How can airborne transmission of COVID-19 indoors be minimised?

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Abstract

During the rapid rise in COVID-19 illnesses and deaths globally, and notwithstanding recommended precautions, questions are voiced about routes of transmission for this pandemic disease. Inhaling small airborne droplets is probable as a third route of infection, in addition to more widely recognized transmission via larger respiratory droplets and direct contact with infected people or contaminated surfaces. While uncertainties remain regarding the relative contributions of the different transmission pathways, we argue that existing evidence is sufficiently strong to warrant engineering controls targeting airborne transmission as part of an overall strategy to limit infection risk indoors. Appropriate building engineering controls include sufficient and effective ventilation, possibly enhanced by particle filtration and air disinfection, avoiding air recirculation and avoiding overcrowding. Often, such measures can be easily implemented and without much cost, but if only they are recognised as significant in contributing to infection control goals. We believe that the use of engineering controls in public buildings, including hospitals, shops, offices, schools, kindergartens, libraries, restaurants, cruise ships, elevators, conference rooms or public transport, in parallel with effective application of other controls (including isolation and quarantine, social distancing and hand hygiene), would be an additional important measure globally to reduce the likelihood of transmission and thereby protect healthcare workers, patients and the general public.

Recognising the potential for the airborne transmission of SARS-CoV-2

The significance of viral transmission via small airborne microdroplets (also commonly referred to as ‘aerosols’) has been intensely discussed in the context of the SARS-CoV-2/COVID-19 (severe acute respiratory syndrome coronavirus-2/coronavirus disease 2019) pandemic (Lewis 2020; Morawska et al. 2020). This is one of three commonly accepted modes of viral transmission, the other two being via larger respiratory droplets (which fall close to where they are expired), and direct contact with contaminated surfaces (fomites). Especially with the ongoing global shortage of personal protective equipment (mainly surgical masks and N95/FFP2/FFP3 respirators) (WHO 2020c), additional methods to reduce the risk of SARS-CoV-2 transmission indoors need to be considered. The need is acute in particular in hospitals and other healthcare facilities managing COVID-19 patients.

While evidence for airborne transmission of COVID-19 is currently incomplete, several hospital-based studies have performed air-sampling for SARS-COV-2, including one published paper (Ong et al. 2020), one early-release paper (Guo et al. 2020) and 5 papers still in pre-print at the time of writing (Chia et al. 2020; Ding et al. 2020; Jiang et al. 2020; Liu et al. 2020; Santarpia et al. 2020). Four of these studies found several positive samples for SARS-CoV-2 genome (RNA) in air using polymerase chain reaction (PCR) testing (Chia et al. 2020; Jiang et al. 2020; Liu et al. 2020; Santarpia et al. 2020), two found very small numbers of positive samples (Ding et al. 2020), and only one (Ong et al. 2020) found no positive air samples. This evidence at least demonstrates a *potential* risk for airborne transmission of SARS-CoV-2.

In addition, amongst these studies, three also reported some quantitative viral RNA data. The Singaporean study found positive air samples in 2 of the 3 patient infection isolation rooms, with samples in the 1-4 µm and >4 µm size ranges containing a range of viral loads (1.8-3.4 viral RNA copies per L of air) (Chia et al. 2020). The study from Nebraska, USA found that 63% of the air samples were positive with a mean viral load of 2.9 copies/L, including in patient rooms and the hallway air (Santarpia et al. 2020). In one case, they sampled close to the patient (mean: 4.1 copies/L) and at >1.8 m (mean: 2.5 copies/L), suggesting some dilution with distance. The highest viral loads were found in personal samplers worn by the sampling team when in the presence of a patient receiving oxygen via nasal cannula (mean: 19 and 48 copies/L), indicating that this treatment may promote the spread of airborne virus. A study in Wuhan, China (Liu et al. 2020) provides quantitative data for their small number of positive air samples, with 0.02 RNA copies/L in a toilet area and 0.02-0.04 copies/L in a room used to remove PPE. More than half the viral RNA in these samples was associated with aerosols <2.5 µm. This study also measured deposition through passive aerosol sampling, reporting deposition rates of 31 and 113 RNA copies/m^2 per h at samplers located approximately 2 m and 3 m from the patients, respectively (Liu et al. 2020).

