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The effectiveness of air-cleaning technologies against COVID-19 transmission in healthcare settings

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Background: The healthcare setting is a high-transmission-risk environment for COVID-19. Attending clinicians and patients are at risk of infection if measures are not established to secure the microbial safety of the health facility. Air cleaning technologies may deliver a safer clinical environment by depleting airborne viral concentrations.

Aim: This systematic review aims to assess the effectiveness of air-cleaning methods in preventing COVID-19 transmission in health facilities and the effectiveness of air cleaning rated by microbial depletion.

Method: This study is a rapid systematic review.

Results: No study assessed COVID-19 transmission relative to the air cleaning methods. HEPA filtration produced a more rapid and thorough removal of aerosols from health facilities. HEPA filtration showed mixed performance in removing COVID-19 viral RNA from a routine care ward and an intensive care unit (ICU). Meta-analyses could not be conducted due to dissimilarities in included studies.

Conclusion: The reviewed papers demonstrate that HEPA filtration hastens the depletion of aerosols from the indoor space in the health facility. Further translation of this finding to prevent COVID-19 transmission should assume the relevance of room occupancy density, virus-free outdoor air supply, recirculated filtered air, virus source strength, number of sources, and the use of facemasks by health workers and visitors to the health facility.

KEYWORDS

air cleaning, aerosols, COVID-19, health facility, HEPA filter, indoor transmission

Introduction

The corona virus disease 2019 (COVID-19) was officially declared a pandemic by the World Health Organisation (WHO) in March of 2020 (1). The primary clinical manifestation of COVID-19 is a severe acute respiratory illness (2) which may progress to a viral pneumonia (3). The pathogen responsible for this disease is the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), a highly transmissible RNA virus.

The virion size is 60–140 nm (4). The dominant mode of transmission is by an inhalation of respiratory aerosols released by an infected person. Larger aerosols (5–

100 μm) and small aerosol ($<5 \mu\text{m}$) (5) entrain large numbers of SARS-CoV-2 particles. The viability of these particles depends on their physical transport and biological inactivation which in turn determine the integrity of their genomic material, nucleoprotein, capsid and envelope. The ambient temperature, humidity, and ultraviolet irradiation affect the stability, transportation, and inactivation of viruses (6, 7). Temperature and humidity also influence the ability of the deposited virus to establish an infection in a potential host. Aerosols in the lower size differentiation have higher residence time in the air. At 5 μm , aerosols can stay suspended in still air at a height of 1.5 m for up to 33 min, at 1 μm , aerosols can remain suspended for more than 12 h. Aerosols of 100 μm remain suspended for 5 s and can be dispersed over a distance of 1–2 m, depending on the local airflow velocity. The larger aerosols settle faster under the influence of gravity (5), but the smaller aerosols, which remain longer in the air, are transported across greater distances (8) depending on their size, the initial velocity of the air stream bearing the aerosols, outdoor windspeed or indoor air drafts. Smaller aerosols also exhibit different deposition characteristics from larger aerosols. Aerosols larger than 5 μm tend to be deposited in different parts of the nasopharynx, but smaller aerosols penetrate deeper down the respiratory tree to settle on the alveoli and bronchioles where SARS-CoV-2 has stronger potential to colonise tissues, multiply, and establish infection. Smaller aerosols have also been demonstrated to contain more viruses (7).

The healthcare setting is a high-transmission risk environment for SARS-Cov-2 because patients and healthcare workers interact mostly in enclosed indoor spaces where the recirculating air tends to concentrate viral particles (9). The proximity of healthcare workers to the patients during clinical care further enhances viral transmissibility. The availability of an infective source(s) (patients in clinics, isolation wards, treatment rooms) guarantees a sustained release of the virus into the surrounding spaces. The SARS-Cov-2 has been detected in aerosols as far as 3 meters from infected patients (10). Moreover, medical and surgical procedures performed on patients can facilitate an increased release of infective aerosols; these aerosol-generating procedures (AGP) reinforce the transmission risk within the health facility. Therefore, healthcare workers (HCW), visitors to the health facility, and other patients who are uninfected by SARS-CoV-2, are at greater risk of infection. In the health facility, there is also the additional risk of cross-infection with different variants of the virus which may cause infections with diverse clinical manifestations.

Reducing transmission risks in health facilities demands regular comprehensive decontamination of indoor hospital spaces (11). It has been recommended that rooms where COVID-19 patients have been managed and rooms used for AGPs be decontaminated between use for successive patients (12). This may involve a procedural mandate requiring these rooms to be left unused after an infected patient has received care until satisfactory decontamination is achieved (13). In addition to providing a safer indoor space in the health facility, decontamination protocols seek to prevent the outdoor egress of

SARS-Cov-2 and accordingly prevent the transmission of the virus in the precinct of the health facility.

Specific recommendations exist for health facility indoor ventilation which seek to, among other things, limit air movements in between service areas and departments; attenuate and eliminate microbial, chemical, radioactive, and odoriferous contaminations; maintain the temperature and humidity demands which are conducive to the operations of different spaces (ASHRAE 2019). An important distinction of the ventilation systems of health facilities in comparison with office complexes, public buildings, schools, and aircrafts, for example, is the principle of zoning. Zoning achieves different ventilation system specifications in different department. Therefore, regular patients wards, isolation wards, intensive care units, operating theatres, recovery rooms, treatment rooms, nurses' stations, laboratories, sterilizing rooms, and administrative offices differ in environmental circulation components (ASHRAE 2019). In addition, health facilities are unique because they operate throughout the day every day of the year, so their air dilution and corresponding energy demands are enormous.

