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Effectiveness of portable air filtration on reducing indoor aerosol transmission: preclinical observational trials

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ARTICLE INFO

Article history:

Received 1 July 2021

Accepted 13 September 2021

Available online 23 September 2021

Keywords:

Aerosol transmission

Indoor ventilation

Air clearance rate

Portable air filtration



SUMMARY

Background: While the range of possible transmission pathways of severe acute respiratory syndrome coronavirus-2 in various settings has been investigated thoroughly, most authorities have recently acknowledged the role of aerosol spread in its transmission, especially in indoor environments where ventilation is poor. Engineering controls are needed to mitigate aerosol transmission in high-risk settings including hospital wards, classrooms and offices.

Aim: To assess the effectiveness of aerosol filtration by portable air cleaning devices with high-efficiency particulate air filters used in addition to a standard building heating ventilation and air conditioning (HVAC) system.

Methods: Test rooms, including a single-bed hospital room, were filled with test aerosol to simulate aerosol movement. Aerosol counts were measured over time with various portable air cleaning devices and room ventilation systems to quantify the overall aerosol clearance rate.

Findings: Portable air cleaning devices were very effective for removal of aerosols. The aerosols were cleared five times faster in a small control room with portable air cleaning devices than in the room with HVAC alone. The single-bed hospital room had an excellent ventilation rate (~14 air changes per hour) and cleared the aerosols in 20 min. However, with the addition of two air cleaning devices, the clearance time was three times faster.

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Conclusions: Inexpensive portable air cleaning devices should be considered for small and enclosed spaces in healthcare settings, such as inpatient rooms and personal protective equipment donning/doffing stations. Portable air cleaning devices are particularly important where there is limited ability to reduce aerosol transmission with building HVAC ventilation.

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Introduction

The range of possible transmission pathways of severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2) and their relative contribution in various settings is still being investigated [1,2]. Recently, most authorities, including the World Health Organization and the US Centers for Disease Control and Prevention, acknowledged the role of aerosol spread in the transmission of SARS-CoV-2. There is growing evidence that transmission via inhalation of aerosol particles plays a dominant role, especially in indoor environments where the ventilation is poor and airflow pathways direct virus-laden air towards people [3–7]. Engineering controls are needed to mitigate aerosol transmission in high-risk settings including hospital wards, classrooms and offices.

Background

Heating, ventilation and air conditioning (HVAC) systems provide fresh/filtered air to a room at a controlled temperature for human comfort. At standard rates in hospital wards, the air change rates provided by the HVAC system do little to mitigate the risk of aerosol transmission [8]. Numerous existing policies and guidelines have suggested the use of portable high-efficiency particulate air (HEPA) filters to improve indoor air quality [9–11], but there has been notably low uptake in the community.

Portable air cleaning devices with HEPA filtration clean the air of aerosols inside a room close to the infected person, providing source control, and improve the aerosol clearance rate beyond the HVAC system. It must be noted that all ‘air change’ methods are not equal from an infection control viewpoint, especially for control of aerosol transmission. The air exchange rate of an HVAC system is defined as the number of times that the volume of air in a room is replaced with fresh/filtered air introduced by the HVAC system in a given period. The commonly used measure of air changes per hour of an HVAC system (ACH_{HVAC}) is the ratio between the volume flow rate of the system (Q_{HVAC}) and the volume of the room (V):

$$ACH_{HVAC} = Q_{HVAC}/V$$

Portable air cleaning devices are designed to filter out aerosols (mainly intended for dust particles and other pollutants) from the air inside a room. Hence, the way that these devices provide ‘air changes’ and reduce the aerosol count in a room differs from HVAC systems: HVAC pushes the aerosol out of a room, while air cleaning devices filter out the aerosols from within the room. The air filtration rate per hour of a portable air cleaning device can be considered as equivalent air changes per hour (ACHE) [13], and defined in a similar way to ACH_{HVAC} :

$$ACHE = Q_{AirCleaner}/V$$

where $Q_{AirCleaner}$ is the volume flow rate of the air cleaning device [also known as the ‘clean air delivery rate’ (CADR)]. Both of these air change methods reduce aerosols in indoor environments such that, in practice, it is possible to combine the two, so air ventilation (ACH_{HVAC}) and air filtration (ACHE) rates can be added into a total air changes per hour (ACH) parameter for the purpose of infection control associated with aerosol transmission [12,13]. Thus:

$$ACH = ACH_{HVAC} + ACH_e$$

In this study, the single parameter ACH will be used to indicate the overall air change rate for reducing the aerosol count.

