COVID-19 Living Evidence Synthesis 15.1: Effectiveness of ventilation for reducing transmission of COVID-19 and other respiratory infections in non-health care community-based settings

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Please note: This living evidence synthesis (LESs) is part of a suite of LESs of the best-available evidence about the effectiveness of six PHSMs (masks, quarantine and isolation, ventilation, physical distancing and reduction of contacts, hand hygiene and respiratory etiquette, cleaning, and disinfecting), as well as combinations of and adherence to these measures, in preventing transmission of COVID-19 and other respiratory infectious diseases in non-health care community-based setting. The LESs are updated every six weeks and include enhancements from the previous versions (e.g., inclusion of additional study designs and updated risk of bias assessments). The most up-to-date version of this and other LESs in the suite are available on the COVID-END website.

Questions

Effectiveness

1. What is the effectiveness of different ventilation strategies in reducing transmission of COVID-19 and other viral respiratory illnesses (e.g. influenza, respiratory syncytial virus (RSV)) in community-based settings (i.e., not clinical or healthcare settings)? Ventilation strategies include ventilation rates (air changes per hour, flow rates), air flow patterns, and the ratio of outdoor air to re-used air.
2. What is the effectiveness of different filter ratings (within ventilation systems) in reducing transmission of COVID-19 or other viral respiratory illnesses in community-based settings?
3. What is the effectiveness of different combinations of ventilation and filtration strategies in reducing transmission of COVID-19 or other viral respiratory illnesses in community-based settings?

Negative outcomes

4. What are the economic impacts of improving mechanical ventilation?
5. What are the negative socio-economic impacts of improving ventilation (e.g., increased inequity in COVID-19 transmission)?

Executive summary

Background

- Airborne (or aerosol) transmission is recognized as a route of transmission of the SARS-CoV-2 virus which causes COVID-19 illness.[1] Airborne transmission occurs when the virus is released by an infected individual in small particles; aerosol droplets tend to follow air flow patterns instead of travelling on their own trajectory. The aerosol droplets travel with the air and may be inhaled by other individuals. Inhalation of these droplets may or may not result in infection and subsequent illness based on various factors, such as viral load and characteristics of the individual. Aerosol droplets can remain airborne, sometimes indefinitely, and can travel long distances. Environmental conditions such as ventilation rates and airflow patterns affect the routes and distances that aerosols travel.

- Heating, ventilation and air conditioning (HVAC) systems within the built environment can increase or mitigate the risk of airborne transmission of aerosols. There are numerous features within HVAC systems that can be modified to potentially alter this risk. This review focused on: ventilation rates (often quantified as air changes per hour); air flow patterns (i.e., where air flows within a space, influenced by various factors including the nature and placements of inlet and outflow of air from a space); the ratio of outdoor (e.g., fresh) air to re-used air (outdoor air is introduced by mechanical HVAC systems as well as by opening doors or windows); and filters within HVAC systems.

- Recent systematic reviews (SRs) have investigated ventilation,[2] filtration,[3] humidity,[4] and ultraviolet irradiation[5] within mechanical HVAC systems and the impact of these features on aerosol transmission. The SR of ventilation (32 studies published between 2004 and 2021; majority modelling studies) confirmed a number of well-understood principles, including increasing ventilation rate is associated with decreased virus transmission. However, multiple factors need to be considered simultaneously "such as ventilation rate, airflow patterns, air balancing, occupancy, and feature placement." The SR of filtration (23 studies published between 1966 and 2021; animal studies n=17, aerosolized virus studies n=7, modelling studies n=9) also confirmed several well-understood principles, including decreased virus transmission with increasing filter efficiency. The review authors concluded that "filtration is one factor offering demonstrated potential for decreased transmission."

- The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) sets standards for testing and application of HVAC features that guide practices in North America. A statement from ASHRAE in April 2021 acknowledged that airborne transmission of SARS-CoV-2 is significant and provided guidance on changes to building operations including HVAC systems.[6]

Key points

- Airborne transmission is a route for COVID-19 infection and involves transmission through aerosols. Ventilation and filtration can affect movement of aerosols within a space, including the patterns and distances that aerosols travel.

- There is a paucity of 'real world' evidence comparing ventilation or filtration strategies for reducing risk of COVID-19 infection.

- Two cross-sectional studies of elementary schools in the U.S. and meat packing plants in Germany found associations between ventilation and incidence of COVID-19 illness. Both studies were considered to have serious risk of bias due to confounding and/or non-response.

- Three studies used modelling to investigate outbreaks of COVID-19 and demonstrated an association between ventilation rates and infection risk or attack rates.
- Many other modelling and simulation studies of ventilation and filtration have been published since the start of the COVID-19 pandemic. Some include risk or probability of transmission or infection; however, many others focus on airflow patterns, dispersion of particles, or concentration of potentially infectious particles (i.e., outcomes that are upstream in the transmission/infection chain). These studies may be challenging to apply to 'real world' scenarios due to the complex interactions of variables related to ventilation parameters themselves as well as other factors in the space (e.g., occupancy, characteristics and movement of infected and non-infected individuals, etc.).
- A number of principles regarding ventilation are well-established and supported by organizations that set standards for the HVAC industry such as ASHRAE. These include maintaining minimum outdoor airflow rates, using combinations of filters and air cleaners that achieve a minimum efficiency, promoting mixing of space air while avoiding strong air currents, and balancing exposure reduction with energy expenditures. They also provide recommendations for HVAC system operation and commissioning. These principles contribute to indoor air quality and also provide health benefits independent of COVID-19 (illnesses or irritation caused by viruses, bacteria, pollutants, allergens, and other agents).
- ***Key points from citizen partners:*** Facilities should ensure that recommended standards for HVAC systems are implemented. This will contribute to improved indoor air quality and lessen other respiratory illnesses, negative health effects, and potential future outbreaks.

