COVID-19 Scientific Advisory Group
Rapid Evidence Report

Key Research Question:

Has there been documented transmission of SARS-CoV-2 virus (or similar viruses) through Heating, Ventilation, and Air Conditioning (HVAC) systems in hospitals or non-hospital settings?

Context

- Respiratory viruses are believed to transmit over multiple routes and the relative significance between aerosol and droplet transmission may vary among pathogens.
- The Public Health Agency of Canada (2020) and the World Health Organization (2020) consider the route of human-to-human transmission of SARS-CoV-2 to be predominantly via respiratory droplets or contact during close and unprotected contact, with a recommendation to use N95 respirators only in the context of aerosol-generating medical procedures.
- A reported outbreak of COVID-19 in an air-conditioned restaurant in Guangzhou, China that involved three family clusters was attributed to a longer range of droplet transmission, with the authors suggesting that was related to airflow generated by air conditioned ventilation but uncertainty over means of transmission remained.
- University of Alberta researchers have received research funding from the Canadian Institutes for Health Research to examine how SARS-CoV-2 may be transmitted through airborne fine particles, and how its movement is controlled by current HVAC designs in non-healthcare settings.
- There is concern about the possibility of promoting transmission of SARS-CoV-2 through HVAC systems inside and outside hospital settings.
- Evaluating the relative contribution of airborne versus droplet and contact transmission of SARS-CoV-2 is beyond the scope of this review. However, this review is presented under the working assumption that SARS-CoV-2 is primarily transmitted through respiratory droplets or contact and potentially short-range aerosols.
- Standards exist for the construction and maintenance of HVAC systems in healthcare and other settings, therefore recommendations for HVAC system design are beyond the scope of this review.

Key Messages from the Evidence Summary

- There is no clear evidence to date of transmission of SARS-CoV-2 associated with HVAC systems in hospitals or health care facilities, although there is a mechanistic possibility of this occurring. Studies that have identified the presence of viral RNA in procedure generated aerosols have not demonstrated viable virus that would be capable of infecting susceptible hosts, however viral culture may be relatively insensitive.
- There is epidemiologic evidence that HVAC conditions may have contributed to transmission of SARS-COV-2 in community settings including a restaurant, call centre and airplane, though in these events spread through close contact was not ruled out, and longer distance localized droplet spread related to airflow (given proximity to the index cases) is more likely than classic airborne transmission.
- The need to assess HVAC systems in the control of SARS-CoV-2 and other viruses is highlighted by various interim guidelines (Saran et al., 2020). Notably, rooms with higher air exchanges tend to have less viral RNA detected in the air, based on the literature identified.
- Given the complexity in the transmission modalities of SARS-CoV-2 and other similar viruses, lack of data on viable virus in air samples, and the wide variety of HVAC systems, studies have not been able to consider and evaluate all HVAC configurations and their potential to affect transmission of infection.

- Epidemiologic studies have not measured the role of ventilation systems and adequately quantifying ventilation rates and their effect on viral load has been challenging (Luongo et al., 2016).
- Studies on the 2003 SARS-CoV outbreak in Hong Kong suggested a possible role of airborne transmission in a major nosocomial outbreak, possibly assisted by imbalanced indoor airflow in an HVAC system in addition to other mechanisms of spread.
- HVAC system factors in buildings may have a role in pathogen transmission and control in hospital and non-hospital settings, particularly in the setting of aerosol generating procedures and/or when HVAC systems are not functioning properly; however more robust studies are needed to explore their direct role in transmitting and removing viable viruses within respiratory droplets or short-range aerosols.
- Measurement of indoor air quality and development of methods to improve the removal of infectious respiratory droplets and short-range aerosols in non-hospital community settings (restaurants, gyms, stores, public transportation) would support other public health measures such as social distancing and the use of masks in the community, to reduce resurgence risk of SARS-CoV-2 outbreaks associated with relaxation of public health restrictions.

