THE *LANCET* COVID-19 COMMISSION
TASK FORCE ON SAFE WORK,
SAFE SCHOOL, AND SAFE TRAVEL

Designing infectious disease resilience into school buildings through improvements to ventilation and air cleaning

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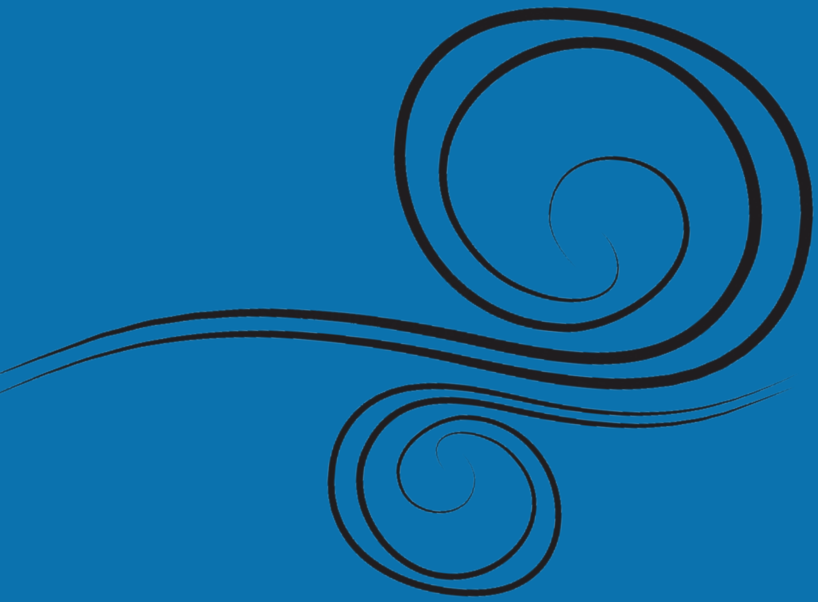

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THE *LANCET*
COVID-19 COMMISSION

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OVERVIEW

Many countries have prioritized schools in their COVID-19 pandemic recovery plans, including providing funding to support costs associated with reopening safely. These resources represent a once-in-a-generation opportunity for health-based improvements to school buildings, such as improving indoor air quality (IAQ), which can reduce the risk of airborne infectious disease transmission as well as benefit health and academic performance. Unfortunately, there are reports of schools spending millions of dollars on unproven or largely ineffective air cleaning technologies like ionizers and other measures such as surface disinfection supplies.[1-5]

School infrastructure has been chronically underfunded, and schools may never see another influx of monies like this. Therefore, it is imperative that pandemic relief for schools be applied to enhancements that are evidence-based, provide long-term value, and do not create additional pollutants that may be harmful to the health of students, teachers, and staff. In this report, we provide a brief overview of the science on ventilation and air cleaning in schools, and then provide a guide on how to direct resources toward building-level public health interventions in school buildings that are best supported by scientific evidence to reduce the risk of COVID-19 transmission and promote long-term health and academic performance.

BUILDINGS PLAY A CRITICAL ROLE IN THE TRANSMISSION OF AIRBORNE INFECTIOUS DISEASES

Buildings play a critical role in minimizing, or conversely exacerbating, the spread of airborne infectious diseases. COVID-19 outbreaks occur indoors,[6] and within-room long-range transmission beyond two meters (six feet) has been well-documented in conditions with no masking and low ventilation rates.[7-12] However, the relationship between building systems and airborne infectious disease transmission predates SARS-CoV-2, the virus that causes COVID-19. Building-related interventions have been shown to reduce the spread of many other airborne infectious diseases, including severe acute respiratory syndrome (SARS), Middle East respiratory syndrome (MERS), tuberculosis, measles, and influenza. [13-17] Following the 2009 H1N1 influenza A pandemic, an epidemiological investigation at a boarding school in Guangzhou, China found that opening windows for outdoor air ventilation was the only control measure that had significantly protected against infection.[18] Other research confirmed that enhanced outdoor air ventilation can reduce influenza[19] and tuberculosis[14] transmission in school buildings. Similarly, upper-room ultraviolet (UV) germicidal irradiation installed in Philadelphia-area schools substantially reduced measles spread during an epidemic.[20]