Overview of evidence and knowledge gaps
- There is a paucity of 'real world' evidence comparing ventilation or filtration strategies for reducing transmission of COVID-19. We identified two studies that met the inclusion criteria.[7,8] Both studies were considered to have serious risk of bias primarily due to confounding or non-response. A cross-sectional study of elementary schools in Georgia, U.S. showed that COVID-19 incidence was 39% lower in schools that implemented some measures to improve ventilation.[7] Further, dilution methods alone (opening doors, opening windows, or using fans) resulted in 35% lower incidence, while a combined approach involving dilution and filtration (using HEPA filters [in air cleaners] with or without using UVGI) resulted in 48% lower incidence. A cross-sectional study of meat and chicken processing plants in Germany examined whether having a ventilation system reduced the chance of testing positive for COVID-19.[8] Results for the multivariable logistic regression showed a significant reduction among temporary and contract workers (aOR 0.541, 95% CI 0.368– 0.796). Assessment of "maximum outdoor air flow per employee" was also associated with reduced chance of COVID-19 infection (aOR 0.996, 95% CI 0.993-0.999).
- Another three studies used modelling and simulations to investigate outbreaks of COVID-19. Two studies used computational fluid dynamics and showed that increasing ventilation rates and fresh-air supply reduced risk of infection in the restaurant in Guangzhou, China where an outbreak occurred in January 2020. A third study investigated an outbreak caused by the same infected individual on two buses in Hunan Province, China in January 2020. Through simulations, they estimated ventilation rates in each bus and found that attack rate (number of infected cases/number of persons) was higher on the bus with the lower ventilation rate.
- The bulk of the scientific literature on these topics is in the form of modelling or simulation studies. It can be challenging to apply results from these studies to practical applications for various reasons. For instance, they may be based on assumptions that vary across specific 'real

world' settings. They may focus on specific configurations that change continuously in real world scenarios (e.g., occupancy, movement, and specific activities of people within a space, presence and characteristics of infected individuals, susceptibility of other individuals). And often they focus on specific steps within the chain of transmission: many modelling or simulation studies examine air flow patterns, dispersion of air particles within a space, or concentration of potentially infectious particles within air samples across time and space considerations; however, they may not consider the impacts in terms of transmission of infectious particles and occurrence of illness.

Suggested Tweet
- #ventilation #filters #hvac affect #coronavirus transmission. #iaq saves lives and money.

Findings

- The search and reference check identified 1,060 studies. Two hundred and nine studies were considered potentially relevant.
- Two studies met the eligibility criteria (Table 1). We also identified three modelling studies that investigated COVID-19 outbreaks (Table 2). Further, we identified 55 modelling and simulation studies that reported on risk or probability of transmission or infection (list of studies included in Appendix 3).
- Figure 1 shows the flow of studies through the search and selection process.

Summary of findings about reducing transmission of COVID-19 or risk of infection

Two studies were included that report on reducing transmission of COVID-19 as an outcome. The characteristics, findings and assessment of risk of bias for each study is presented in Table 1.

A cross-sectional study examined the association between COVID-19 incidence and public health measures implemented at elementary schools in Georgia, United States.[7] Public health measures included "ventilation improvements" overall, and type of improvement (opening doors/windows, using fans to increase effectiveness of open windows, installation of HEPA filtration systems in high-risk areas, or installation of UVGI in high-risk areas). Among 169 schools, those that implemented ventilation improvements (n=87) showed reduced risk of COVID-19 incidence (risk ratio 0.61, 95% CI 0.43–0.87). Based on 123 schools with

Box 1: Our approach

We retrieved studies by searching: 1) PubMed via COVID-19+ Evidence Alerts; 2) pre-print servers through iCITE; 3) Compendex; and 4) Web of Science. Searches were conducted for studies reported in English, conducted with humans and published since 1 January 2020 (to coincide with the emergence of COVID-19 as a global pandemic). Detailed search strategy is included in **Appendix 1**, and eligibility criteria in **Appendix 2.**

Studies identified up to December 16, 2022 that reported on empirical data with a comparator were considered for inclusion. Modelling and simulation studies were identified but not included for review, unless they investigated an actual COVID-19 outbreak. Other study designs may be considered for future versions in the absence of other forms of evidence. A full list of included studies is provided in **Table 1**. **Table 2** lists modelling studies that investigated COVID-19 outbreaks. Studies excluded at the last stages of reviewing are provided in **Appendix 3**.

Population of interest: All population groups that report data related to all COVID-19 variants and sub-variants.

Intervention and control/comparator: Different rates and mechanisms (i.e., mechanical, natural, or infiltration) of air dilution; different filter ratings; and, different combinations of ventilation and filtration strategies. Definitions provided in **Appendix 4**.

Effectiveness outcomes. Primary outcome: Reduction in transmission of COVID-19. **Secondary outcomes**: Reduction in transmission of other respiratory infections.

Study selection: One reviewer screened all titles and abstracts; a second reviewer screened those that were excluded by the first reviewer to ensure no potentially relevant records were missed. The full text of potentially relevant studies was reviewed by one reviewer. All team members discussed those that were unclear.

Data extraction: Data extraction was conducted by one team member and checked for accuracy and consistency by another using the template provided in **Appendix 5**.

Critical appraisal: Risk of Bias (ROB) of individual studies was assessed using validated ROB tools. For observational studies, we used ROBINS-I. Judgements for the domains within these tools were decided by consensus between at least two team members. Modelling studies were not assessed for ROB, as these are considered to provide indirect evidence of effects. Our detailed approach to critical appraisal is provided in **Appendix 6**.

Summaries: We synthesized the evidence by presenting a narrative summary of each study's findings. This document will be updated every six weeks up to the end of March 2023.

available data, the following were associated with reduced risk of COVID-19 incidence compared to no ventilation improvements (n=37): dilution methods only (opening doors, opening windows, or using fans; n=39, 0.65, 95% CI 0.43–0.98); filtration +/- purification only (using HEPA filters with or without using UVGI and not opening doors, opening windows, or using fans; n=16, 0.69, 95% CI 0.40-1.21); and, dilution and filtration ± purification (opening doors, opening windows, or using fans, and using HEPA filters with or without using UVGI; n=31, 0.52, 95% CI 0.32–0.83). The study was considered at serious risk of bias due to lack of control for confounding (including other public health measures) and low response (11.6% of 1,461 schools).