Committee Discussion

Based on the evidence identified, the committee felt there is no compelling evidence of documented transmission of SARS-CoV-2 through HVAC systems and so key messages were revised. Further, some reviewers highlighted that this review should focus on viruses most similar to SARS-CoV-2, which would include SARS-CoV, MERS-CoV and other coronaviruses over influenza or other pathogens. The literature search did include other viruses with limited restrictions, however there was not a substantive number of studies identified related to other viruses and HVAC systems, including Influenza. While the committee acknowledged the focus on coronaviruses, it felt the studies of influenza provided helpful context. Additional references were provided by committee members to include in this review. These references were reviewed and included if they evaluated or discussed the role of HVAC systems in the movement or transmission of SARS-CoV-2 or similar viruses.

The key messages and recommendations were discussed and there was consensus for all except the first key message, where one reviewer felt there is strong evidence to indicate that this mode of transmission exists under certain circumstances ('opportunistic'), and that it is mechanistically probable. A reviewer also suggested that, consistent with AHS Infection Prevention and Control recommendations, the ‘negative pressure’ rooms in all AHS hospitals should be checked for correctness of airflow (ie, not reversed to ‘positive’ pressure, and all COVID units checked for airflow imbalance. Following the meeting, another reviewer shared a new paper that provides useful guidance for engineers to minimize indoor airborne transmission in public buildings (L. Morawska et al., 2020). Key recommendations include increasing ventilation rates and effectiveness; eliminating recirculation; using portable air cleaners in areas with poor circulation; using disinfection devices such as germicidal ultraviolet irradiation in crowded, poorly ventilated environments; and ensuring adequate replacement of filters (L. Morawska et al., 2020).

Recommendations

1. We recommend that the CMOH advocate for a provincial multidisciplinary team consisting of HVAC engineers, medical and public health experts (e.g. Epidemiologists, microbiologists, virologists, infectious diseases experts, health economists, infectious disease modelers etc.) to be established to explore the role of HVAC systems in the transmission of viral pathogens including SARS COV-2. These teams should strive to use robust epidemiologic, engineering, and aerodynamics/aerobiology study designs to identify associations between virus detected by PCR or culture collected from aerosols and the environment, with viable virus and ultimately with transmission.
2. It is recommended that healthcare facility maintenance and engineering HVAC teams continue to follow, and ensure clear documentation of their facilities’ ongoing adherence to CSA standards.
3. Facility operations leads should periodically request and review documented HVAC measurements of airflow levels in negative pressure rooms, surgical operation and procedure rooms and COVID isolation units to ensure that they are meeting the expected requirements.

Practical Considerations

1. Facilities maintenance and engineering departments and staff for hospitals and non-hospital public buildings should consult the standards and practice guidance provided by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), the Canadian Standards Association (CSA), the European Federation of Heating and Ventilation Engineers (RHEVA), and Chartered Institution of Building Services Engineers (CIBSE) on how to *operate* and use building services to minimize the spread of any potential pathogens through HVAC systems. This is particularly important in the setting of COVID-19 wards /hospitals, and should include assessment of airflow in care areas.
2. Practical recommendations for *non-hospital public settings* include, but are not limited to, increasing air supply and exhaust ventilation for extended operation times, keep exhaust ventilation systems of toilets on continuously, supply as much outside air as reasonably possible (except in toilet rooms/washrooms), do not change humidification systems' setpoints, and avoiding central recirculation (REHVA, 2020).
3. In 2007, the World Health Organization released new guidelines promoting natural ventilation for infection control in health care and described the basic principles of how to design, construct, operate and maintain an effective natural ventilation system (Atkinson et al., 2009). It should be noted that the *design* of HVAC systems is regulated and legislated by the Alberta Building Code (by the version in force when the building was designed), based on the Canadian Building Code, which references the applicable CSA and ASHRAE standards.