For practical purposes, predicting the clearance time for sufficiently high aerosol removal efficiency (e.g. >90% clearance) is important to control the risk of aerosol transmission. An equation to estimate the clearance time for a given clearance rate with increasing ACH ($ACH_{HVAC} + ACH_e$) for aerosol removal is given by:

$$t_2 - t_1 = -\frac{\ln(C_2/C_1)}{ACH} \quad (1)$$

where t_1 and t_2 are the initial and final time stamps, and C_1 and C_2 are the initial and final concentrations of aerosol. $t_2 - t_1$ is the clearance time with the assumption that aerosols are mixed homogeneously [14]. This clearance time can be used to investigate the effectiveness of air ventilation and filtration systems for a given ACH.

This study aimed to assess the effectiveness of several common portable air cleaning devices to reduce the aerosol particle count with simulated or actual building ventilation systems to demonstrate practical performance.

Methods

A full-sized ‘control room’ designed to replicate the size of a standard single bedroom or office was constructed in the Michell Hydrodynamics Laboratory at the University of Melbourne, Australia. The room was well sealed and blackened for experimental flow visualization purposes. The floor area of the room was 10.5 m² and the volume was approximately 24 m³. A schematic of the room is shown in Figure 1(a). A fan with a flow rate of 55 m³/h was used to deliver clean air (HEPA-filtered) through a ceiling duct, with a conical diffuser installed to simulate standard HVAC (hereafter referred to as ‘control room HVAC’). A single exhaust vent for the air to leave the room was installed close to the ceiling, replicating common practice in indoor spaces. This airflow rate was calculated to be equivalent to 2.3 ACH for the tested control room. For experiments with

