilation rate (l/s) | | |
| Air cleaner equivalent ventilation rate (ach) | | 1 |
| Air cleaner equivalent ventilation rate (l/s) | | |
| REI | 0.992 | 0.829 |
| Median REI Improvement | | 16% |

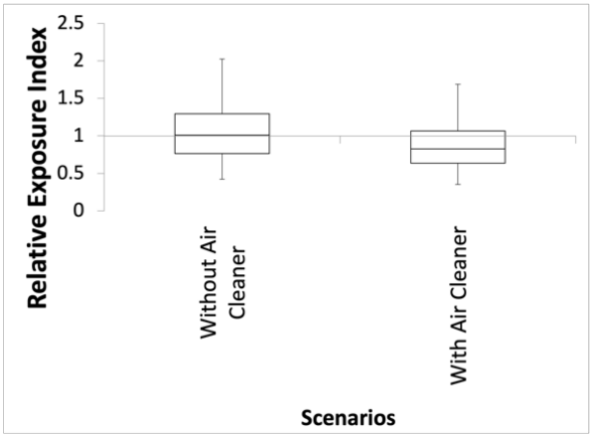


Figure 8a (left) A sample calculation using a ventilation rate of 5 l/s/p and an air cleaner ventilation rate of 1 ACH; and Figure 8b (right) the resulting box whisker plot

Alternatively, the outside air ventilation rate could be increased from 5 l/s/person to 10 l/s/person, which would reduce the median REI by 46%, as shown below:

| | 5 l/s | 10 l/s |
|---|---|---|
| Room width (m) | 7.42 | 7.42 |
| Room length (m) | 7.42 | 7.42 |
| Room height (m) | 2.7 | 2.7 |
| Number of occupants | 32 | 32 |
| Breathing rate | Children sitting | Children sitting |
| Respiratory activity: Breathing | 75 | 75 |
| Respiratory activity: Talking | 25 | 25 |
| Respiratory activity: Vocalising | | |
| Occupation time (hours) | 7 | 7 |
| Air change rate (ach) | | |
| Ventilation rate (l/s/person) | 5 | 10 |
| Ventilation rate (l/s) | | |
| Air cleaner equivalent ventilation rate (ach) | | |
| Air cleaner equivalent ventilation rate (l/s) | | |
| REI | 1.012 | 0.543 |
| Median REI Improvement | | 46% |

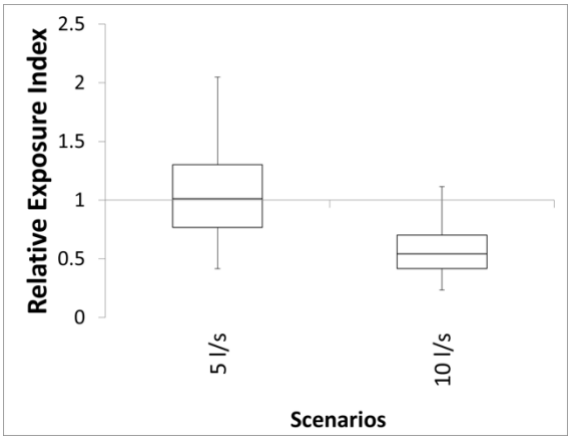


Figure 9a (left) A sample calculation using ventilation rates of 5 l/s/p and 10 l/s/p with no air cleaner; and Figure 9b (right) the resulting box whisker plot

# Appendix: How to assess removal rate claims

Many device suppliers make claims such as 'removes 99.9% of viruses in two hours'. Claims such as these should not be taken at face value, as any performance claims should be based on performance against benchmark microbes (Raeiszadeh & Adeli, 2020). However, in the absence of CADR or similar data, it is possible to approximate the performance of a device using these claims.

In order to determine the benefit of applying a system, it is useful to calculate what equivalent ventilation rate would produce the same pathogen reduction as the device claim. The equivalent ventilation rate can then be used in the Relative Exposure Index Calculator (CIBSE, 2021).

Products are generally tested in a small chamber, and a known amount of pathogen is aerosolised and added to the air of the chamber. Several samples are then taken over time, and the amount of pathogen within the sample is measured.

It is unlikely to see product data specifically for SARS-CoV-2 virus; but other viruses that possess similar properties but are not harmful to humans are often used, such as bacteriophages.

These biological entities have a natural decay over time (due to biological inactivation of the pathogen, and deposition of the pathogen onto surfaces of the room) and so measurements should be taken both with and without the product in place. The test without the product enables the natural decay of the pathogen to be measured, and this can then be compared with improvement when the product in place.

It is important to distinguish, in product claims, what reduction in pathogen concentration is due to the product and what is due to natural decay.