To create safer indoor air-quality conditions in the health facility, different procedures, protocols, and technologies can be deployed to facilitate decontamination (12). Engineering technologies in health facilities are designed to achieve differential air pressure gradients between spaces, control directional airflow, filter delivered air and exhausts in order to improve microbial air quality (ASHRAE 2019) (9). The heating, ventilation and air-conditioning (HVAC) system can be set to allow unidirectional airflows into high infection risk rooms by creating negative air pressure in these rooms. The HVAC uses a system of fans, ducts, and pressure differentials between rooms to set the airflow rate, direction, controlled-room-air diffusion, and air exchange and dilution (14). The system segregates rooms based on these mechanisms and correspondingly prevents uncontrolled diffusion of air between rooms. The airflow rate, air diffusion, air mixing, and flow direction have to be calibrated to facilitate efficient particles (viruses, bacteria, fungi, aerosols, particulates) removal (15). Air volumes which exit these rooms can then be sequestered through a single exhaust to remove airborne pathogens (9). Particle-removal effectiveness can be improved by integrating HEPA filters and other purification technologies (16).

Highly-efficient particle arrestance (HEPA) filters (commonly known as high-efficiency particulate air filters) have been fixed to air duct vents or used in portable HEPA filter air cleaners to accelerate indoor attrition of particulate air pollutants. The same technology has shown promising efficacy against indoor airborne viruses (5, 17). The HEPA-filter mechanism can be integrated with air-flow streams and air diffusion patterns generated by the HVACs to promote the transport of airborne viruses to the filters and their subsequent removal. Ultraviolet (UV) irradiation (18), ozone fumigation (19) can be used separately, as an alternative to HEPA filtration, or combined with HEPA filtration to inactivate airborne or trapped viruses and surface-impacted viruses (20).

The HEPA filters are composed of multiple layers of interlaced microfibers which trap airborne particles as air currents diffuse

between the fibres. These filters have a 99.97% removal rate for size-segregated particles of 0.3 μm in diameter (17). Particles are removed by the combined mechanisms of impaction, interception, and diffusion. The mechanism largely depends on the particle size (17). Removed particles adhere to the filter microfibres by electrostatic attraction, capillary action and Van der Waals forces (5). The removal efficiency of these filters is rated using the Minimum Efficiency Reporting Values (MERVs) metric. The MERV rating expresses a filter's ability to trap and retain particles within the size range of 0.3–10 μm . The HEPA filter typically has a MERV rating ≥ 13 (15). Other air purification technologies, such as ultraviolet irradiation (21) and ozone fumigation are adapted to air cleaning because of their germicidal properties. These methods inactivate viruses by damaging their nucleic acids and biomolecules. Ultraviolet irradiation releases energy which denatures the genomic structure of the virus (18) while ozone releases free radicals which initiate a damaging powerful oxidizing action (22).

At the height of the COVID-19 pandemic, the morbidity and hospitalisation rates from this infection imposed such an extraordinary burden on the healthcare resources and manpower to the extent that admission to hospitals for in-patient care was selective. Persons with mild to moderate infection had to self-isolate at home. Healthcare workers faced the composite risk of acquiring the infection and the relentless workload. The WHO acknowledged the challenge the pandemic presented to human health and development; in particular, the threat to health-sector manpower. The year 2021 was therefore designated as the International Year of Health and Care Workers (YHCW) (23). Even as COVID-19 has evolved into an endemic infection, the imperative to guarantee indoor safety of the health facility and the protection of healthcare workers and patients from threats of local transmission justifies this systematic review of air cleaning methods. This review aims to assess the effectiveness of physical and chemical air purification methods (intervention) in preventing SARS-CoV-2 transmission in the health facility and compare them with equivalent ventilation provided by natural or mechanical modes (control). A secondary objective is to assess the effectiveness of air cleaning in health facilities.

Methods

Eligibility criteria

Criteria for including studies in this review:

Types of studies

This protocol (24) proposed to include studies which assessed incident SARS-CoV-2 infection rates in health facilities where air purification methods were used and compared these with control facilities without air cleaning. The proposed study designs were cohort studies, interrupted time series, and case-control studies. The electronic search did not reveal any study with these designs. We included experiments which compared the effectiveness of air-cleaning in the health facility to the more customary

mechanical or natural ventilation. The rationale for this was that, although numerous studies exist whose investigators assessed the air cleaning effectiveness of HEPA filter-based devices, a significant proportion of these studies were conducted outside of the health facility in laboratories, rooms, offices, or other types of buildings.

Recommendations exist for health facility indoor ventilation, some of which apply to specific areas of the hospital such as the operating theatre. These recommendations were developed with the aim to guarantee indoor comfort in the health facility as well as safety from microbial contamination. An assessment of the microbial-depleting efficacy of air cleaners in buildings designed with different ventilation objectives in mind or in experimental chambers where the ventilation settings maximise the air-cleaning performance, is unlikely to represent the functionality of these air cleaners in real-world healthcare settings. The studies included in this review were mostly “before and after” studies with self-control or “before and after” studies with parallel control.

Types of participants

We proposed to assess the differential transmission risk experienced by health-workers and in-patients in relation to the presence or absence of air-cleaning devices. As electronic searches did not reveal studies which examined transmissions, we could only focus on studies which assessed the effectiveness of different air cleaning technologies in healthcare settings such as hospital wards, dental hospitals, dental clinics, operating theatres, and treatment rooms.