Whilst this evidence may be deemed to be incomplete at present, more will arise as the COVID-19 pandemic continues. In contrast, the end-stage pathway to infection of the droplet and contact transmission routes has always been assumed to be via self-inoculation into mucous membranes (of the eyes, nose and mouth). Surprisingly, no direct confirmatory evidence of this phenomenon has been reported, e.g. where there have been: (i) follow-up of fomite or droplet-contaminated fingers of a host, self-inoculated to the mucous membranes to cause infection, through the related disease incubation period, to the development of disease, and (ii) followed by diagnostic sampling, detection, sequencing and phylogenetic analysis of that pathogen genome to then match the sample pathogen sequence back to that in the original fomite or droplet. It is scientifically incongruous that the level of evidence required to demonstrate airborne transmission is so much higher than for these other transmission modes (Morawska et al. 2020).

The infectious agents of several other diseases (tuberculosis, measles, chickenpox) are recognised to be transmissible via the airborne route, either by the short-range (face-to-face, conversational exposure) or by longer-range aerosols (Department of Health 2015; Tellier et al. 2019). Measles and varicella zoster (the virus causing chickenpox) can also be efficiently transmitted through direct contact during their acute phase of infection (e.g. by kissing). During a close contact situation, all transmission routes can be potentially responsible for infection.

For other respiratory viruses, including SARS-CoV, MERS-CoV (Middle-East Respiratory Syndrome coronavirus), respiratory syncytial virus (RSV – a common cause of bronchiolitis in infants) and influenza, both short-range and longer-range airborne transmission are possible, but the predominance of longer range transmission route in various exposure scenarios is difficult to quantify (Booth et al. 2013; Kim et al. 2016; Kulkarni et al. 2016; Li et al. 2007; Tellier et al. 2019), and may at times be opportunistic (Roy et al. 2004).

A recent mechanistic modelling study showed that short-range airborne transmission dominates exposure during close contact (Chen W et al. 2020). Other studies investigating the transport of human-expired microdroplets and airflow patterns between people also provide substantive support for this transmission route (Ai et al. 2019; Li et al. 2007; Liu et al. 2017). Therefore, in light of this body of evidence for these other respiratory viruses; we believe that SARS-CoV-2 should not be treated any differently – with at least the potential for airborne transmission indoors.

Yet despite this, international health organisations, like the WHO (World Health Organization) (WHO 2020b), continue to place insufficient emphasis on protection from small, virus laden, airborne droplets. Other organisations that deal with building environmental control systems, such as REHVA (the Federation of European Heating, Ventilation and Air Conditioning Associations) and ASHRAE (the American Society of Heating, Ventilating, and Air-Conditioning Engineers), have acknowledged the potential airborne hazard indoors and recommended ventilation control measures accordingly (ASHRAE 2020a; REHVA 2020).

Infection control specialists also often inquire about the relative contribution of airborne transmission compared to the other transmission modes (‘contact’ and ‘droplet’). Multiple studies provide strong evidence for indoor airborne transmission of viruses, particularly in crowded, poorly ventilated environments (Coleman et al. 2018; Distasio et al. 1990; Knibbs et al. 2012; Li et al. 2005; Moser et al. 1979; Nishiura et al. 2020). However, it is generally difficult to quantitatively compare and conclude which transmission route is the most significant in a given situation. Infection may occur via all routes to different degrees depending on the specific exposure circumstances. Effective infection control necessitates protection against all potentially important exposure pathways.

Here, in the face of such uncertainty, we argue that the benefits of an effective ventilation system, possibly enhanced by particle filtration and air disinfection, for contributing to an overall reduction in the indoor airborne infection risk, are obvious (Eames et al. 2009).

Engineering controls to reduce the potential airborne transmission of SARS-CoV-2

To maximise protection of the population against the airborne spread of SARS-CoV-2 and any other airborne virus-containing small microdroplets, several recommendations are necessary as presented below. These focus on indoor environments, because this is where most transmission occurs (Nishiura et al. 2020). Further, the measures mostly apply to public buildings. In residential houses and apartments, normal practices (e.g. segregating infected individuals, opening windows and doors, and using portable air-cleaning devices when practical) to ensure healthy indoor air, should stay in place at any moment.