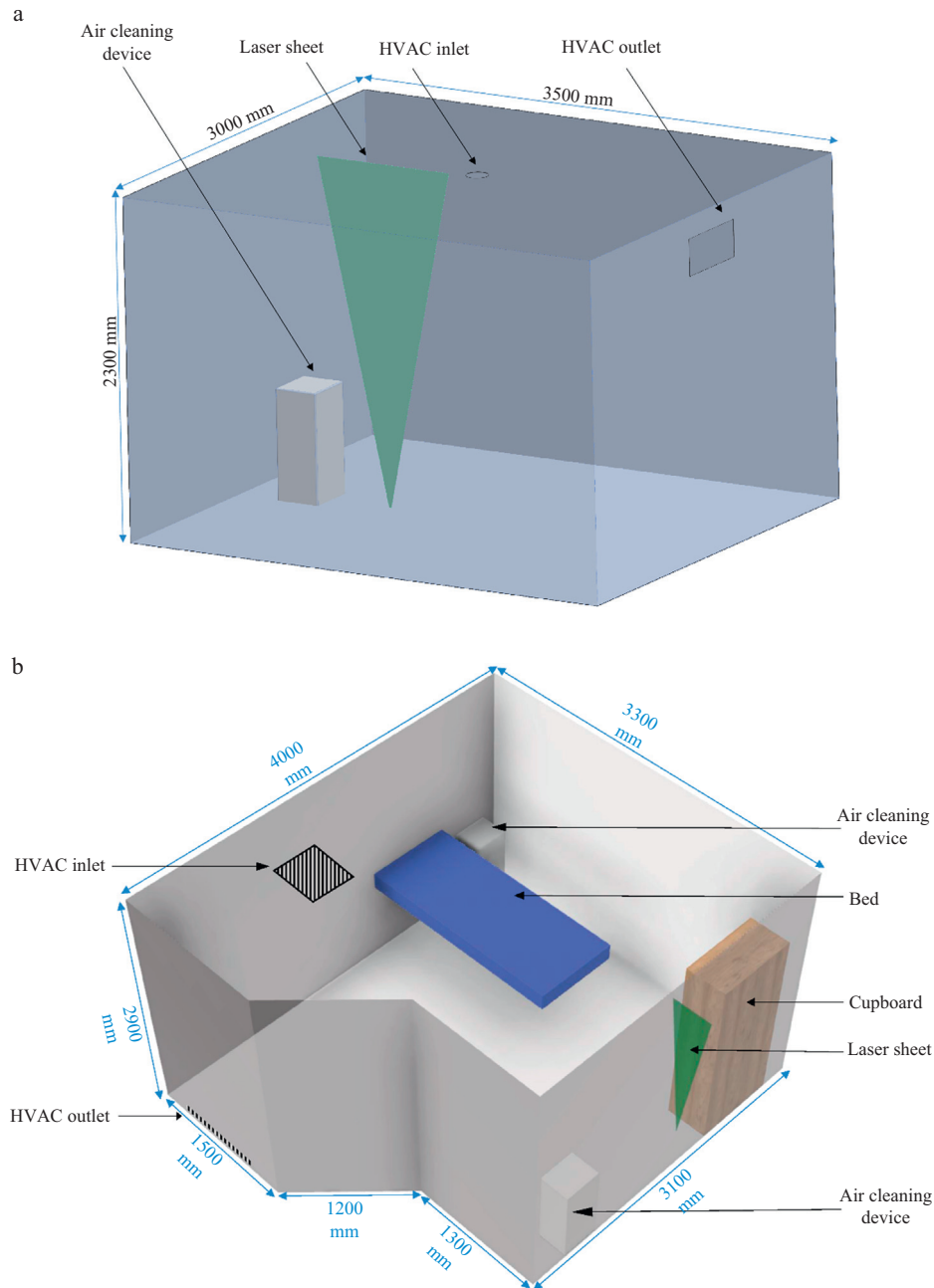


Figure 1. (a) Control room at the University of Melbourne and (b) room geometry and illustration of laser-based smoke measurement set-up in a single-bed hospital room. HVAC, heating, ventilation and air conditioning system.

an air cleaning devices, the portable unit was placed at one end of the room, as shown in Figure 1. A particle illumination technique with laser light was used to quantify the aerosol density in the room. The main purpose of this method is to acquire images of aerosol particles illuminated by the laser sheet. As each particle reflects laser light to a camera, the number of particles illuminated can be counted effectively (indirectly) by measuring the amount of light reflected by the particles within an acquired image. That is, a brighter image indicates that more particles are in the plane of the laser sheet and a darker image indicates fewer particles. A laser sheet was created using a 150-mW, 532-nm (green) laser and a cylindrical lens. A Canon XA40 digital camera was used as an imaging

device. This particle illumination method is identical to the particle image velocimetry technique which is widely used in experimental fluid mechanics [15], and is similar to the imaging system used by Bluysen *et al.* [16] to track aerosol counts. With no aerosols added to the control room, the aerosol particles were not visible through the camera, suggesting that the room was sufficiently clean of aerosol/dust particles prior to experimentation. Also, the preliminary measurement showed (not included here for brevity) that only the reflected light from particles within the laser sheet affect the brightness of the image (i.e. negligible light is absorbed by particles between the laser sheet and the camera). For all experiments, theatrical smoke (aqueous glycol solution; mean aerosol size 1 μm)

Table 1

Summary of experimental configurations and parameters including tested room volumes, air flow rates and air changes per hour (ACH)

Case	ACH=Q/V	Air flow rate or CADR, Q (m ³ /h)	95% clearance time (min)
Clean room measurements (V=24 m ³)			
1	Control room HVAC	2.3	55.1
2	Air Cleaning Device A	8.3	31.8
3	Air Cleaning Device B	16.7	12.2
4	Air Cleaning Device C	19.6	9.1
Hospital room measurements (V=37 m ³)			
5	Hospital HVAC	13.9	19.3
6	2 × Air Cleaning Device C and hospital HVAC	39.2	6.5

CADR, clean air delivery rate; HVAC, heating, ventilation and air conditioning system; Q, volume flow rate; V, room volume.

was injected for 15 s to introduce aerosol particles into the room. The smoke particles were used as tracer aerosols to investigate aerosol movement within the room. Once the smoke particles were injected, an additional 10-min waiting period was given for the smoke to mix and for transient flows due to injection to stabilize before each device was switched on and the experiments began. When aerosols were disseminated through the room, the images showed the green laser sheet lighting up the smoke particles. Over time, as the air cleaning devices or HVAC system cleared the smoke particles, the acquired images became less bright. The measured light intensity over a subregion of the images as a function of time was acquired, and the particle images were acquired until the illuminated aerosol was no longer visible by the camera.