A cross-sectional study of 22 meat and chicken processing plants in Germany assessed the association between infections and possible risk factors including ventilation, which was quantified as: outdoor air flow per employee in a working area = outdoor air flow / (number of employees in a working area / number of shifts in the working area). Based on results of multivariable logistic regression analysis (for subsample of companies with many infected workers), having a ventilation system reduced chance of testing positive for COVID-19. The results overall (6,522 workers) were not statistically significant (adjusted OR 0.757, 95% CI 0.563– 1.018). Results by type of worker showed no significant association for regular workers (aOR 1.076, 95% CI 0.619– 1.869) but a significant reduction for temporary and contract workers (aOR 0.541, 95% CI 0.368– 0.796). Overall results of multivariable logistic regression for maximum outdoor air flow (OAF) per employee found no significant difference (aOR 1.000 (95% CI 1.000– 1.000). However, when the delivery, stunning/slinging/hanging, and slaughter areas were excluded from analysis (these areas have a process related high ventilation rate) (n=2,334) the association was significant (aOR 0.996, 95% CI 0.993–0.999; including interaction term for temperature and OAF, aOR 0.984, 95% CI 0.971– 0.996. This study was considered at serious risk of bias due to lack of control for all possible sources of confounding.

Three studies used modelling and simulations to investigate outbreaks of COVID-19 (Table 2). Two studies used computational fluid dynamics and found that increasing ventilation rates and fresh-air supply reduced risk of infection in the restaurant in Guangzhou, China where an outbreak occurred in January 2020.[9,10] Ho et al 2021 showed that increasing the percentage of fresh-air in the supply air (by 10%, 50%, 100%) resulted in lower probability of infection (by 11%, 37%, and 51%, respectively). Liu et al 2020 simulated aerosol exposure index for individuals sitting at different tables in the restaurant and determined that infection risk for each individual was lower with increased ventilation. A third study investigated an outbreak caused by the same infected individual on two buses in Hunan Province, China in January 2020.[11] Through simulations, they estimated ventilation rates in each bus and found that attack rate (number of infected cases/number of persons) was higher on the bus with the lower ventilation rate (15.2% vs. 11.8%).

Summary of findings about negative outcomes

No studies were identified that reported on negative outcomes (e.g., costs, inequities).

Discussion

Several epidemiologic investigations of COVID-19 outbreaks in different community-based settings (e.g., restaurant, meat processing plant, sports facility, etc.) have determined that airborne transmission was a likely cause and that ventilation in the space was a contributing factor, either due to low ventilation rates, high occupancy, and/or air flow patterns created by air conditioning.[12-14]

Recent systematic reviews (SRs) have investigated the impact of ventilation,[2] filtration,[3] humidity,[4] and ultraviolet irradiation[5] within mechanical HVAC systems and the impact of these features on aerosol transmission.

A SR of ventilation included 32 studies (published between 2004 and 2021; majority modelling studies) examining the impact of ventilation rates and airflow patterns on coronavirus transmission. The findings confirmed a number of well-understood principles: "increased ventilation rate was associated with decreased transmission…; increased ventilation rate decreased risk at longer exposure times; some ventilation was better than no ventilation; airflow patterns affected transmission; ventilation feature (e.g., supply/exhaust, fans) placement influenced particle distribution." However, the review found few studies that offered specific quantitative ventilation parameters. While the review authors offered some implications for practice, they highlighted that there is "not a one-solution-fits-all approach" as multiple "factors such as ventilation rate, airflow patterns, air balancing, occupancy, and feature placement" influence aerosol transmission and risk.

A SR of filtration included 23 studies (published between 1966 and 2021) examining seven viruses and three bacteriophages and included animal studies (n=17), aerosolized virus studies (n=7) and modelling studies (n=9). This review also confirmed several well-understood principles: "filtration was associated with decreased transmission; filters removed viruses from the air; increasing filter efficiency (efficiency of particle removal) was associated with decreased transmission, decreased infection risk, and increased viral filtration efficiency (efficiency of virus removal); increasing filter efficiency above MERV 13 was associated with limited benefit in further reduction of virus concentration and infection risk; and filters with the same efficiency rating from different companies showed variable performance." The review authors concluded that "adapting HVAC systems to mitigate virus transmission requires a multi-factorial approach and filtration is one factor offering demonstrated potential for decreased transmission." Review authors noted that the costs associated with increasing filter efficiency may be "lower than the cost of ventilation options with the equivalent reduction in transmission."

The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) sets standards for testing and application of HVAC features that guide practices in North America. A statement from ASHRAE in April 2021 acknowledged that airborne transmission of SARS-CoV-2 is significant and provided guidance on changes to building operations including HVAC systems.[6] A summary of their recommendations can be found at https://www.ashrae.org/file%20library/technical%20resources/covid-19/core-recommendations-for-reducing-airborne-infectious-aerosol-exposure.pdf, while guidance for specific settings (e.g., industrial settings, residential buildings, schools, dining structures, etc.) is available at https://www.ashrae.org/technical-resources/covid-19-one-page-guidance-documents. The Heating, Refrigeration and Air Conditioning Institute (HRAI) of Canada represents the HVAC industry in Canada and follows ASHRAE standards. HRAI has produced HVAC guidance for schools in the context of COVID-19.[15]