Types of interventions

From the search results, the interventions which met the inclusion criteria were those in which HEPA filters in portable or fixed air-cleaning systems were used either alone or in combination with other air cleaning technologies. The comparators were mechanical or natural ventilation which met acceptable indoor air quality (IAQ) standards.

Types of outcome measures

Primary outcomes

The proposed primary outcome measures were the incidence rates of COVID-19 in healthcare workers and patients who were under admission for some other disease, and prevalence rates of COVID-19 infections in healthcare workers. No studies examined this outcome.

Secondary outcomes

The secondary outcome measure was the air cleaning effectiveness of the methods used in primary studies. We, therefore, examined the removal rate/efficacy of viruses from the indoor air.

Information sources and search strategy

On the 5th of September, 2022, we searched the following databases: The Cochrane Library—Central Register of Controlled

Trials (CENTRAL) and Cochrane Database of systematic reviews; MEDLINE and EMBASE. In addition to these databases, we also assessed the references of all included studies for studies which met the inclusion criteria.

We applied no date or language restrictions to our search and we used the PRISMA guideline and flow diagram to report the search process and selection of studies. The search strategy included text words and controlled vocabulary for air cleaning/purifier technologies and Corona Virus Disease such as: “High Efficiency Particulate Arrestance”, “High Efficiency Particulate Air”, “Clean Air Delivery Rate”, “Heat Recovery Ventilator”, “Energy Recovery Ventilator”, HVAC, HEPA, ultraviolet, ozone, air filter, “COVID-19”, “SARS-CoV-2”, “Severe Acute Respiratory Syndrome Coronavirus 2”, “NCOV”, “2019 NCOV” and Coronavirus. For search strategy (MEDLINE) and terms used, see [Supplementary S1](#).

Selection process

Study titles and abstracts from the search results were independently screened by two pairs of reviewers (C.E. and M.B.; M.C. and V.M.B.) using the eligibility criteria. Studies selected from the screening, or studies, which did not provide sufficient information to support an inclusion decision, were retrieved in full text for further assessment. The authors independently applied the inclusion criteria to the full-text reports using a pre-tested eligibility form. Publications were scrutinized to eliminate duplicated reports. The teams resolved disagreements between author pairs by broad discussions leading to consensus among team members. Excluded studies and the reasons for their exclusion were listed in a table.

Data collection process

We extracted data on the author names and year of publication, study title, status of study (published, unpublished), study objectives, study location, study design, type of health facility, and reference to coronavirus disease (covid-19, covid, sars-cov-2, 2019-ncov, coronavirus disease). We also extracted data on the type of room ventilation (natural or mechanical), meteorological conditions in the room (principally temperature and relative humidity), air exchange rate, medical procedure (which were likely to generate aerosol), artificial aerosol-generating procedure, type of intervention and implementation of co-interventions, air sampling techniques and analysis methods, duration of air sampling, outcome metric.

Two author pairs (C.E. and M.B.; M.C. and V.M.B.) independently extracted data using a customised and pre-tested data extraction form. Disagreements were resolved by discussions between all review authors. For each outcome the authors extracted either the air sampling metric with the corresponding standard deviation or surface sampling metric with standard deviation. We extracted results for both the intervention arm, and the comparator arm if that was available.

Risk of bias assessment

The author pairs independently assessed the risk of bias of each included study using a “Risk of bias” (ROB) assessment tool. Disagreements between author pairs were resolved by the lead author. It is notable that no epidemiologic study was retrieved and the included studies were interventional exposure assessment experiments. The risk of bias assessment tool was adapted from the Risk of Bias Assessment Instrument for Systematic Reviews Informing WHO Global Air Quality Guidelines (25) and the Principles and Framework for Assessing the Risk of Bias for Studies Included in Comparative Quantitative Environmental Systematic Reviews (26).

The risk of bias was assessed in 4 domains: performance bias, exposure assessment, confounding, and selective outcome reporting. Each domain had 1–5 subdomains which were represented by questions designed to elicit the pertinent methodological detail. Judgement calls of “yes”, “no”, and “unclear” were made to indicate a low, high, or unclear (moderate) risk of bias. If any subdomain was rated “unclear”, the entire domain was rated as having an unclear risk of bias if no rating of high risk of bias was made. However, if any subdomain had a rating of a high risk of bias, the entire domain was rated to have a high risk of bias regardless of other subdomains ratings. If the study had any domain rated as having a high ROB, then the entire study was rated as having a high ROB despite the ratings of other domains. Similarly, a study had a rating of unclear or moderate ROB if at least one domain was rated as being of moderate ROB, but none was rated as having a high ROB. A study was rated as being of low ROB if all the domains had low ROB.

Effect measures

The measures of intervention effect varied across studies. In general, these metrics measured the rate and extent of depletion of SARS-CoV-2 viral particles or aerosols of human origin or their proxies. They included: the elimination of SARS-Cov-2 RNA; the rate of reduction of aerosol concentration to 1% of baseline maximum; percent reduction of particle concentration; clearance time for 95% of the aerosol concentration; percent reduction in aerosol concentration at 6 min and 12 min; and particle decay constant. In papers where investigators used measures which had similar labels, sometimes the mathematical equations for deriving those measures were different.

Synthesis methods

Dissimilarities in methodology and outcome metrics in the included studies prevented a meta-analysis of outcome measures. Furthermore, most of the studies provided only descriptive outcome measures without an inferential test statistic which

assessed outcome differences between the intervention and control arms.

Reporting bias assessment

We checked to see if there were unexplained omissions of results from analyses which were mentioned in the methods section of the primary studies but were not accounted for in the results, discussion, or supplements.