Research Gaps

1. Based on the reviews highlighted below by Li et al (2007) and Luongo et al. (2016) and the committee discussion, the role of HVAC system factors in buildings in the transmission of pathogens requires additional attention. Organizations such as ASHRAE and CSA are committed to supporting research that advances the knowledge base of indoor air-management strategies and standards aimed to reduce exposure to infectious aerosols (ASHRAE, 2020a). Expansion of these teams needs to include medical and public health experts (e.g. epidemiologists, microbiologists, infectious diseases experts, health economists, infectious disease modelers, virologists etc.) to explore the role of HVAC systems in the transmission of viral pathogens, including SARS-CoV-2 using robust epidemiologic, aerodynamic or aerobiology and virologic study designs. This expanded team would aim to identify associations between viral particles collected from aerosols and the environment with viable virus capable of infecting susceptible hosts.

2. In the context of hospital or other healthcare settings, infection prevention and control and facilities management departments have developed working relationships to ensure new or maintenance projects with HVAC systems meet standards, guidelines and recommendations required to reduce transmission of pathogens through these systems. This partnership can be enhanced with the inclusion of additional researchers in the fields of infectious diseases epidemiology or modeling and engineering.

Strength of Evidence

Given the complexities of the function of HVAC systems in different physical environments and settings, assessing the quality of evidence in engineering study designs was not feasible. The epidemiologic study designs were observational in nature, with small sample sizes and lacked comparator groups and thus considered of low quality. Most articles related to SARS-CoV-2 were preprints.

Limitations of this review

This review did not include aerodynamic or aerobiology studies of SARS-CoV-2 or other viruses which aim to identify and quantify the presence or viral load in the air. Studies included were those that considered the role of HVAC systems in the movement of these viruses across environments which could have contributed to transmission among humans. The viruses considered like SARS-CoV-2 in transmissibility and included in this review were SARS-CoV, MERS-CoV, and Influenza. Information from the studies presented here have not been critically appraised. This is attributed to the limited understanding of HVAC systems and methodologies used to test factors of these systems in the context of epidemiologic studies on outbreaks.

Summary of Evidence

A total of 80 abstracts were identified using the search strategies. Of these, 24 of these were retrieved for full article review. Twelve of the 24 were included in the summary below, and 20 additional references (primary and grey literature) were identified through bibliographies of relevant articles or through additional Google searches.

Evidence from secondary and grey literature

American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), the **European Federation of Heating and Ventilation Engineers (RHEVA)**, and **Chartered Institution of Building Services Engineers (CIBSE)** - the United Kingdom member of RHEVA - have developed guidance on how to operate and use building services to minimize the spread of the virus through HVAC systems. These organizations offer guidance based on the fact that HVAC systems impact on the distribution and bio-burden of infectious aerosols and that these infectious aerosols can pose an exposure risk, regardless of whether a disease is classically defined as an airborne infectious disease (ASHRAE, 2020a, 2020b; CIBSE, 2020; REHVA, 2020).

ASHRAE released a statement on 14 April 2020 indicating that the transmission of SARS-CoV-2 through the air is sufficiently likely that airborne exposure to the virus should be controlled. Changes to building operations, including the operation of heating, ventilating and air conditioning systems can reduce airborne exposures. Ventilation and filtration provided by HVAC systems can reduce airborne concentration of SARS-CoV-2 and thus the risk of transmission through the air (ASHRAE, 2020b).

In response to the COVID-19 outbreak the CSA Group has made a selection of relevant standards available for organizations. These standards include CSA Z317.2:19: Special requirements for HVAC systems in health care facilities and CAN/CSA-Z317.13-17: Infection control during construction, renovation, and maintenance of health care facilities, among others (CSA, 2020).

The Centers for Disease Control and Prevention have also published guidelines for environmental infection control in healthcare facilities based on expert consensus among authorities having jurisdiction, governmental regulatory agencies, healthcare professionals, professional organizations and accrediting organizations. These guidelines are not specific to SARS-CoV-2 but reflect the overall purposes of HVAC systems in healthcare facilities (CDC, 2003). More recently, the CDC published guidelines and recommendations for employers in preparation for reopening businesses and office buildings, primarily based on ASHRAE standards. These included ensuring ventilation systems operate properly, increasing percentage of outdoor air, increase total airflow supply to occupied spaces, disabling demand-control ventilation controls that reduce air supply based on temperature or occupancy, using natural ventilation, improving central air filtration, running the ventilation system during unoccupied times, generating clean-to-less-clean air movement, considering using portable high-efficiency particulate air (HEPA) fan/filtration systems, ensuring exhaust fans in restroom facilities are functional and operating, and considering using ultraviolet germicidal irradiation as a supplement (CDC, 2020).