The same method was then used in a single-bed hospital room at the Royal Melbourne Hospital, shown in Figure 1(b). The room floor space and volume were approximately 12 m² and 37 m³, respectively, and this room had an HVAC system

with 13.9 ACH (hereafter referred to as 'hospital HVAC'). This dataset was collected as part of a collaborative measurement campaign performed at the Royal Melbourne Hospital. Further details of the measurement campaign are available in Busing *et al.* [17].

Three commercial air cleaning devices with three different inlet flow rates were tested in the control clean room in the laboratory. The flow rates (i.e. CADR) were approximately 200 m³/h (Device A; Industrial Air Cleaner 1, Westaflex, Heidelberg, Australia), 400 m³/h (Device B; Industrial Air Cleaner 2, Westaflex) and 467 m³/h (Device C; Air Purifier AX60RR5080WD, Samsung Electronics, Seoul, South Korea). All tested air cleaning devices were equipped with standard HEPA filters capable of filtering 99.97% of particles >0.3 μm.

Based on laboratory testing, for the size of the hospital room, two air cleaning devices (both Device C) were required to achieve a comparable air filtration rate to the control room measurement with one air cleaning device (Device C). The air

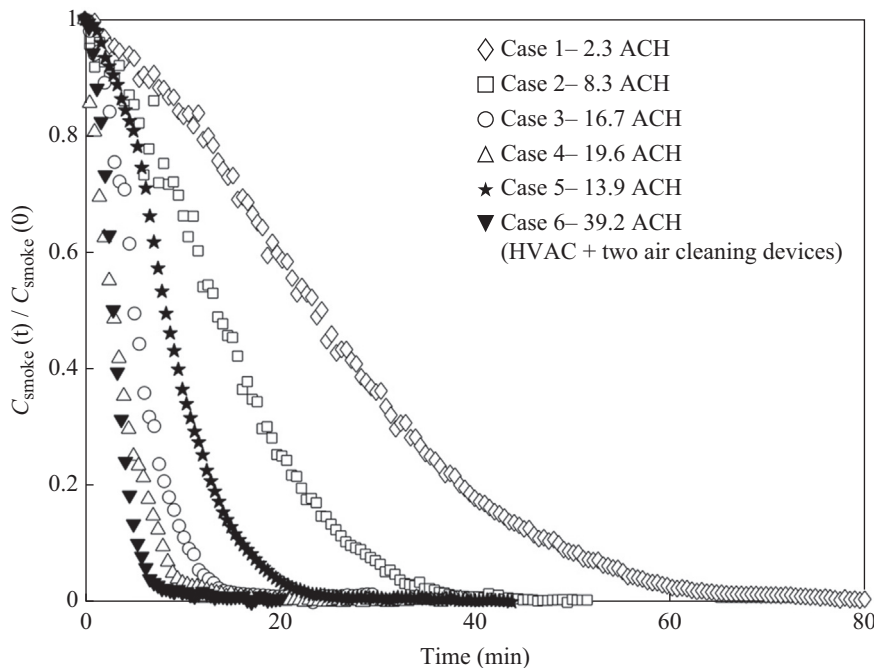


Figure 2. Decay in smoke particle density with time. Aerosol particle density, $C_{\text{smoke}}(t)$, is measured as light intensity of images acquired, and normalization is by the initial light intensity, $C_{\text{smoke}}(0)$, which is smoke particle density. The white and black symbols indicate the smoke concentration decay rate measured in the control room and the hospital room, respectively. ACH, air changes per hour; HVAC, heating, ventilation and air conditioning system.

cleaning devices were placed in regions that were close to a hospital bed and suspected to have poor air circulation by inspection. Contaminated particles could potentially stay in these regions longer than regions of the room with high circulation, increasing the risk of infection. Ethical approval for this study was obtained from the Office of Research Ethics and Integrity, The University of Melbourne.

Results

The configurations of the rooms tested are provided in Table I. Figure 2 shows the decrease in aerosol particle density, $C_{\text{smoke}}(t)$, as a function of time for a range of ACH. Taking the initial light intensity as a measure of the initial density of the smoke particles, $C_{\text{smoke}}(0)$, the intensity data in Figure 2 is computed by dividing the average light intensity associated with the number of illuminated particles at any given time by the initial intensity. Figure 2 shows a very clear decrease in aerosol clearance time with increasing ACH. This is important as it shows that the effect of the air cleaning devices is to increase the aerosol clearance rate at a given ACH.