Certainty assessment

The certainty of findings was assessed using the Grade Profiler (27).

Results

Search results

The electronic search yielded 3,063 references; from these 936 duplicates were removed. A further 2107 studies were removed by screening of titles and abstracts leaving 20 studies for full-text retrieval. Thirteen of these studies did not meet the inclusion

criteria; only seven were suitable for data extraction. No additional studies were included from an assessment the references in the included studies (Figure 1). None of the included studies assessed the primary outcome of this systematic review which is the COVID-19 transmission change in the health facility due to air-cleaning.

Study selection

The included studies were conducted in Australia, China, Italy, Saudi Arabia, the United Kingdom, and the United States of America. All included studies used the before and after design. Thus, the pre-implementation arm of the study was the control, while the post-implementation arm was the intervention phase. Only one study (28) had a parallel control.

Three of studies were conducted in dental-care facilities, and three in designated COVID-19 hospital wards, including an intensive care unit (29). One study was conducted in an ambulatory clinic. Five of the studies used portable air cleaners (PAC) while two studies used fixed air cleaners. All air cleaners were fitted with HEPA filters, but one study used a HEPA-fitted PAC in combination with a ultra-violet (UV) sterilizer. Further details of the included studies are provided in Table 1.

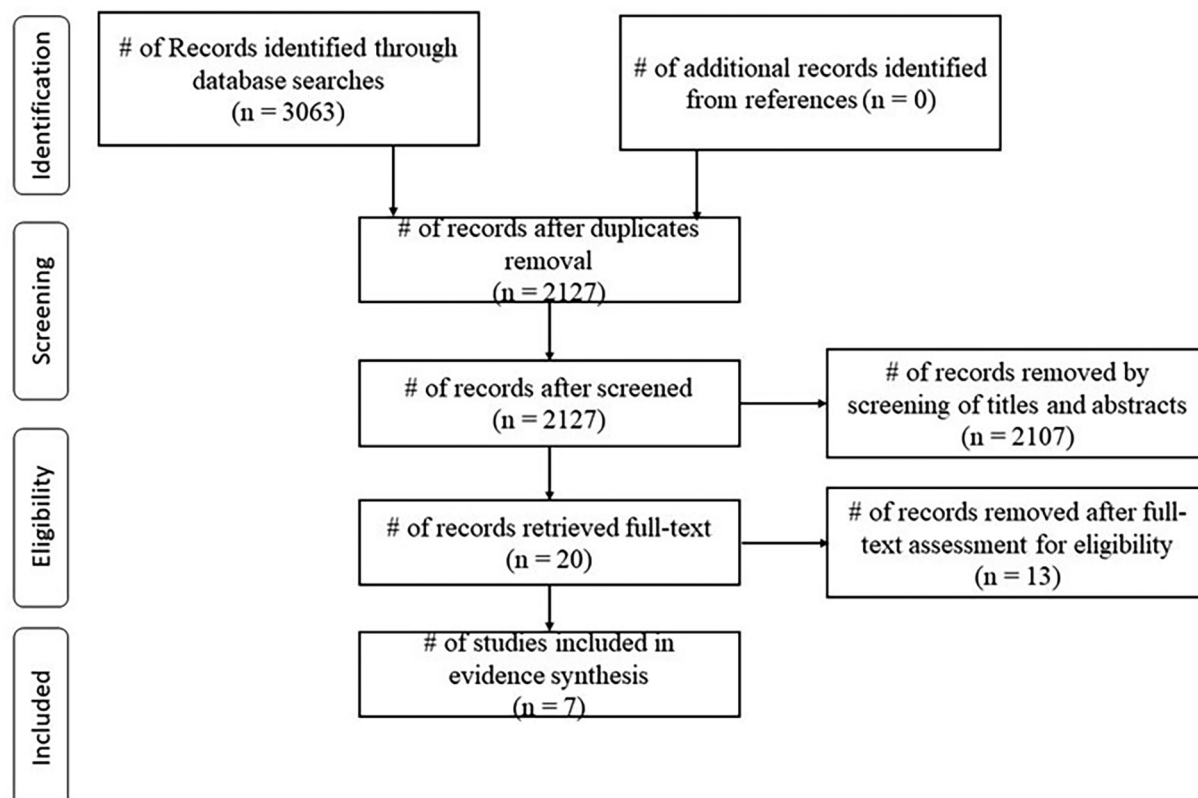


FIGURE 1
The flow diagram for study inclusion.

TABLE 1 Characteristics and results of included studies.