Ventilation airborne protection measures which already exist can be easily enhanced at a relatively low cost to reduce the number of infections and consequently to save lives. The options discussed below should always be implemented in combination with other existing measures (like hand-washing and use of PPE) to reduce infection via other important routes of transmission, as none of them can be completely excluded in any exposure event. The remainder of this article will only cover recommendations for ‘engineering level’ controls, as described in the traditional infection control hierarchy (Figure 1) to reduce the environmental risks for airborne transmission.

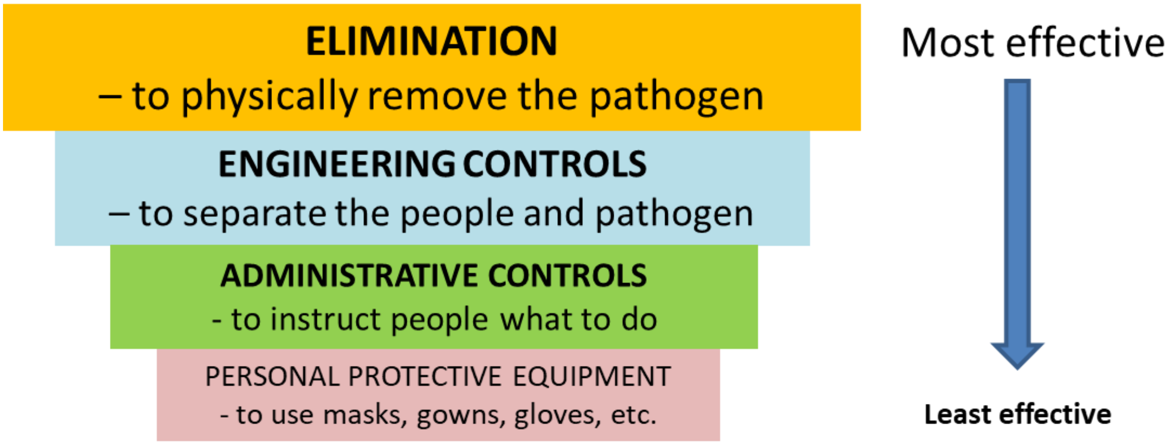

Figure 1. Traditional infection control pyramid adapted from the US Centers for Disease Control (CDC 2015).

i) Ventilation should be recognised as a means to reduce airborne transmission

Ventilation is the process of providing outdoor air to a space or building by natural or mechanical means (ISO 2017). It controls how quickly room air is removed and replaced over a period of time. In some cases, it is necessary to remove pollution from outdoor air before bringing it into a building, by using adequate filtration systems. Ventilation plays a critical role in removing exhaled virus-laden air, thus lowering the overall concentration and therefore any subsequent dose inhaled by the occupants.

Appropriate distribution of ventilation (e.g. placement of supply and exhaust vents) ensures that adequate dilution is achieved where and when needed, avoiding the build-up of viral contamination (Melikov 2011; Melikov 2016; Thatiparti et al. 2016;2017). The central guiding principle is to replace contaminated air with clean air, but sometimes local barriers to this process may occur, e.g. where partitions are used or curtains drawn for privacy or medical procedures. If these barriers are in use, secondary or auxiliary measures may be needed to achieve requisite ventilation effectiveness.

Good ventilation practices are already in place in many hospital settings, as part of everyday and emergency measures to protect against droplet and contact transmission (Phiri 2014). Good ventilation also protects the occupants against airborne transmission. The capacity to increase ventilation rates when needed (such as during the COVID-19 pandemic) may differ, and may be somewhat limited by their original design specifications and implementation.

Note that many hospitals are naturally ventilated in ward areas, including in some rooms used for critical care. However, if the airflow passage is obstructed (e.g. by closing windows and doors), airborne pathogen concentration can sharply rise leading to an increased risk of airborne transmission and infection (Gilkeson et al. 2013a). Natural ventilation concepts apply to healthcare facilities in both developed and resource-limited countries in favourable climatic conditions. The design, operation and maintenance of naturally ventilated facilities is not straightforward, and comprehensive guidance is available (WHO 2009). For instance WHO in March, (WHO 2020a) specifies that in a COVID-19 infective ward at least 160 L/s/patient have to be provided if natural ventilation is used.