To further assess the practical performance of the portable air cleaning devices for reducing aerosols, the aerosol clearance time as a function of ACH was employed. Figure 3 shows the experimental results (symbols) from both the control room and the hospital room for 63%, 90% and 95% clearances. The clearance time estimation profiles (lines) obtained from Eqn (1) at matched clearance rates to the experiments are plotted for comparison. The resulting clearance time from the experimental data clearly indicate that portable air cleaning devices with high flow rates (16.7 and 19.6 ACH) reduced the clearance time significantly. In the small control room, the aerosols were

almost completely cleared four to five times faster (<12 min) with portable air cleaning devices than the control room with the HVAC system alone (2.3 ACH). The low-flow-rate portable air cleaning device with 8.3 ACH (Case 3) was still significantly better than the HVAC system alone. The hospital room with an HVAC alone had a relatively high flow rate at baseline (13.9 ACH); however, when there were two air cleaning devices in the room (39.2 ACH in total), the clearance time was significantly improved to three times faster (<10 min).

Discussion

In this study, portable air cleaning devices were shown to be very effective for removing aerosols rapidly by providing high aerosol filtration rates in indoor spaces. The aerosol clearance time results shown in Figure 3 indicate that providing sufficiently high ACH for aerosol filtration (~25 ACH), which is not difficult to achieve with portable air cleaning devices, would reduce the aerosol clearance time significantly. Comparison of the clearance time between the estimations [computed using Eqn (1)] and the experimental results showed some discrepancy in the low ACH cases (ACH <15); however, the measured clearance times agreed reasonably well with the estimation when ACH was sufficiently high, such as Cases 4 and 6 with 19.6 ACH and 39.2 ACH, respectively. The discrepancy observed in the low ACH cases, such as Cases 2 (8.3 ACH) and 5 (13.9 ACH), could be due to the large flow recirculation regions – or ‘deadzones’ – set up in the room that traps the aerosols, delaying particle motion during clearance. These recirculation regions likely do not exist at extremely low ACH (e.g. Case 1 with 2.3 ACH) because the flow will be entirely laminar and, in any case, the logarithmic decay estimation may not hold at

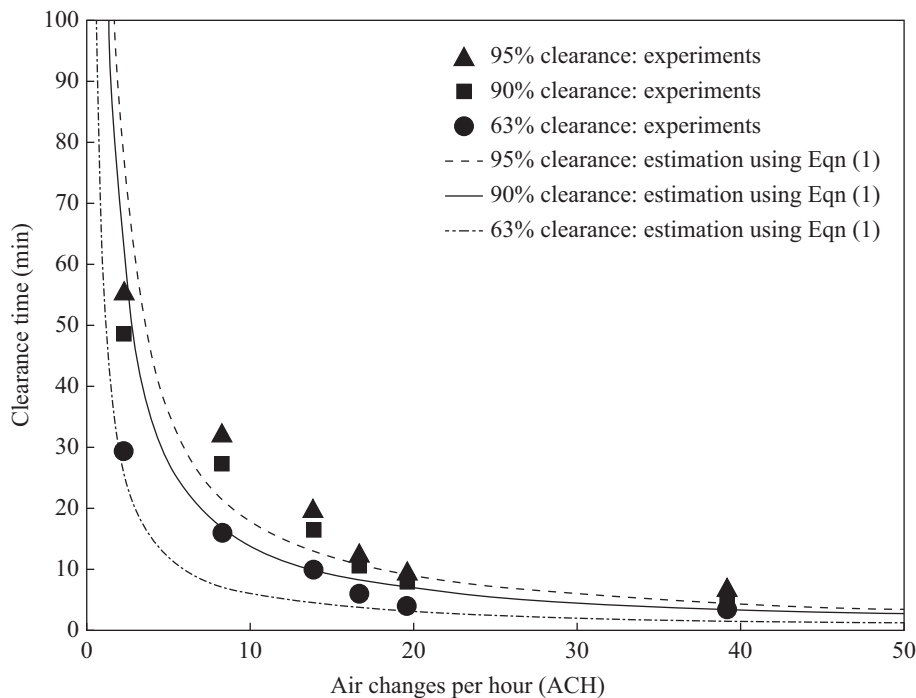


Figure 3. Clearance time as a function of air changes per hour with 63%, 90% and 95% clearance efficiencies. The symbols represent the experimental data for all the cases listed in Table I. The dashed, solid and dot-dashed lines show 63%, 90% and 95% clearance efficiencies, respectively.

such a low flow rate. This could be because the slow timescale processes such as condensation, leakage through small gaps and weak external pressure variations become relevant during such a slow clearance process. At high ACH, there is likely a sufficient flow rate for homogeneous mixing in a room, meaning no significant recirculation regions to delay clearance of the aerosols. When ACH is relatively low ($ACH < 15$), there is potentially imperfect mixing due to recirculation regions or other airflow anomalies, and aerosol mixing in the room improves with increasing ACH.