As of early 2021, no in situ research has evaluated the independent impact of ventilation and air cleaning for reducing the risk of COVID-19 transmission in schools. However, there are a number of studies in which enhanced ventilation was used as part of layered risk reduction strategy, resulting in the successful reduction of COVID-19 infections. For example, COVID-19 cases and mitigation strategies were tracked in schools in two cities in Missouri in December 2020. Schools that used a combination of mitigation strategies including improved outdoor air ventilation were found to have lower rates of transmission compared to the rest of the community.[21] COVID-19 transmission among children in Baden-Württemberg, Germany was also rare in schools and childcare settings that employed mitigation strategies which included improved ventilation.[22]

Conversely, inadequate outdoor air ventilation has been explicitly implicated in several large COVID-19 outbreaks across various indoor environments. Case studies have included a choir rehearsal with poor ventilation and no masks;[10] a meat processing facility with low air exchange rates and high rates of unfiltered recirculated air;[23] a spin class without masks and inadequate air circulation;[24] a bus with an air conditioning system on recirculating mode,[12] and a restaurant with poor ventilation and an air conditioner that recirculated air through the dining room.[25] These counterexamples demonstrate that building-level strategies, including ventilation and air cleaning, are key components of risk reduction strategies for airborne infectious diseases including COVID-19.

SCHOOLS ARE CHRONICALLY UNDER VENTILATED

Current ventilation and air cleaning standards for buildings are not designed with a focus on reducing airborne infectious disease transmission; they are designed for comfort and minimally acceptable IAQ, focusing largely on controlling temperature, pollutants emitted from the human body, and other common chemical exposures. As a result, most buildings are not designed or operated in a manner that supports the rapid dilution or removal of infectious respiratory particles.

Most schools do not meet even the minimum American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) ventilation design standard of approximately five liters per second per person (l/s/p).[26,27] For example, in a study of 100 US classrooms, 87 had ventilation rates below recommended minimum standards.[28] A study in Texas found similar results; excessive peak CO_2 concentrations were identified in up to 88% of elementary school classrooms, and time-averaged CO_2 concentrations exceeded recommended thresholds in 66% of classrooms, suggesting inadequate ventilation rates.[29] In a recent study of 46 classrooms across seven high schools, the mean and median ventilation rates were one half to one third of minimum standards.[30] Further, in an international review of classrooms in more than thirteen countries, a widespread failure to provide the minimum ventilation rate was revealed.[27]

HEALTH CO-BENEFITS GO BEYOND DISEASE TRANSMISSION

The benefits of improving IAQ and increasing ventilation rates above minimum standards go well beyond COVID-19 and disease avoidance, underscoring the significance of historic underventilation and poor IAQ in schools. Nearly one in thirteen children in the US has asthma, which is triggered by indoor allergens commonly found in schools, and is the leading cause of school absenteeism due to chronic illness.[31] Components of outdoor air pollution can penetrate inside buildings; childhood exposure to this air pollution can impact neurodevelopment and academic performance, and can lead to childhood cancer.[32] Children who have been exposed to high levels of air pollution may also be at greater risk for chronic diseases such as cardiovascular disease later in life.[32] In particular, schools in developing countries and students of lower socio-economic status are disproportionately impacted by indoor air pollution.[33,34] These schools are typically closer in proximity to busy roads or other environmental hazards. In addition, they are more likely to be overcrowded and underfunded, with aging infrastructure and fewer resources for adequate building maintenance. Further, indoor sources of pollution, such as volatile organic compounds (VOC) commonly found from cleaning products, off-gassing from building materials, and other arts and crafts supplies degrade IAQ and impact student and teacher health.[35,36] Classroom exposures to allergens, outdoor air pollution that penetrates indoors, and pollution from indoor sources can all be reduced by proper ventilation and air cleaning.

In addition to decreased airborne infectious disease transmission, research shows that ventilation and air cleaning improvements are likely to lead to improved academic performance (in particular reading and math performance),[27,28] fewer missed school days for students,[37] higher scores on cognitive function tests,[38] and many benefits for teachers including decreased respiratory symptoms,[39] increased teacher retention,[40] and improved morale.[41] Further evidence supporting the diverse benefits of ventilation and air cleaning improvements in schools is detailed in Table 1.

HEALTHY SCHOOL BUILDING INTERVENTIONS FOR AIRBORNE INFECTIOUS DISEASES MUST BE EVIDENCE-BASED

To provide schools with strategic, evidence-based guidance for healthy building-level interventions to reduce risk of airborne infectious disease transmission in schools, we recommend prioritizing the following five control strategies.