We have recently seen the creation of very large emergency hospital wards, within exhibition centres for example, which house hundreds or even thousands of patients (MSN 2020). Although these facilities will have mechanical ventilation that is adequate for normal exhibition or conference use, it is not clear if sufficient ventilation will be available for patient management and infection control purposes when they are adapted for such purposes, as during the COVID-19 pandemic.

The situation can be worse in public buildings and other shared spaces, such as shops, offices, schools, kindergartens, libraries, restaurants, cruise ships, elevators, conference rooms or public transport, where ventilation systems can range from purpose-designed mechanical systems to simply relying on open doors and windows. In most of these environments, ventilation rates are significantly lower than in hospitals for various reasons, including limiting airflows for energy and cost savings.

Hence, in such environments, with lower ventilation rates intended primarily to control indoor air quality (which may also include some hospital emergency, acute admissions, general ward and clinic areas) (Booth et al. 2013; Jo et al. 2019; Kulkarni et al. 2016; Rule et al. 2018; Sornboot et al. 2019), the likelihood of infected persons sharing air with susceptible occupants is high, posing an infection risk contributing to the spread of the infectious disease.

Various studies have been performed on the survival of airborne pathogens (Brown et al. 2015; Kim et al. 2016; Kormuth et al. 2018; Kulkarni et al. 2016; Marr et al. 2019;

Pyankov et al. 2018; Tang 2009). The SARS-CoV-2 virus has been shown to be stable in airborne particles with a half-life of more than one hour (van Doremalen et al. 2020), so it can potentially be inhaled by susceptible individuals causing infection and further spreading of the disease.

As 'stay-at-home' lockdown measures are gradually relaxed, much of the population may return to spending increasing amounts of time in inadequately ventilated workplaces, offices, schools and other public buildings, where they may be exposed to a risk of acquiring viral infections by inhalation.

ii) Ventilation rates should be increased by system modifications.

In a mechanically ventilated building, ventilation air is typically provided by a heating, ventilating and air conditioning (HVAC) system. Sometimes, ventilation air is provided by dedicated fans or outdoor air units.

HVAC system control strategies can usually be modified to increase ventilation to a certain extent in the occupied zones, with relatively little additional cost, to reduce the risks of airborne transmission between occupants. However, this is not via a simple 'flick of a switch', as HVAC systems are complex and usually designed for individual buildings within standard specific operating parameters. Many requirements need to be considered apart from the ventilation rate, including control of temperature, relative humidity, air flow distribution and direction.

Such systems can be specifically customised as needed by HVAC engineers, e.g. to reduce the risks of airborne transmission. Indeed, the ventilation guidance of ASHRAE (The American Society of Heating, Refrigerating, and Air-conditioning Engineers), REHVA, SHASE (The Society of Heating, Air-Conditioning and Sanitary Engineers of Japan) have all just been updated to address the spread of COVID-19 (ASHRAE 2020b; REHVA 2020; SHASE 2020). Another example is the modification of a hospital ward ventilation system to create a negative pressure isolation ward (Miller et al. 2017).

If ventilation is provided using windows openings (aeration) or other means (fixed openings, e.g., natural ventilation), an estimation of the possible outdoor flow rate can be made using CEN Standard, EN 16798-7:2017 (CEN 2017), or other available references as (AIVC 1996; CIBSE 2005). The outdoor air flow rate that is achieved is strongly dependent on the specific local conditions (opening sizes, relative positions, climatic and weather conditions, etc.) and should be estimated case by case; it can easily range from 2 up to 50 ACH or more.

For naturally ventilated public buildings, particularly in cold climates, other challenges will arise, but these can also be addressed in order to reduce the risk of airborne infection transmission. It may be necessary to provide additional heating in some buildings to maintain thermal comfort, particularly where the occupants are vulnerable.

iii) ***Avoid air recirculation***

The recirculation of air is a measure for saving energy, but care must be taken, as it can transport airborne contaminants (including infectious viruses) from one space and distribute them to other spaces connected to the same system, potentially increasing the risk of airborne infection in areas that otherwise would not have been contaminated. This concern has been noted previously in regard to the possible recirculation of biological agents during terrorist attacks that have investigated the effectiveness of eliminating recirculation (e.g. providing 100% outside air to spaces and exhausting all of it) as a countermeasure following an indoor release of the agent (Persily et al. 2007). A study modelling the risk of airborne influenza transmission in passenger cars provided also a case against air recirculation in such situations (Knibbs et al. 2012).