Study ID	Study Objective	Study design	Aerosol Generating Procedure	Intervention	Outcome(s)	Estimates	Notes
Buising 2021	To assess the airflow, transmission, and clearance of aerosols in COVID-19 wards in a hospital, with and without use of PAC	Exposure assessment: Before and after design	Experimentally generated glycerine-based aerosol smoke with a mean diameter of 1 μm	Samsung air cleaners equipped with H13 HEPA filters. Control: Self-controlled; aerosol clearance with HVAC	Reduction rate to 1% of baseline maximum (minutes)	Intervention: 5.5 min Control: 16 min	Location: Melbourne, Australia; Date: December, 2020; Setting: COVID-19 ward in a University hospital.
Cappare 2022	To evaluate the effectiveness of PAC devices with HEPA 14 filters in microbial abatement.	Exposure assessment study: Before and after design	Dental procedure and surgery	PAC with HEPA 14 filter. Control: Self-controlled, aerosol abatement by HVAC system implied.	% reduction in aerosol concentration	Intervention: 49%–73% reduction during professional dental hygiene activity; 76%–83% during simple surgery procedure from levels obtained during control phase after 60 min. Control: N.A.	Location: Milan, Italy; Setting: Dental department (clinic and surgery) of a hospital; Duration of sampling: 60 min
Lee 2022	To assess the effectiveness of aerosol filtration by PAC with HEPA filters in addition to a standard HVAC system	Exposure assessment study: Before and after design	Theatrical smoke made by aerosolising aqueous glycol solution with mean aerosol diameter of 1 μm	Two industrial air cleaners equipped with HEPA filters. Control: Self-controlled; aerosol abatement with HVAC	Clearance time of 95% aerosol concentration	Intervention: 6.5 min Control: 19.3 min	Location: Melbourne, Australia; Setting: COVID-19 ward in a University hospital.
Morris 2022	To assess the elimination of SARS-CoV-2 by portable air filters and UV light	Exposure assessment: Before and after design	Not applicable	Continuous air cleaning using a portable air cleaner fitted with HEPA13 filter and UV sterilizer. Control: Self-controlled, natural ventilation	Elimination of SARS-Cov-2 RNA from indoor air	Intervention: No virus was detected in the ward during the 5 days of viral RNA testing in the week the filter on. But, In the ICU there was viral detection in the week the filter was in operation. Control: SARS-CoV-2 RNA was extracted every day for the entire week when the air filter was absent from the ward. In the ICU, no viral RNA was detected in the week the air filter was absent.	Location: Cambridge/UK; Date: 18th January–5th February, 2021; COVID-19 wards and ICU in a University hospital; Duration of sampling: 6 h daily.
Pirkle 2021	To evaluate the efficacy of PACs fitted with HEPA filters	Exposure assessment: Controlled before and after design	Glo Germ (Glo Germ Moab, UT) powder aerosolized using a DeVilbiss Powder Blower	PAC fitted with HEPA filters. Control: Parallel control. Examination rooms with only HVAC system	Average percent reduction at 6 and 12 min (%)	Intervention: <i>Room centre</i> : 92.71% and 99.49% at 6 and 12 min, respectively. <i>Room corner</i> : 95.99% and 99.47% at 6 and 12 min, respectively. Control: Not reported	Location: Georgia, USA; Setting: Outpatients exam rooms of an ambulatory clinic; Duration of sampling: 6 min and 12 min
Ren 2021	To assess the effectiveness of aerosol removal by mechanical ventilation and a portable air cleaner (PAC) with a HEPA filter	Exposure assessment: Before and after design	Suspended particles experimentally generated by burning of incense	PAC with 360 degree circular HEPA filter. Control: Self-controlled. Aerosol abatement by HVAC system.	1) Average concentration of aerosols (0.3 μm) post-intervention; 2) Particle (0.3 μm) decay constant.	Intervention: 1) Average concentrations of 0.3 μm aerosol particle = $1.0 \times 10^7/\text{m}^3$ after 30 min of observation; 2) Particle decay constant = 25.8 ± 7.7 Control: 1) Average concentrations of 0.3 μm particles at baseline = $9.6 \times 10^5/\text{m}^3$ after 30 min of observation; 2) Particle decay constant = 10.7 ± 7.7	Location: Rochester, USA; Setting: Dental hospital; Duration of sampling: 30 min.
Zhao 2020	To assess the efficacy of air purifiers as a supplementary protective measure in dental clinics and units for organized emergency dental care	Exposure assessment: Before and after design	Not applicable	Air purifier integrated with HEPA, H12 class, filter. Control: Self-controlled. Ventilation type was not reported.	% reduction in aerosol concentration	Intervention: 83% reduction in aerosol concentration compared to levels seen when the PAC was absent.	Location: Beijing, China; Setting: Dental clinic. The mode of ventilation in the control arm was not stated.

Twelve studies were excluded in total. Three excluded studies were conducted outside the healthcare setting. Three others were authors' viewpoints and reports expressed in letters to the Editor, while three studies examined the efficacy of air cleaning against other microbial organisms (bacteria and bacteriophages). Two studies were computational fluid dynamic studies, one study was a methodological proposal, and another was a systematic review. A list of the excluded studies and justifications for the exclusion is presented in [Supplementary S2](#).

Risk of bias in studies

An assessment of the risk of bias in the included studies is presented in [Table 2](#).

Reporting bias assessment

One study (28), contrary to the stated methods, only reported results for the intervention arm but omitted results for the control arm. Another study (30) described the mode of ventilation in the intervention phase of the study, but omitted similar information for the control phase of the study.

Results of individual studies

We present the secondary outcomes of this systematic review in relation to comparisons made in the primary studies:

- I. Air filter use vs. mechanical ventilation
- II. Air filter + U.V. sterilization vs. natural ventilation
- I Air filter use vs. mechanical ventilation

1. Rate of reduction of aerosol to 1% of baseline maximum concentration

This outcome was assessed in one study (31). The aerosol concentration dropped to 1% of the baseline maximum in 5.5 min in the intervention arm of the study while the control arm achieved similar abatement in 16 min.

2. Average percent reduction at 6 min and 12 min of sampling

In the intervention group, the mean aerosol decrease at 6 min was 92.71% in the centre of the rooms and 95.99% in the corner of the rooms. The mean decrease at the 12 min mark in the centre and corner of the rooms were 99.49% and 99.47%, respectively. Results from the control phase were unreported (28).

3. Percent reduction in aerosol concentration

The authors recorded about 49%–73% reduction of particles during professional dental hygiene activity and 76%–83% reduction during simple surgical procedures compared to the levels obtained without air cleaning (32).