## Exponential decay

An exponential decay curve will be fitted to the product test data in the form:

$$c_t = ae^{-kt}$$

Where

$c_t$ Concentration of active pathogen at time $t$

$a$ Initial concentration of active pathogen at $t$ = 0

$k$ Decay constant of the pathogen (derived from product test data) and is in units of time$^{-1}$ (e.g. if $t$ is in hours, then $k$ is expressed in h$^{-1}$)

$t$ Time (check the units in the test data; this may be in seconds, minutes or hours)

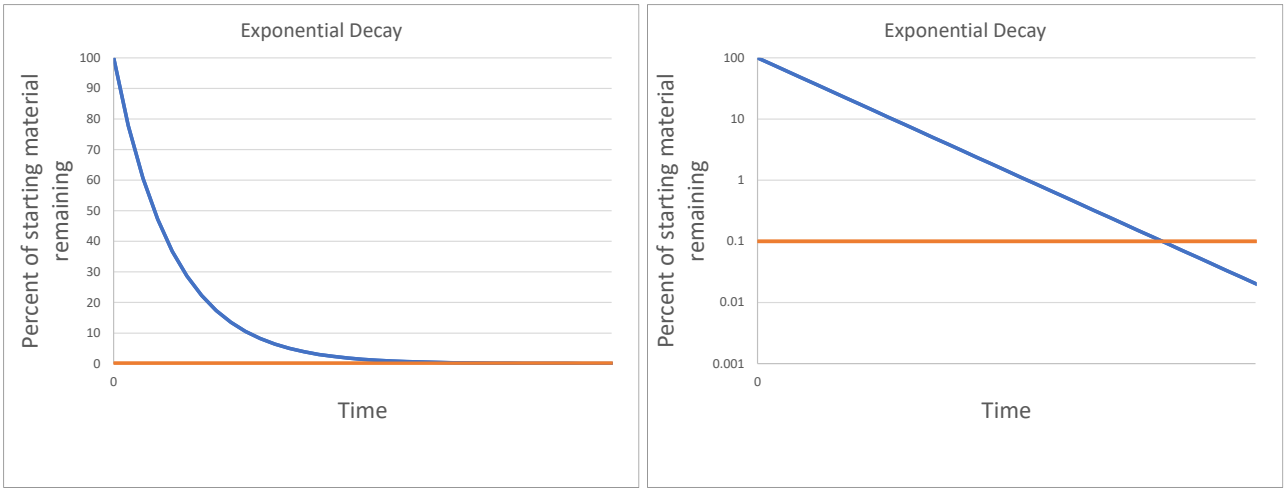


Figure 10 Example of an exponential decay curve (blue) with the 99.9% reduction shown in orange; in the image on the right, the exponential decay curve is plotted on a log scale and the decay curve is then linear

If decay constants are provided in the product test data, then one is able to calculate the equivalent ventilation flow that would result in the same decay as follows.

## Example (with product data decay constants)

To determine the decay attributable to the product from test data, the following equation should be used:

$$k_n t + k_p t = (k_n + k_p)t = k_c t$$

Where

$k_c$ Combined decay

$k_p$ Product decay

$k_n$ Natural (biological) decay

**Example:**

Given a combined decay constant of 11 $h^{-1}$ and a natural (biological) decay constant of 4.5 $h^{-1}$, what is the decay attributable to the product?

Rearranging equation above:

$$k_c - k_n = k_p$$

Product decay constant $k_p$ = 11 $h^{-1}$ - 4.5 $h^{-1}$ = 6.5 $h^{-1}$

The equivalent ventilation flow to achieve the same decay as the product would therefore be 6.5 $h^{-1}$ or 6.5 air changes per hour.

It is important to convert air changes per hour into an equivalent ventilation flow by using the volume of the test chamber in which the product was tested. For example, if the test chamber is 25 $m^3$ the equivalent ventilation flow rate for 6.5 air changes per hour is 25 x 6.5 = 162.5 $m^3h^{-1}$, or approximately 45 l/s.

The value of 45 l/s can now be used in the Relative Exposure Index Calculator (CIBSE, 2021) (see section 8.4 and section 9) to assess the relative impact of installing the product in a space.

## Example (without product data decay constants)

If there is no decay constant available, then the constant can be derived from percentage reductions – however, it is important to be able to distinguish between natural (biological) decay and decay with the product.

If this data is not forthcoming, then any claims in pathogen decay will be overestimates as they will be inclusive of the natural (biological) decay.

**Example:**

Claim – 99.9% reduction in virus attributable to product (i.e. not inclusive of natural biological decay).

Reviewing the test data associated with the device, this shows a 99.9% reduction in viable virus after two hours in a test chamber with a volume of 20 $m^3$.

What air change rate could achieve a 99.9% reduction in virus?

$$ach = (-1/t).ln(n)$$

where

$n$ = is ratio of pollutant after time $t$, in this case = 0.001

$t$ is time in hours, in this case 2 hours

$ach$ = 3.45

or

3.45 x 20 $m^3$ = 69 $m^3$/hour ≈ 19 l/s

So, the device has an equivalent ventilation rate of 19 l/s.

This equivalent ventilation rate can be used in the Relative Exposure Index Calculator (CIBSE, 2021) to establish the anticipated reduction in relative far field viral transmission risk (see section 8.4 and section 9). It is important to input the flow rate in litres per second, as this is space volume independent.

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