Particulate filters and disinfection equipment in recirculated air streams can reduce this risk, but they need to be purposely designed to control risk of airborne infection and need regular service to maintain their effectiveness. Many systems are designed for filters that are intended to remove larger particles that may affect the functioning of equipment and that are not effective at removing small, sub micrometre or micrometre size particles associated with adverse health effects. Filter ratings by test methods, such as ASHRAE Standard 52.2 (ASHRAE 2017) that give an indication of performance as a function of particle size should be utilized in choosing appropriate filters.

Following the above considerations, during an epidemic, including the current COVID-19 pandemic, air should not be recirculated as far as practically possible, to avoid the dissemination of virus-laden particles throughout the indoor environment For central air handling units at a building level or serving multiple zones, recirculation should be avoided, and the system operated on 100% outdoor air (OA) if possible. Disabling recirculation can be achieved by closing the recirculation dampers and opening outdoor air dampers. In systems where it is not possible, one should try to maximize the OA-level and apply filtering or ultraviolet germicidal irradiation to remove or deactivate potential viral contamination from the recirculated air. In many health care settings, air recirculation is, in most cases not allowed at all, though though recirculation is commonly used in non-hospital settings for improving energy efficiency. At a room (decentral) level, secondary air circulation systems may be installed. One needs to assure that any of such systems also provides ventilation with outdoor air (e.g., induction units). If this is the case, such a system should not be switched off. Other systems, which do not have this feature (e.g., split air-conditioning units) should if possible be turned off, to avoid potential transfer of virus through air flows between people. When such a system is needed for cooling then additional ventilation with outdoor air should be secured by regular/periodic ventilation through, e.g., window opening.

iv) ***Air cleaning and disinfection devices may be beneficial***

In environments where it is difficult to improve ventilation, the addition of local air cleaning or disinfection devices, such as germicidal ultraviolet (GUV, or UVGI - ultraviolet germicidal irradiation) may offer benefits. Under laboratory conditions GUV has been shown to be effective against a suite of microorganisms including coronaviruses (Walker et al. 2007), vaccinia (McDevitt et al. 2007) and *Mycobacteria* (Xu et al. 2003), and even influenza (McDevitt et al. 2012; McLean 1961). Several studies show that inactivation decreases with increased humidity for both bacterial (Xu et al. 2005) and viral aerosols (McDevitt et al. 2012). Darnell et al. (2004) showed that SARS-CoV-1 could be inactivated by UV-C, while Bedell et al. (2016) showed a UV-C decontamination device could inactivate MERS-CoV at 1.22m, with almost a 6 log reduction 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.

One application that grew dramatically during the multi-drug resistant tuberculosis outbreaks of the 1980s (Young et al. 1994), is the ‘upper-room’ system in which lamps are placed in the upper part of the room, either on the walls or mounted on the ceiling, directing the UV light into the upper zone with louvers and limiting UV exposure in the occupied space (Xu et al. 2005; Xu et al. 2003). Upper-room GUV is a good technology to consider in crowded, poorly ventilated environments where aerosol transmission could occur and where the ability to increase ventilation is limited. Long ago, McLean (1961) presented data showing interruption of influenza transmission in a hospital setting. It has been estimated that upper-room GUV may reduce infection risk by an amount equivalent to doubling the ventilation rate (Noakes et al. 2015). Escombe et al. (2009) showed 77% reduction in human to guinea pig transmission in a hospital setting, while chamber based studies show the effectiveness of GUV against a number of bacterial aerosols (Xu et al. 2005; Xu et al. 2003; Yang et al. 2012). These concur with modelling studies (Gilkeson et al. 2013b; Noakes et al.