4. Clearance time of 95% of aerosol concentration

In the intervention arm of the study, 95% aerosol clearance was achieved in 6.5 min, but in the control arm of the study, this was achieved in 19.3 min (33).

5. Aerosol abatement after 30 min of sampling

In the intervention group, the average concentrations of the 0.3 μm aerosol particle observed after 30 min was $1.0 \times 10^7/\text{m}^3$, and $9.6 \times 10^5/\text{m}^3$ for the control arm (34).

6. Particle decay constant

The study referenced above (34) also assessed the particle decay constant. In the intervention arm, this was 25.8 ± 7.7 , against 10.7 ± 7.7 obtained in the control arm.

II Air filter + U.V. sterilization vs. natural ventilation

1. Elimination of SARS-Cov-2 RNA

Only one study (29) assessed this outcome. The SARS-CoV-2 RNA was extracted everyday in the first week of sampling, when the air filter was absent from the ward. The viral RNA extraction tests yielded no virus in the second week of sampling during which the PAC filter was operational. The viral RNA could not be extracted in the third week when the PAC was placed in the ward but wasn't operational.

In the intensive care unit (ICU), air sampling results were contrary to what was obtained in the wards. The SARS-CoV-2 RNA could be detected during the intervention week but was indeterminate during the control week.

Zhao and colleagues (30) assessed the filtration efficiency of PAC expressed as percent-decrease in aerosol concentration from the control phase. There was an 83% reduction in aerosol concentration post-intervention compared to the control aerosol levels. This study did not specify the mode of ventilation in the control arm; therefore, it could not be placed in any of the comparison categories.

Certainty of evidence

The quality of evidence from these individual studies was low, firstly because of the indirectness of evidence which was a limitation in every study. Secondly, the majority of included studies appeared to base their results on just one reading from their experiment. The absence of a distribution of readings from these studies minimized our confidence in the representativeness of their findings. Thirdly, incomplete reporting of results was noticeable in several studies. Some studies completely omitted results for the control arm of the experiment. In reporting a diminished viral or bioaerosol count from the pre-intervention to post-intervention, completeness of reporting requires stating absolute pollutant levels for both arms of the study ([Table 3](#)).

Discussion

We found studies which examined different metrics representing partial, total, or time-bound clearance of airborne aerosols or viral RNA as a consequence of HEPA filtration. In general, conclusions from individual studies seem to suggest a faster or more effective clearance of aerosols by HEPA-filtration in comparison with mechanical or natural ventilation. Air cleaning by filtration produced a higher particle decay constant and higher percent clearance per unit of time. Viral RNA was

TABLE 2 Risk of bias assessment.

Domains	Sub-domains	Buising 2021	Cappare 2022	Lee 2022	Morris 2022	Pirkle 2021	Ren 2021	Zhao 2020
Performance bias	1. Were the research questions or objectives clearly stated?							
	3. Was the intervention (independent variables) clearly defined, valid, reliable, and implemented consistently across all study units?							
	4. Was the timeframe between intervention and outcome sufficient to reasonably expect to find an association between intervention and outcome?	The duration of monitoring was not stated		The duration of monitoring was not stated				The duration of monitoring was not stated
Exposure assessment	5. Were the intervention(s) of interest measured prior to the outcome(s) being measured? ("outcome" could be either a health outcome or an environmental sample)							This detail was not provided
	6. For interventions that can vary in amount or level, did the study examine different levels of the interventions relative to the outcome? (e.g., use of one or more air purifying technology to determine virus or respiratory droplets removal efficacy)	Only one setting of the intervention was used			Only one setting of the intervention was used			Only one setting of the intervention was used
	7. Was the intervention(s) assessed more than once over time?	The outcome was assessed just once	The outcome was assessed just once	The outcome was assessed just once		The outcome was assessed just once	The outcome was assessed just once	The outcome was assessed just once
	8. Was there a control group? For before and after studies, the arm before the intervention is the control group.							
	11. Were appropriate experimental methods used and adequately described? Was the method valid and verifiable? (e.g. quality assurance/quality control procedures reported, calibration of detection system, storage and transfer of samples, model validation, risk of bias reported, or other steps taken to assure quality)							Key details on the methodology were unreported
Confounding	12. Were key potential confounding variables measured and taken into account? E.g. Room conditions (temperature, humidity, air exchange rate, room volume)	Temperature and relative humidity were not reported		Temperature and relative humidity were not reported	Temperature, relative humidity, and room dimensions were not reported	Temperature and relative humidity were not reported		Temperature, relative humidity, and room dimensions were not reported

(Continued)

TABLE 2 Continued

Domains	Sub-domains	Buising 2021	Cappare 2022	Lee 2022	Morris 2022	Pirkle 2021	Ren 2021	Zhao 2020
Selective reporting	9. Was the study outcome clearly stated prior to obtaining results? E.g. outcome measures (dependent variables) clearly defined, valid, reliable, and implemented consistently across all study units?							
	10. Was the outcome adequately reported? E.g. the environmental (air or surface) concentration of viruses or aerosols before and after intervention				The outcome was not reported for the control group	The outcome was not reported for the control group		The outcome was not reported for the control group
		Low risk						
		Unclear						
		High risk						

TABLE 3 Summary of findings Table.