Figure 1: Flow diagram for study identification (from Preferred Reporting Items for Systematic Reviews and Meta-Analyses, PRISMA)
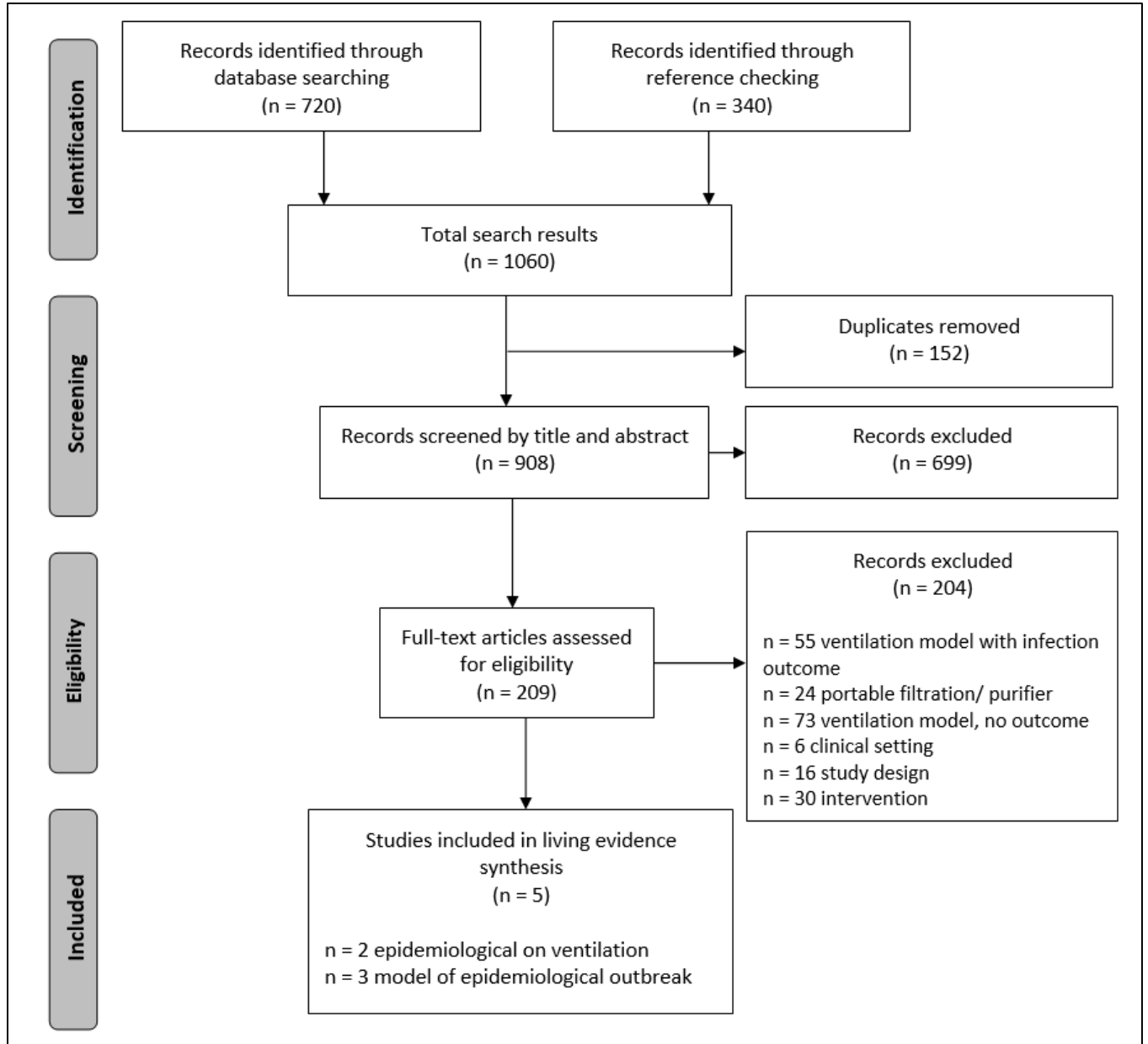
Table 1: Summary of studies reporting on effectiveness of ventilation in reducing COVID-19 infections

Author Year/Date Country	Setting and time covered	Study characteristics	Summary of key findings in relation to the outcome(s)	Risk of bias rating
Gettings[7] May 28, 2021 USA [139]	Georgia state elementary schools (kindergarten through grade 5) November 16 – December 11, 2020	**Design**: cross-sectional study (self-reported cases to state public health department; online survey completed by school representatives) **Intervention**: ventilation improvements: "steps being taken to improve air quality and increase the ventilation in the school"; those who responded "yes" were asked to select one or more of the following: opening doors/windows, using fans to increase effectiveness of open windows, installation of HEPA filtration systems in high-risk areas, or installation of UVGI in high-risk areas **Sample**: 169 (11.6% of 1,461) schools including 91,893 students with available case data (number of cases = 566) **Key outcomes**: COVID-19 cases and incidence **Agents assessed**: SARS-CoV-2	• COVID-19 incidence 39% lower in schools that improved ventilation, compared with schools that did not (RR 0.61, 95% CI 0.43–0.87 • Ventilation strategies associated with lower school incidence included methods to dilute airborne particles alone by opening windows, opening doors, or using fans (35% lower incidence, RR=0.65, 95% CI: 0.43–0.98), or in combination with methods to filter airborne particles using HEPA filtration with or without purification with UVGI (48% lower incidence, RR=0.52, 95% CI: 0.32–0.83)	Serious risk of bias

Pokora[8] June 10, 2021 Germany [338]	Meat and poultry processing plants in Germany
	
	June to September 2020
		Design: cross-sectional study (self-administered questionnaire)
		
		Intervention: multiple possible risk factors including ventilation, quantified as outdoor air flow per employee in a working area = outdoor air flow / (number of employees in a working area / number of shifts in the working area)
		
		Sample: 22 companies for 19,027 employees, including 880 COVID-19 infected workers divided into the following groups:
		• 7 = many infected workers prevalence between 2.94 to 35.10 infections per 100 employees
		• 5 = with fewer than 10 infected workers
		• 10 = with no infected workers
		