2004; Sung et al. 2010; Yang et al. 2012) showing that the effectiveness depends on the placement of the lamps relative to the ventilation flow and that addition of a ceiling fan enhances GUV effectiveness (Xu et al. 2013; Zhu et al. 2014).

Factors that must be considered when evaluating the ability of upper-room GUV to kill or inactivate airborne microorganisms include the sensitivity of the microorganisms to GUV and the dose received by a microorganism or population of microorganisms. GUV dose is the ultraviolet (UV) irradiance multiplied by the time of exposure and is usually expressed as $\mu W \cdot s/cm^2$. Well-designed upper-room GUV may be effective in killing or inactivating most airborne droplet nuclei containing mycobacteria if designed to provide an average UV fluence rate in the upper room in the range of 30 $\mu W/cm^2$ to 50 $\mu W/cm^2$, provided the other elements stipulated in these guidelines are met. In addition, the fixtures should be installed to provide as uniform a UVGI distribution in the upper room as possible (CDC/NIOSH 2009). A zonal infection risk model (Noakes et al. 2015) suggests that an upper-room GUV with a plane average irradiance of 0.2 W/m^2 at the UV fixtures could be comparable to increasing the ventilation rate from 3 to 6 ACH.

Portable consumer air cleaning devices may be beneficial in smaller rooms, although it should be recognised that such devices must be appropriately sized for the space (Miller-Leiden et al. 1996). There is wide variation in performance of air cleaners depending on air cleaner design and size of room in which it is used (Shaughnessy et al. 2006). A useful metric for determining performance is the clean air delivery rate, which is equivalent to the volumetric flow rate of particle-free air produced by the air cleaner (Foarde 1999). Kujundzic et al. (2006) reported air cleaners were similarly effective against removing both airborne bacterial and fungal spores from the air at clean air delivery rates of between 26 and 980 m^3/h corresponding to effective cleaning of between 5 and 189 m^3 room volumes respectively.

GUV ‘in-duct’ application within air-conditioning systems and ventilation ducts may also be a practical approach for disinfecting contaminated extracts or in cases where it is not possible to stop recirculation of ventilation flows (Kujundzic et al. 2007). However, these systems are of little benefit against person-to-person transmission when installed in the supply air of once-through systems that do not recirculate air within the space or building. The US Centers for Disease Control has approved both upper-room and in-duct systems for use in controlling tuberculosis transmission as an adjunct to HEPA filtration (CDC/NIOSH 2009).

v) Minimise the number of people within the same indoor environment in an epidemic

This measure is self-explanatory in the context of the need to lower the concentration of airborne virus-carrying particles, and reduce the number of people who can be exposed at any time. There is no one specific value for a number of people who could share the same space during pandemics, and this measure should be considered in conjunction with the engineering measures discussed above, and particularly in relation to the ventilation parameters of the space. Although the physical distance required to avoid transmission through direct contact dictates the requirements for the floor area per person, the rate of ventilation provided and the efficiency of ventilation are the parameters that control the concentration of virus-laden microdroplets in the air exhaled by the occupants, and will guide decisions on safe occupancy numbers. In a school or a supermarket, for example, if the number of infected students or shoppers is low, and the ventilation rate is high, the risk of airborne transmission can be low. Similarly, during an epidemic, reducing the number of people using public or private transport *at the same time*, e.g. in subway train systems or busses, is part of effective social distancing (Knibbs et al. 2012; Stopera et al. 2020).

Conclusions

Until effective pharmacological treatments or vaccines are available to reduce the effective reproductive number to less than 1.0 and stop the ongoing COVID-19 pandemic, enhanced ventilation may be a key element in limiting the spread of the SARS-CoV-2 virus. These are the key ventilation-associated recommendations (see Figure 2):

1) To remind and highlight to building managers and hospital administrators and infection control teams that engineering controls are effective to control and reduce the risks of airborne infection – and SARS-CoV-2 has the potential and is likely to be causing some infections by this route.
2) To increase the existing ventilation rates (outdoor air change rate) and enhance ventilation effectiveness - using existing systems.
3) To eliminate any air-recirculation within the ventilation system so as to just supply fresh (outdoor) air.
4) To supplement existing ventilation with portable air cleaners (with mechanical filtration systems to capture the airborne microdroplets), where there are areas of known air stagnation (which are not well-ventilated with the existing system), or

isolate high patient exhaled airborne viral loads (e.g. on COVID-19 cohort patient bays or wards). Adequate replacement of the filters in the air cleaners and their maintenance is crucial.