[Equivalent ventilation using air cleaning technologies] compared to [Natural or mechanical ventilation] for [Preventing transmission of SARS-CoV-2 in health facilities]			
Patient or population: [Preventing transmission of SARS-CoV-2 in health facilities]			
Setting: Healthcare facilities			
Intervention: [Equivalent ventilation using air cleaning technologies]			
Comparison: [Natural or mechanical ventilation]			
Outcomes	N ^o of participants (studies) Follow-up	Certainty of the evidence (GRADE)	Impact
Rate of reduction to 1% of baseline maximum (Reduction to 1% of baseline)	(1 observational study)	⊕○○○ Very low ^{a,b}	5.5 min for aerosol concentration to drop to 1% of baseline maximum in the intervention group; 16 min in the control group
Percent reduction in aerosol concentration (% reduction)	(2 observational studies)	⊕⊕○○ Low ^{c,d}	Study 1: 49–73% reduction during professional dental hygiene activity and 76–83% during simple surgery procedure from levels obtained when the PAC was off. Study 2: 83% reduction in aerosol concentration in the intervention arm, no results for the control arm
Clearance time for 95% of aerosol	(1 observational study)	⊕⊕○○ Low ^{b,c}	95% aerosol concentration cleared in 6.5 min during intervention and 19.3 min in the control phase.
Elimination of SARS-CoV-2 RNA from indoor air	(1 observational study)	⊕⊕○○ Low ^{d,e}	In wards: Intervention arm—no virus detected during 5 days of sampling with filter on; Control arm—viral RNA detected everyday for 1 week. In the ICU, detected SARS-CoV-2 RNA in the intervention phase, but limited evidence of airborne SARS-CoV-2 in ICU in the control phase.
Percent decrease in aerosol concentration at 6 min and 12 min	(1 observational study)	⊕○○○ Very low ^{a,b}	Intervention group: the mean decrease at 6 min in Zones A (centre of the room) and B (corner of the room) was 92.71% and 95.99%, respectively. The mean % decrease at the 12 min mark for Zones A and B were 99.49% and 99.47%, respectively. No reports for the control phase.
Particle decay constant	(1 observational study)	⊕○○○ Very low ^{b,c}	Intervention group, average concentrations of the 0.3 μm aerosol particle = $1.0 \times 107/\text{m}^3$ after 30 min of observation, particle decay constant = 25.8 ± 7.7 ; for the control arm, average concentrations of the 0.3 μm particles = $9.6 \times 105/\text{m}^3$ after 30 min of observation, particle decay constant = 10.7 ± 7.7 .
GRADE Working Group grades of evidence			
High certainty: we are very confident that the true effect lies close to that of the estimate of the effect.			
Moderate certainty: we are moderately confident in the effect estimate: the true effect is likely to be close to the estimate of the effect, but there is a possibility that it is substantially different.			
Low certainty: our confidence in the effect estimate is limited: the true effect may be substantially different from the estimate of the effect.			
Very low certainty: we have very little confidence in the effect estimate: the true effect is likely to be substantially different from the estimate of effect.			

Explanations

^aDifferent levels of the intervention were not reported, the intervention effect was assessed just once, and the outcome was inadequately reported.^bDid not measure reduction of viral RNA, and a proxy was used for aerosols.^cIntervention was assessed only once, no replicates.^dMeasured bioaerosols used as proxy for virus.^eIntervention effect was assessed only once and the outcome was inadequately reported.

found to be absent in a routine care ward when air filtration was implemented, but paradoxically, viral RNA was detected in the ICU despite the integration of HEPA-filtration with U.V. sterilisation.

Transmission by aerosols and indirectness of data

None of the included studies investigated human transmission as an endpoint of the intervention. Only one investigator looked at the impact of air cleaning on SARS-CoV-2 RNA airborne concentration. Airborne viruses are transmitted in aerosols and droplets which escape from the respiratory passages of infected persons. To wit: the aerosol concentration would be a proxy for viral levels, but the closeness of this approximation is uncertain. Subtypes of viable viruses may differ with regard to their infectivity (dose-response relationship) (35), while the current state of health and specific immune resistance of the exposed individual may modify deposition dynamics and infectivity despite airborne viral levels. Furthermore, not all viruses entrained in the expelled aerosol are viable. Furthermore, environmental factors like sunlight (36), temperature, and humidity (37) determine the stability and viability of viruses borne in aerosols.

The virus aerosols are a mixture of electrolytes, proteins, surfactants, organic material, surface-active compounds, and other components of the fluid lining of respiratory passages (7). During the transfer from the breathing zone of the shedding host and that of the healthy host, the situational temperature and relative humidity (RH) change from human physiologic values on exit (100% RH and 36°C) to that of the immediate room environment through which it transits. The room temperature and relative humidity modify the surface evaporation of the aerosols which in turn influence physico-chemical properties, phase-transition, and size distribution of the aerosols (38). The residence time, dispersal range, and stability of the virion are therefore subject to temperature and RH variations in different zones of the air volume in an enclosed space. Low temperature and RH are conducive to the survival and transmission of influenza viruses. At higher RH (40%–60%) the phospholipid-protein complexes of enveloped viruses are prone to denature in the air. Peak influenza virus decay is observed at RH 50% (range 40%–70%). At low RH (<30%), water evaporates more rapidly from aerosols leaving smaller involatile droplet nuclei which have higher content of proteins and salts, are environmentally more stable, capable of longer air residence times, and consequently have elevated transmission risk (38). The RH and temperature also modulate virus aerosol fate at the inhalation-deposition interface. Dry air provokes an inflammatory response which is accompanied by an increased mucous production and a depressed muco-ciliary clearance of deposits from the respiratory mucosal surfaces (39). Depositing aerosols are less likely to be removed. Moreover, inflammation creates breaches in the protective respiratory mucosa and impairs the local epithelial immune response. These conditions enable the settling of virus

aerosols deeper down the respiratory tree and a greater likelihood of an established infective process (38).