1. **Commission buildings and examine existing systems.** Commissioning is the process of checking heating, ventilation, and air conditioning (HVAC) performance to ensure that systems are operating as designed. Schools should engage with trained professionals to verify building performance after long periods of vacancy, and then should conduct intermittent commissioning every three to five years to identify and resolve building issues on an ongoing basis. The use of sensors to monitor CO_2 concentrations in real-time as a proxy for ventilation is also

Table 1. Additional benefits of higher ventilation and improved air quality in schools beyond airborne infectious disease transmission.

Impact of Ventilation	Context	Findings	Reference
↑ Test scores	Ventilation renovations were completed to improve IAQ in all school buildings within a single Texas school district.	Math and reading test scores significantly improved, with an increased probability of passing by 2% and 3%, respectively.	42
↑ Cognitive function	CO_2 concentrations were measured as a proxy for ventilation rates in classrooms.	Cognitive testing of students shows a 5% decrease in 'power of attention' in poorly ventilated classrooms. Researchers equate this to the effect of a student skipping breakfast.	38
↑ Math, reading, and science scores	Classroom ventilation rates were measured in 140 fifth grade US classrooms.	Mean mathematics scores increased by up to 0.5% per each liter per second per person increase in ventilation rate, with similar effects on reading and science scores.	43
↓ Asthma symptoms	Exposure factors were measured in 100 primary and secondary school classrooms with and without new ventilation systems.	Pupils who attended schools with new ventilation systems reported fewer asthmatic symptoms.	44
↓Respiratory symptoms ↓ Missed school days	Over 4,000 sixth graders from 297 schools participated in a survey of indoor environmental quality in schools.	Lower ventilation rates, moisture, and dampness were all independently associated with a higher incidence of respiratory symptoms. Inadequate ventilation was also associated with more missed school days.	45
↓Child absenteeism	Increased ventilation rates and child sick days were studied for 635 children attending 20 day-care centers in Denmark.	A 12% decrease in sick days was found per hour increase in the air exchange rates.	46
↓ Missed school days	CO_2 as a proxy for ventilation was studied in 60 naturally ventilated primary school classrooms in Scotland.	For each 100 ppm increase in time average CO_2 concentration, student attendance decreased by about 0.4 days per year.	47
↓Illness absence	CO_2 concentration was measured continuously over two years in 162 US primary school classrooms with a mixture of mechanical and natural ventilation.	For each 1 L/s (2.2 cfm) per occupant increase in ventilation rate, illness absence decreased 1.6%.	26

recommended as a continuous strategy to ensure ventilation systems are performing as intended. The cost of commissioning a building varies depending on building size, age, and location, but is typically considered to be highly cost effective, and provides several additional benefits beyond controlling infectious disease transmission. These additional benefits include significant energy savings and associated greenhouse gas emissions reductions (e.g., median 16% whole-building energy savings), reduced operating costs (e.g., median cost benefit ratio of 4.5), and improved overall IAQ (e.g., in a sample of 10 US schools, 37% of the issues identified during commissioning improved IAQ).[48]

2. **Ventilate with clean outdoor air.** Ventilation improvements are recommended to dilute the concentration of airborne virus. We recommend that the dilution exceed the recommended minimum acceptable standards for ventilation rates. To the extent possible, schools should maximize outdoor air delivery and minimize or eliminate recirculation of unfiltered air during a pandemic. (In cases where ventilation equipment, outdoor air pollution, or safety concerns limit the ability to ventilate with sufficient outdoor air, schools should focus on air cleaning as described below. Alternatively, concerns about using polluted outdoor air for ventilation can be addressed by pairing ventilation with other solutions, such as sorption filtration for nitrogen oxides and ozone.) The net annual costs of increasing ventilation rates above minimum standards in schools have been estimated at less than 0.1% of typical public spending on elementary and secondary education in the US.[27]

3. **Improve the building's air cleaning efficiency through evidence-based air cleaning treatment such as filtration.** Improving the air cleaning efficiency on recirculated air can help remove infectious particles from air throughout the building. Schools should use an air filter rated at the highest possible efficiency for the system's design, and review airflow patterns to ensure that sufficient airflow is maintained across the filter. Schools should aim to switch from a Minimum Efficiency Reporting Value (MERV) 8 to a MERV 13 or higher. If the HVAC system cannot maintain flow across the filter, then installing one with as high a rating as possible is still beneficial. Studies have found relatively low costs for purchasing, installing, and maintaining HVAC filtration systems with enhanced efficiency ratings; for example, across a variety of climate zones, the total annual cost of MERV 13 filtration for recirculating air was estimated at $156 for a typical commercial building.[49]