		Key outcomes: COVID-19 infection
		
		Agents assessed: SARS-CoV-2
			• Based on results of multivariable logistic regression analysis (for subsample of companies with many infected workers), having a ventilation system reduced chance of testing positive for COVID-19:
			  • overall (6,522 workers): aOR 0.757 (95% CI 0.563– 1.018)
			  • results also presented by type of worker: regular workers (aOR 1.076, 95% CI 0.619– 1.869) vs. temporary and contract (aOR 0.541, 95% CI 0.368– 0.796)
			• results of multivariable logistic regression for maximum outdoor air flow (OAF) per employee:
			  • when delivery, stunning/slinging/hanging, and slaughter areas were excluded from analysis (these areas have a process related high ventilation rate) (n=2,334), aOR 0.996 95% (CI 0.993–0.999); including interaction term for temperature and OAF, aOR 0.984 (0.971– 0.996)
				Serious risk of bias

Abbreviations: aOR=adjusted odds ratio; HEPA=high-efficiency particulate absorbing; OR=odds ratio; RR=rate ratio; UVGI=ultraviolet germicidal irradiation

Table 2: Summary of modelling studies investigating COVID-19 outbreaks and reporting on effect of ventilation in reducing COVID-19 infection risk or probability

Reference Year/Date Country	Objective / Summary	Methods / Experiments	Transmission / Infection Outcomes	Summary of Findings
Ho[9] 2021 China [167]	To develop CFD simulations and methods to model the airflow, exposure, and probability of infection for the reported conditions at the Guangzhou restaurant (where an outbreak of COVID-19 occurred in January 2020). Different configurations of the air conditioning (direction and magnitude of air flow, percentage of fresh air supplied) and boundary conditions (e.g., temperature, pressure, humidity) were investigated to determine the sensitivity of the results to these parameters and processes.	CFD models were used to simulate expelled aerosol plume transport and dispersion and to perform comparative studies of exposure risks under various scenarios. Spatial and temporal simulations of the relative concentrations of the expelled pathogen (assumed to be uniformly distributed in the vapour plume) are compared and used to determine risks of exposure and probability of infection.	Probability of infection	Simulations confirmed that poor ventilation and recirculation increased pathogen concentrations and probability of infection. Increasing the fresh-air supply to the ventilation decreased the pathogen concentrations and probability of infection. Increasing the fresh-air percentage to 10%, 50%, and 100% of the supply air reduced the accumulated pathogen mass in the room by an average of ~30%, ~70%, and ~80%, respectively, over 73 min. The probability of infection was reduced by 11%, 37%, and 51%, respectively.
Liu[10] 2020 USA [248]	CFD-based investigation of indoor air flow and the associated aerosol transport in a restaurant setting (Guangzhou, China; January 2020), where likely cases of airborne infection of COVID-19 caused by asymptomatic individuals were widely reported by the media. To demonstrate direct linkage between the simulation results (under different ventilation and thermal settings) and reported infection patterns as well as the corresponding detailed physical mechanisms that lead to airborne disease transmission.	We employed an advanced in-house large eddy simulation solver and other cutting-edge numerical methods to resolve complex indoor processes simultaneously, including turbulence, flow–aerosol interplay, thermal effect, and the filtration effect by air conditioners. Using the aerosol exposure index derived from the simulation, we are able to provide a spatial map of the airborne infection risk under different settings.	Infection risk	In simulation with increased ventilation, the risk of infection is decreased (Fig 13 and 14, values presented graphically for each individual based on position at tables relative to infected source). The infection risk evaluation from our current CFD is only derived from the aerosol exposure index. To yield a more substantiated metric of infection risk, a relevant infection-dose model, currently not available for SARS-CoV-2, is needed.

Reference Year/Date Country	Objective / Summary	Methods / Experiments	Transmission / Infection Outcomes	Summary of Findings
Ou[11] 2022 China [615]	CFD was utilized to model airflows and investigate ventilation requirements of airborne transmission in a COVID-19 outbreak initiating with a 24-year old man. Two buses (B1 and B2) were involved, with 10 non-associated infected passengers. We collected epidemiological data, bus itineraries, the seating plans of passengers, and the details of the ventilation systems and operation, and we performed detailed ventilation and dispersion measurements on the two buses with the original drivers on the original route.	Dates of symptom onset and the seating arrangements on the two buses were obtained, as well as interviews with drivers and passengers. Various combinations of air conditioning/heating and windows open/ closed were considered to simulate the airflow at the time of infection. The ventilation rates on the buses were measured using a tracer-concentration decay method with the original driver on the original route. We measured and calculated the spread of the exhaled virus-laden droplet tracer from the suspected index case.	Infection risk / attack rate	On both buses, the distribution of the exhaled tracer gas was rather uniform due to the airflow patterns. **Bus1** - Attack rate = 7/46, 15.2% - Ventilation rate = 1.72 L/s per person 1.72 L/s per person - Exposure time = 200 minutes **Bus2** - Attack rate = 2/17, 11.8% - Ventilation rate = 3.22 L/s per person - Exposure time = 60 minutes The ventilation rate of a bus depended on the driving speed and extent of window opening. The difference in ventilation rates and exposure time could explain why B1 had a higher attack rate than B2. Airborne transmission due to poor ventilation below 3.2 L/s played a role in this two-bus outbreak of COVID-19.