The healthcare environment vs. other settings

Recommendations for health facility indoor ventilation are very specific and they seek to, among other things, limit air movements in between service areas and departments; attenuate and eliminate microbial, chemical, radioactive, and odoriferous contaminations; maintain the temperature and humidity demands which are conducive to the operations of different spaces (40). An important distinction of the ventilation systems of health facilities in comparison with office complexes, public buildings, schools, and aircrafts, for example, is the principle of zoning. Zoning achieves different ventilation system specifications in different department. Therefore, regular patients wards, isolation wards, intensive care units, operating theatres, recovery rooms, treatment rooms, nurses' stations, laboratories, sterilizing rooms, and administrative offices differ in environmental circulation components (40). In addition, health facilities are unique because they operate throughout the day every day of the year, so their air dilution and corresponding energy costs are enormous.

The effectiveness of a ventilation system in preventing virus transmission depends on the average amount of virus-free air that is provided to each occupant in a volume of space (41, 42). Effective air cleaning must incorporate the ventilation and preferred atmospherics of hospital spaces, but should also take into account the strength and persistence of virus production, and the number of sources (41). Studies included in this systematic review present a range of ventilation settings which were determined by the volume of the rooms, the room occupancy, the specific use to which a room was put, and the engineering and comfort-oriented requirements the healthcare setting (43, 44). Several studies specified the ventilation parameters of the study area and the adjustment of filtration devices to match the air-change rates of the inherent mode of room ventilation.

The HVAC modulation of airborne virus exposure in a room depends more on the occupancy density (which is the spatial volume of the room divided by the number of occupants), than it does on the outdoor air supplied per person, and reintroduced filtered air supplied per person. The occupancy density determines the time needed to attain the maximum virus concentration in uniformly mixed air while outdoor air supply and reintroduced filtered air determine the set point of virus maximum concentration. The implication is that spaces may have identical equilibrium concentration (when viral-laden aerosols settle into a uniform concentration in the entire volume of a well-mixed space) and exposure time, but higher infectivity is more likely to occur in those spaces with higher occupancy density because the highest inhalation dose is reached in shorter time (42). By implication, higher occupancy density reduces the fraction of virus-free outside air that is available for ventilation in demarcated floor area (45). The equilibrium concentration and

the time to attain it also decreased in response to viral settling, and deactivation. At this concentration, the transmission rate of the virus is constant (6). Reviewed studies in this paper did not demonstrate or highlight how occupancy density affected their results.

The uniqueness of recommended ventilation in healthcare spaces justify focusing this review only on studies which were conducted in the health facility. It is worth emphasising that although the studies included in this review offer some evidence of effective aerosol abatement from air-filtration, this may not translate to similar abatement of viral transmission. The air cleaning technologies are designed to deplete background levels of aerosols. However, the immediate breathing zone of the patient would be rich in aerosols, thus increasing the exposure of the health worker, who often has to interact in close proximity with the patient, despite background air cleaning (20). Therefore, the potential viral abatement offered by air cleaning technologies should supplement other protective measures such as the use of personal protective equipment (PPE).

Absence of comparative analysis

Most of the included studies simply presented summary statistics which contrasted scenarios with and without air filtration. Actual comparative statistical analyses of aerosol concentrations between those scenarios were absent from most of these studies. This limitation makes it impractical to conclude that the observed differences in measured concentrations were not subject to extraneous influences. In addition, some methodological inadequacies did not permit such analysis as it seemed investigators used single experimental readings without replicating the experiment.

Side effects of air cleaners

The use of air-cleaning technologies can have undesired environmental consequences. Only two studies measured noise generated by the air filtering devices. Such side-effects may affect patients' recovery and overall well-being; especially, for noise-sensitive patients, but also for patients whose disease conditions may be worsened by the nature of the side-effect. For example, patients with overt or underlying respiratory conditions may experience worsening of symptoms from ozone, an established respiratory irritant. Ozone is known to be generated by U.V. light, electrostatic precipitators, and ion generators (20, 46).

Authors' conclusions

Implications for practice

In summary, the reviewed studies offer some evidence of accelerated aerosols removal by air filters. The implication of this finding for transmission have been supported by other studies which have shown the reduction in the transmission of other

viruses and bacteria by HEPA filtration. However, a quantification of the expected reduction in the transmission of SAR-CoV-2 cannot be implied as the research evidence does not exist. Thus, the care of confirmed COVID-19 patients and potentially infected persons in the health facility cannot be separated from policies which prioritise the use of PPEs. The between-use wait-time of clinics, treatment rooms, and operating theatres would still be subject to existing standards as this systematic review does not provide sufficient evidence for a policy review.

Implications for research

Investigators in this discipline should agree on a limited set of metrics for quantifying the outcome of air-cleaning devices on the transmission potential of SARS-CoV-2 and other pathogens. There should be adherence to uniformity in the measurement and calculation of these metrics even when investigators explore different environmental and interventional scenarios. The consistency of findings between studies can be meaningfully assessed if methodologies and outcome metrics are comparable between studies.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

EO: Writing – original draft, Writing – review & editing, Formal analysis, Investigation, Methodology, Project administration. MC: Investigation, Methodology, Writing – original draft. CE: Writing – original draft. MB: Investigation, Writing – original draft. VB: Investigation, Writing – original draft. AO-I: Conceptualization, Project administration, Writing – original draft. MM: Conceptualization, Methodology, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The author(s) declare that no Generative AI was used in the creation of this manuscript.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fenvh.2025.1548272/full#supplementary-material>

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