4. **If the ability to upgrade ventilation and air cleaning is limited, use portable air cleaners with high efficiency particulate air (HEPA) filtration.** In schools without mechanical ventilation systems (or without the ability to meet improved ventilation demands), or in schools that cannot support higher efficiency HVAC filtration, properly sized portable air cleaners (sized in relation to the volume of the space), with HEPA filters and high clean air delivery rates can be effective in reducing exposures to airborne infectious respiratory particles. Portable air cleaners can significantly increase the clean air supply in a classroom, and therefore can be considered a cost-effective supplementary measure where the total ventilation airflow rate is insufficient.[50]

5. **Consider other evidence-based air cleaning approaches in the context of existing strategies.** If improved ventilation and air cleaning through filtration is not possible, then other science-based technologies should be considered, such as in-duct germicidal UV lights or upper-room germicidal UV. UV technology has been well-studied and utilized for decades to control transmission of airborne infectious diseases, and the Centers for Disease Control and Prevention (CDC) have provided guidelines for effective design and operation of such systems. This approach can be particularly cost effective in larger spaces, or spaces that are not ventilated.

Other strategies that have recently been implemented or considered in many schools (such as bipolar ionization, plasma systems, portable air cleaning units with ionizers or UV, dry hydrogen peroxide, photocatalytic oxidation) are generally considered less scientifically defensible due to their often unproven efficacies and due to their potential for degrading the quality of the air through the generation of harmful secondary pollutants.[51-54] Untargeted and excessive deep surface cleaning efforts (e.g., using foggers or electrostatic sprayers) should not be employed for the same reasons.[55] Instead, schools should focus their resources on reducing the risk of SARS-CoV-2 airborne transmission.

The cost of ventilation and air cleaning upgrades can vary depending on the region, the condition of the existing building, and the size of the school, but generally, maximizing the delivery of clean outdoor air and improving air cleaning efficiency are less expensive than other efforts,[56] especially when accounting for the additional return on investment associated with the long-term benefits of increased ventilation and improved air quality in schools.

VENTILATION AND AIR CLEANING ENHANCEMENTS CAN ALLOW SAFE REOPENING AND PROVIDE LONG-TERM VALUE

There is an urgent need for facility improvements to help schools that are open to stay open, and help those that are closed to safely reopen. The cost of school closures due to the COVID-19 pandemic are devastating – these include academic losses and increases in mental health issues across all ages.[57-60] Examples include increased reports of suicidal thoughts among young adults in some locations;[58] lack of access to food;[61] mass 'virtual dropouts';[62,63] and reports of higher risk of abuse, neglect, exploitation, and violence, particularly among girls.[64-66] These issues disproportionately affect the most disadvantaged children, deepening existing inequalities.

Building-level strategies to reduce the risk of airborne infectious disease transmission in schools must be considered in the context of a layered defense approach. Masks are a critical control strategy during an airborne infectious disease pandemic because they significantly reduce the concentration of infectious respiratory particles emitted by the wearer who is infected ('source control'), and reduce the concentration of particles breathed in by the wearer who is susceptible ('receptor').[67] However, masks vary with respect to filtration efficiency and fit, resulting in the imperfect capture of respiratory particles.[68] Once infectious aerosol are released into the indoor environment, ventilation and air cleaning play critical roles in reducing infection risk by diluting, removing, and inactivating infectious respiratory particles that can accumulate in indoor air. Maintaining distance between individuals can also mitigate the effects of imperfect capture of respiratory particles by masks.

Policy makers, public health officials, educators, and parents must work together using limited resources to reopen schools safely, and keep them open – not only during this pandemic, but in the event of future disease outbreaks as well. As government pandemic relief becomes available to schools, there is an unprecedented opportunity to address a decades-long neglect of school building infrastructure, but also a significant risk of squandering funds on inappropriate, unproven and/or ineffective technologies. Robust and smart investments in healthy school buildings are essential, cost effective tools for safely reopening schools, in addition to providing many substantial benefits well beyond infection mitigation.

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