Abbreviations: CFD=computational fluid dynamics

Acknowledgements

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Appendices

Appendix 1: Detailed search strategy (PubMed)

#1 ("COVID 19"[MeSH] OR "COVID 19"[All Fields] OR "sars cov 2"[All Fields] OR "sars cov 2"[MeSH] OR "severe acute respiratory syndrome coronavirus 2"[All Fields] OR ncov[All Fields] OR "2019 ncov"[All Fields] OR "coronavirus infections"[MeSH] OR coronavirus[MeSH] OR coronavirus[All Fields] OR coronaviruses[All Fields] OR betacoronavirus[MeSH] OR betacoronavirus[All Fields] OR betacoronaviruses[All Fields] OR "wuhan coronavirus"[All Fields] OR 2019nCoV[All Fields] OR Betacoronavirus*[All Fields] OR "Corona Virus*"[All Fields] OR Coronavirus*[All Fields] OR Coronovirus*[All Fields] OR CoV[All Fields] OR CoV2[All Fields] OR COVID[All Fields] OR COVID19[All Fields] OR COVID-19[All Fields] OR HCoV-19[All Fields] OR nCoV[All Fields] OR "SARS CoV 2"[All Fields] OR SARS2[All Fields] OR SARSCoV[All Fields] OR SARS-CoV[All Fields] OR SARS-CoV2[All Fields]) AND English[la])

#2 (environment, controlled[MeSH] OR air conditioning[MeSH] OR ventilation[MeSH] OR sanitary engineering[MeSH] OR filtration[MeSH] OR filtration[TIAB] OR "air condition*"[TIAB] OR "building ventilation"[TIAB] OR "ventilation system"[TIAB] OR "indoor ventilation"[TIAB] OR HVAC[TIAB] OR air samples[TIAB]) AND (Disease Transmission, Infectious*[Mesh] OR Air Pollution, Indoor[MeSH] OR transmission[Subheading] OR Infections[Mesh:NoExp] OR transmi*[TIAB] OR infect*[TIAB] OR contagi*[TIAB] OR outbreak*[TIAB] OR spread*[TIAB] OR decontamination[TIAB]) AND (Aerosols[MeSH] OR Air Microbiology[MeSH] OR Aerosol*[TIAB] OR bioaerosol*[TIAB] OR airborne[TIAB] OR droplet*[TIAB] OR "air exchange"[TIAB] OR "air change"[TIAB] OR "air flow"[TIAB] OR airflow[TIAB] OR "fluid dynamics"[TIAB])

#1 and #2

#4 search*[Title/Abstract] OR meta-analysis[Publication Type] OR meta analysis[Title/Abstract] OR meta analysis[MeSH Terms] OR review[Publication Type] OR diagnosis[MeSH Subheading] OR associated[Title/Abstract]

#5 (clinical[TIAB] AND trial[TIAB]) OR clinical trials as topic[MeSH] OR clinical trial[Publication Type] OR random*[TIAB] OR random allocation[MeSH] OR therapeutic use[MeSH Subheading]

#6 comparative study[pt] OR Controlled Clinical Trial[pt] OR quasiexperiment[TIAB] OR "quasi experiment"[TIAB] OR quasiexperimental[TIAB] OR "quasi experimental"[TIAB] OR quasi-randomized[TIAB] OR "natural experiment"[TIAB] OR "natural control"[TIAB] OR "Matched control"[TIAB] OR (unobserved[TI] AND heterogeneity[TI]) OR "interrupted time series"[TIAB] OR "difference studies"[TIAB] OR "two stage residual inclusion"[TIAB] OR "regression discontinuity"[TIAB] OR non-randomized[TIAB] OR pretest-posttest[TIAB]

#7 cohort studies[mesh:noexp] OR longitudinal studies[mesh:noexp] OR follow-up studies[mesh:noexp] OR prospective studies[mesh:noexp] OR retrospective studies[mesh:noexp] OR cohort[TIAB] OR longitudinal[TIAB] OR prospective[TIAB] OR retrospective[TIAB]

#8 Case-Control Studies[Mesh:noexp] OR retrospective studies[mesh:noexp] OR Control Groups[Mesh:noexp] OR (case[TIAB] AND control[TIAB]) OR (cases[TIAB] AND controls[TIAB]) OR (cases[TIAB] AND controlled[TIAB]) OR (case[TIAB] AND comparison*[TIAB]) OR (cases[TIAB] AND comparison*[TIAB]) OR "control group"[TIAB] OR "control groups"[TIAB]

#9   #3 and #4 (will retrieve Reviews)

#10 #3 and #5 (will retrieve RCTs)

#11 #3 and #6 (will retrieve Quasi-experimental studies)

#12 #3 and #7 (will retrieve Cohort studies)

#13 #3 and #8

#14 #9 or #10 or #11 or #12 or #13

#15 #14 NOT (Animals[Mesh] NOT (Animals[Mesh] AND Humans[Mesh]))

Appendix 2: Detailed study eligibility criteria

Characteristic	Inclusion Criteria	Exclusion Criteria
Publication date	January 01, 2020	Prior to 2020
Language	English	Languages other than English
Study design	Epidemiological / Ecological: experimental studies at the population or group level with a comparator Primary / Experimental: quantitative with comparator Primary / Observational: cohort, case-control, cross-sectional Modelling / Simulation: TBD*	Opinions pieces: commentaries or editorials published in peer-reviewed journals Qualitative data Reviews: narrative and literature reviews; check references of systematic/rapid reviews or meta-analysis with relevant to any of the public health measures
Population	Involving animals or humans	None
Setting	Indoor built environments such as: office buildings, public buildings (schools, day cares), residential buildings, retail buildings (malls, restaurants), athletic facilities (gyms), transport vehicles (aircraft) or hubs (airports)	Healthcare or clinical settings
Intervention	Ventilation systems in the built environment Filters or filtration features within mechanical ventilation systems [TBD for subsequent deliverables: (1) portable ventilators or air filtration devices that are not part of mechanical ventilation systems; (2) pure modelling studies with outcome of interest]	Open air / outdoor environments
Comparison	Different rates and mechanisms (i.e., mechanical, natural, or filtration) of air dilution (including flow rates, air flow patterns, ratio of outdoor air to re-used air) Different filter ratings Different combinations of ventilation and filtration strategies	No comparison of ventilation parameters
Outcome	Primary: quantitative data evaluating virus transmission in reducing transmission of COVID-19 (i.e., attack rates, reproduction number, etc.) Secondary: probability or risk of transmission or infection Negative effects, e.g., costs, inequities	Qualitative data

Abbreviations: TBD=to be determined
* for the first report, we included modelling/simulation studies that investigated actual outbreaks of COVID-19 and met other eligibility criteria

Appendix 3: Studies excluded at the last stages of reviewing

Excluded – modelling studies with infection outcome (n = 55)

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Excluded – portable filtration/purifier (n = 24)

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Excluded – modelling studies without infection outcome (n = 73)

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Appendix 4: Definitions

Ventilation refers to dilution of indoor air with outdoor air. Air dilution can occur through natural means (e.g., opening windows or doors) or mechanical means (e.g., Heating, Ventilation and Air Condition [HVAC] systems). Improving ventilation helps to limit the number of infectious particles indoors by diluting indoor air with outdoor air that has fewer infectious particles.