It is important to note that the hospital room HVAC system (13.9 ACH) remained on while the two air cleaning devices (25.3 ACH) were tested, which provided a total of 39.2 ACH (Case 6) when the 'air changes' rate of the HVAC system (ACH_{HVAC}) and two air cleaning devices (ACH_e) were simply combined. As discussed in the Introduction, these two types of air ventilation and air filtration methods are fundamentally different, such that air changeovers by the HVAC system and 'changeovers' by air cleaning devices are not directly equivalent. The role of an HVAC system is to first bring fresh/filtered air into a room, then circulate this heated/cooled air around a room before exiting it through, or towards, an exhaust vent, thereby pushing out any gaseous pollutants and/or aerosols. Air cleaning devices draw air from inside a room to filter out aerosols, and then release aerosol-free air back into the room; while this has the consequence of circulating air around the room, the devices are not designed for air circulation. In the case of both an HVAC system and air cleaning devices operating together, as the HVAC system circulates air around the room, the strong local flow fields generated by the air cleaning devices may capture the aerosols before they have the opportunity to travel out of the room. In some cases, it is possible that the rate of aerosol capture of the air cleaning devices could overwhelm the rate of aerosols pushed out of the room by the HVAC system. This would only occur when the flow rate of the air cleaning device is sufficiently high relative to the HVAC system. A similar explanation was suggested by Miller-Leiden *et al.* [12] based on the findings from their experiments. Further studies are required to prove this postulation but, if correct, this means that portable air cleaning devices are particularly beneficial in positively pressurized rooms (made positive by the design of the HVAC system) that, without such in-room cleaning, serve to push infectious aerosols outside a room, potentially reaching susceptible persons in hallways or nursing stations.

Using Eqn (1) to obtain the clearance time estimation profiles can serve as a useful estimation tool for predicting the clearance time for high clearance efficiency at high ACH, which accounts for mixing effects in a room with an inbuilt building HVAC system or portable air cleaning devices. However, caution should be used with such an assumption as this does not account for other airflow anomalies, such as airflow leakage via room entrances for room geometries that might differ significantly from the rooms studied here. The optimal inlet position of the portable air cleaning device varies depending on the configurations of individual spaces, but the inlet should be placed close to the source (e.g. patients with COVID-19) to capture a high concentration of human exhaled aerosol particles, and the return outlet of the portable air cleaning device where filtered air flows out should direct away from the source to mitigate the dispersal of aerosol. Also, it is recommended that a filter maintenance process for air cleaning devices

should be established in consultation with infection prevention personnel, especially for units used in the rooms of patients with respiratory diseases. As there is a high risk that these portable air cleaning devices and HEPA filters contain the infectious disease, appropriate guidelines for infection control, including personal protective equipment, must be followed to ensure their safe and effective use. Further work should include investigating a larger room with an assessment of multiple small air cleaning devices versus a smaller number of higher flow rate air cleaning devices, alongside a study to investigate the best placement of the devices.

In conclusion, standard rates of HVAC air exchanges alone are unlikely to provide sufficient aerosol clearance rates to control aerosol transmission, but relatively low-cost portable air cleaning devices can dramatically improve the clearance of aerosols in enclosed indoor spaces. Importantly, HVAC systems are designed to circulate air and relocate aerosols from one place to another, whereas air cleaning devices capture and contain the aerosols within the space where those devices are deployed. To clear a room of aerosols in < 10 min would require approximately 25 air changes per hour, which is difficult with an HVAC system but is feasible with air cleaning devices.

Conflict of interest statement

FM and JM filed a patent application for the personal ventilation hood by the University of Melbourne/Western Health. All other authors declare no conflict of interests. All authors confirm that the work was not funded in any way by either Westaflex or Samsung Electronics, and have no interest in the sale of any commercial air cleaning devices.

Funding

This work was funded by the University of Melbourne, Australia.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jhin.2021.09.012>.

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