5) To avoid over-crowding, e.g. pupils sitting at every other desk in school classrooms, or customers at every other table in restaurants, or every other seat in public transport, cinemas, etc.

If implemented correctly, these recommended building-related measures will lower the overall environmental concentrations of airborne pathogens and thus will reduce the spread of infection by the airborne route. Together with other guidance on minimising the risk of contact and droplet transmission (through hand-washing, cleaning of hand-touch sites, and the appropriate use of PPE), these ventilation-related interventions will reduce the airborne infection rates not just for SARS-CoV-2 in the current COVID-19 pandemic, but also for other airborne infectious agents.

While much of the focus has been on case finding, isolation and quarantine, social distancing and hand hygiene, we emphasise that a parallel reduction in airborne transmission using such engineering controls in hospitals and other public buildings will further protect healthcare workers, patients and the general public.

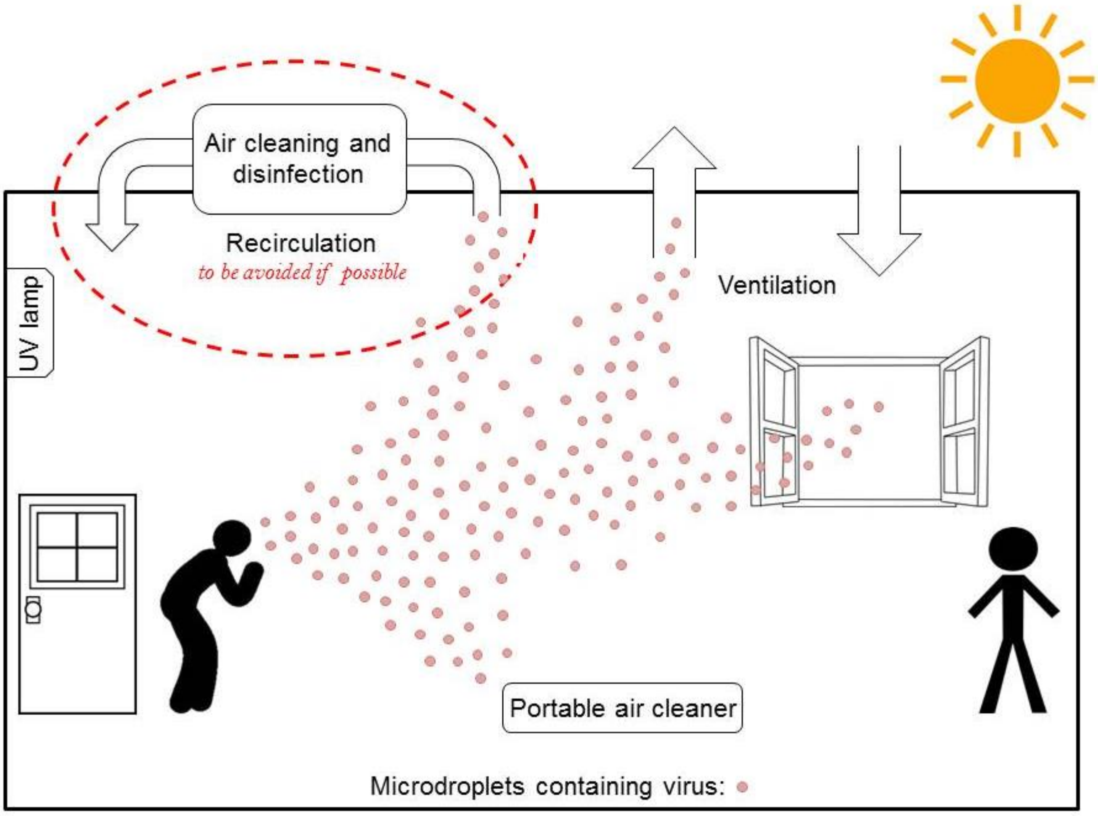

Figure 2. Engineering level controls to reduce the environmental risks for airborne transmission

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