Air filtration refers to removing unwanted matter (e.g., particles, droplets) from the air stream by passing the airflow through fine mesh obstructions. In principle, some fraction of the unwanted matter will stay upstream of the filter and relatively cleaner air will flow downstream of the filter.

Appendix 5: Data extraction form

Data extraction for studies reporting outcomes on effectiveness of ventilation in reducing COVID-19 infections (Table 1)

Data extraction category	Data extraction element
Reference details	First author Date of publication Country of publication
Study characteristics	Design Intervention Key outcomes Agents assessed
Population characteristics	Sample description
Results	Summary of key findings in relation to infection/transmission outcome

Data extraction for studies modelling COVID-19 outbreaks reporting on effectiveness of ventilation in reducing COVID-19 infections (Table 2)

Data extraction category	Data extraction element
Reference details	First author Date of publication Country of publication
Study characteristics	Objective/summary of study Description of methods/model Key outcomes
Results	Summary of key findings in relation to infection/transmission outcome

Appendix 6: Approach to critical appraisal

For all epidemiological studies reporting on effectiveness of ventilation in reducing COVID-19 infections RoB will be assessed. For RCTs the ROB-2 will be applied and for observational studies the ROBINS-I tool will be applied.

RoB-2 domains assessed

Domain 1: Risk of bias arising from the randomization process	
Signaling questions	**Response options**
1.1 Was the allocation sequence random?	Y / PY / PN / N / NI
1.2 Was the allocation sequence concealed until participants were enrolled and assigned to interventions?	Y / PY / PN / N / NI
1.3 Did baseline differences between intervention groups suggest a problem with the randomization process?	Y / PY / PN / N / NI
Domain 2a: Risk of bias due to deviations from the intended interventions (effect of assignment to intervention)	
Signaling questions	**Response options**
2.1. Were participants aware of their assigned intervention during the trial?	Y / PY / PN / N / NI
2.2. Were carers and people delivering the interventions aware of participants' assigned intervention during the trial?	Y / PY / PN / N / NI
2.3. If Y/PY/NI to 2.1 or 2.2: Were there deviations from the intended intervention that arose because of the trial context?	NA / Y / PY / PN / N / NI
2.4 If Y/PY to 2.3: Were these deviations likely to have affected the outcome?	NA / Y / PY / PN / N / NI
2.5. If Y/PY/NI to 2.4: Were these deviations from intended intervention balanced between groups?	NA / Y / PY / PN / N / NI
2.6 Was an appropriate analysis used to estimate the effect of assignment to intervention?	Y / PY / PN / N / NI
2.7 If N/PN/NI to 2.6: Was there potential for a substantial impact (on the result) of the failure to analyse participants in the group to which they were randomized?	NA / Y / PY / PN / N / NI
Domain 2b: Risk of bias due to deviations from the intended interventions (effect of adhering to intervention)	
Signaling questions	**Response options**
2.1. Were participants aware of their assigned intervention during the trial?	Y / PY / PN / N / NI
2.2. Were carers and people delivering the interventions aware of participants' assigned intervention during the trial?	Y / PY / PN / N / NI
2.3. [If applicable:] If Y/PY/NI to 2.1 or 2.2: Were important non-protocol interventions balanced across intervention groups?	NA / Y / PY / PN / N / NI
2.4. [If applicable:] Were there failures in implementing the intervention that could have affected the outcome?	NA / Y / PY / PN / N / NI
2.5. [If applicable:] Was there non-adherence to the assigned intervention regimen that could have affected participants' outcomes?	NA / Y / PY / PN / N / NI
2.6. If N/PN/NI to 2.3, or Y/PY/NI to 2.4 or 2.5: Was an appropriate analysis used to estimate the effect of adhering to the intervention?	NA / Y / PY / PN / N / NI
Domain 3: Missing outcome data	
Signaling questions	**Response options**
3.1 Were data for this outcome available for all, or nearly all, participants randomized?	Y / PY / PN / N / NI
3.2 If N/PN/NI to 3.1: Is there evidence that the result was not biased by missing outcome data?	NA / Y / PY / PN / N
3.3 If N/PN to 3.2: Could missingness in the outcome depend on its true value?	NA / Y / PY / PN / N / NI
3.4 If Y/PY/NI to 3.3: Is it likely that missingness in the	NA / Y / PY / PN / N / NI
Domain 4: Risk of bias in measurement of the outcome	
Signaling questions	**Response options**
4.1 Was the method of measuring the outcome inappropriate?	Y / PY / PN / N / NI
4.2 Could measurement or ascertainment of the outcome have differed between	Y / PY / PN / N / NI

intervention groups?	
4.3 If N/PN/NI to 4.1 and 4.2: Were outcome assessors aware of the intervention received by study participants?	NA / Y / PY / PN / N / NI
4.4 If Y/PY/NI to 4.3: Could assessment of the outcome have been influenced by knowledge of intervention received?	NA / Y / PY / PN / N / NI
4.5 If Y/PY/NI to 4.4: Is it likely that assessment of the outcome was influenced	NA / Y / PY / PN / N / NI
Domain 5: Risk of bias in selection of the reported result	
Signaling questions	**Response options**
5.1 Were the data that produced this result analysed in accordance with a pre-specified analysis plan that was finalized before unblinded outcome data were available for analysis?	Y / PY / PN / N / NI
Is the numerical result being assessed likely to have been selected, on the basis of the results, from... 5.2. ... multiple eligible outcome measurements (e.g. scales, definitions, time points) within the outcome domain?	Y / PY / PN / N / NI
5.3 ... multiple eligible analyses of the data?	Y / PY / PN / N / NI

ROBINS-I domains assessed

Domain 1: Bias due to confounding	
Signaling questions	**Response options**
1.1 Is there potential for confounding of the effect of intervention in this study? If N/PN to 1.1: the study can be considered to be at low risk of bias due to confounding and no further signaling questions need be considered	Y / PY / PN / N
If Y/PY to 1.1: determine whether there is a need to assess time-varying confounding: 1.2. Was the analysis based on splitting participants' follow up time according to intervention received? If N/PN, answer questions relating to baseline confounding (1.4 to 1.6) If Y/PY, go to question 1.3.	NA / Y / PY / PN / N / NI
1.3. Were intervention discontinuations or switches likely to be related to factors that are prognostic for the outcome? If N/PN, answer questions relating to baseline confounding (1.4 to 1.6) If Y/PY, answer questions relating to both baseline and time-varying confounding (1.7 and 1.8)	NA / Y / PY / PN / N / NI
Questions relating to baseline confounding only 1.4. Did the authors use an appropriate analysis method that controlled for all the important confounding domains?	NA / Y / PY / PN / N / NI
1.5. If Y/PY to 1.4: Were confounding domains that were controlled for measured validly and reliably by the variables available in this study?	NA / Y / PY / PN / N / NI
1.6. Did the authors control for any post-intervention variables that could have been affected by the intervention?	NA / Y / PY / PN / N / NI
Questions relating to baseline and time-varying confounding 1.7. Did the authors use an appropriate analysis method that controlled for all the important confounding domains and for time-varying confounding?	NA / Y / PY / PN / N / NI
1.8. If Y/PY to 1.7: Were confounding domains that were controlled for measured validly and reliably by the variables available in this study?	NA / Y / PY / PN / N / NI
Domain 2: Bias in selection of participants into the study	
Signaling questions	**Response options**
2.1. Was selection of participants into the study (or into the analysis) based on participant characteristics observed after the start of intervention?	Y / PY / PN / N / NI
If N/PN to 2.1: go to 2.4 2.2. If Y/PY to 2.1: Were the post-intervention variables that influenced selection likely to be associated with intervention?	NA / Y / PY / PN / N / NI
2.3 If Y/PY to 2.2: Were the post-intervention variables that influenced selection likely to be influenced by the outcome or a cause of the outcome?	NA / Y / PY / PN / N / NI
2.4. Do start of follow-up and start of intervention coincide for most participants?	Y / PY / PN / N / NI

2.5. If Y/PY to 2.2 and 2.3, or N/PN to 2.4: Were adjustment techniques used that are likely to correct for the presence of selection biases?	NA / Y / PY / PN / N / NI
Domain 3: Bias in classifications of intervention	
Signaling questions	**Response options**
3.1 Were intervention groups clearly defined?	Y / PY / PN / N / NI
3.2 Was the information used to define intervention groups recorded at the start of the intervention?	Y / PY / PN / N / NI
3.3 Could classification of intervention status have been affected by knowledge of the outcome or risk of the outcome?	Y / PY / PN / N / NI
Domain 4: Bias due to deviations from intended interventions	
Signaling questions	**Response options**
4.1. Were there deviations from the intended intervention beyond what would be expected in usual practice?	Y / PY / PN / N / NI
4.2. If Y/PY to 4.1: Were these deviations from intended intervention unbalanced between groups and likely to have affected the outcome?	NA / Y / PY / PN / N / NI
4.3. Were important co-interventions balanced across intervention groups?	Y / PY / PN / N / NI
4.4. Was the intervention implemented successfully for most participants?	Y / PY / PN / N / NI
4.5. Did study participants adhere to the assigned intervention regimen?	Y / PY / PN / N / NI
4.6. If N/PN to 4.3, 4.4 or 4.5: Was an appropriate analysis used to estimate the effect of starting and adhering to the intervention?	NA / Y / PY / PN / N / NI
Domain 5: Bias due to missing data	
Signaling questions	**Response options**
5.1 Were outcome data available for all, or nearly all, participants?	Y / PY / PN / N / NI
5.2 Were participants excluded due to missing data on intervention status?	Y / PY / PN / N / NI
5.3 Were participants excluded due to missing data on other variables needed for the analysis?	Y / PY / PN / N / NI
5.4 If PN/N to 5.1, or Y/PY to 5.2 or 5.3: Are the proportion of participants and reasons for missing data similar across interventions?	NA / Y / PY / PN / N / NI
5.5 If PN/N to 5.1, or Y/PY to 5.2 or 5.3: Is there evidence that results were robust to the presence of missing data?	NA / Y / PY / PN / N / NI
Domain 6: Bias in measurement of outcomes	
Signaling questions	**Response options**
6.1 Could the outcome measure have been influenced by knowledge of the intervention received?	Y / PY / PN / N / NI
6.2 Were outcome assessors aware of the intervention received by study participants?	Y / PY / PN / N / NI
6.3 Were the methods of outcome assessment comparable across intervention groups?	Y / PY / PN / N / NI
6.4 Were any systematic errors in measurement of the outcome related to intervention received?	Y / PY / PN / N / NI
Domain 7: Bias in selection of the reported results	
Signaling questions	**Response options**
Is the reported effect estimate likely to be selected, on the basis of the results, from... 7.1. ... multiple outcome measurements within the outcome domain?	Y / PY / PN / N / NI
7.2 ... multiple analyses of the intervention-outcome relationship?	Y / PY / PN / N / NI
7.3 ... different subgroups?	Y / PY / PN / N / NI