Evidence from the primary literature

Li et al. (2007) conducted a systematic review of the literature from 1965 to March 2005 to examine whether there was sufficiently strong evidence to substantiate contributory role of ventilation rates and airflow patterns in the airborne transmission of infectious agents in different indoor settings (Y. Li et al., 2007). The authors included a multidisciplinary panel of experts in medicine and public health and engineering. Their review focused on source-to-person airborne transmission, without an intermediate non-air medium such as fomites. Of the 40 studies included, 12 were partly conclusive and 10 were clearly conclusive in supporting the role of ventilation rate or airflow pattern to the airborne spread of infectious agents. They concluded that there is strong and enough evidence to demonstrate the association between ventilation, air movements in buildings and the transmission or spread of infectious diseases such as measles, tuberculosis, chickenpox, influenza, smallpox and SARS. There is insufficient data to specify and quantify the minimum ventilation requirements in hospitals, schools, offices, homes and isolation rooms in relation to spread of infectious diseases via the airborne route. Many of the epidemiological studies did not include adequate airflow studies (Y. Li et al., 2007).

Luongo et al. (2016) systematic review assessed epidemiologic studies published after 2000 and investigating the association of at least one HVAC-related parameter with an infectious disease-related outcome in buildings. The authors indicate that the data implies that HVAC system factors in buildings have a role in airborne pathogen transmission, but more robust, interventional studies are needed (Luongo et al., 2016).

SARS-CoV-2 & HVAC Systems in Healthcare Settings

Liu et al. (2020) investigated the aerodynamic nature of SARS-CoV-2 by measuring viral RNA in aerosols in different areas of two Wuhan hospitals during the COVID-19 outbreak in February and March 2020 (Liu et al., 2020). They collected thirty-five aerosol samples of three different types (total suspended particles, size-segregated, and deposition aerosol) in Patient Areas (PAA) and Medical Staff Areas (MSA) of Renmin Hospital of Wuhan University (Renmin) and Wuchang Fangcang Field Hospital (Fangcang), and Public Areas (PUA) in Wuhan, China during the outbreak. The ICU, CCU and general patient rooms inside Renmin, patient hall inside Fangcang had undetectable or low airborne SARS-CoV-2 concentration but deposition samples inside ICU and air sample in Fangcang patient mobile toilet room tested positive. The toilet room was a temporary single toilet room of approximately 1m^2 in area without ventilation and had the highest viral load detected (19 copies/m^2). The airborne SARS-CoV-2 in Fangcang MSA had bimodal distribution with higher concentrations than those in Renmin during the outbreak but were negative after number of patients were reduced and rigorous sanitization was implemented. Public areas had undetectable airborne SARS-CoV-2 concentration but obviously increased with accumulating crowd flow. The authors interpreted this to suggest overall low risks in the well ventilated or open public venues. The authors also concluded that room ventilation, open space, proper use and disinfection of toilets can effectively limit aerosol transmission of SARS-CoV-2. For example, the negative pressure ventilation and high air exchange rate inside ICU, CCU and ward room of Renmin Hospital were effective in minimizing airborne SARS-CoV-2. The authors further concluded that transmission within crowds via airborne transmission is possible. The virus aerosol deposition on protective apparel or floor surface and their subsequent resuspension is a potential transmission pathway and effective sanitization is critical in minimizing aerosol transmission of SARS-CoV-2 (Liu et al., 2020).

Guo et al. (2020) tested surface and air (including air outlets) samples for SARS-CoV-2 using real-time PCR from an ICU and a general COVID-19 ward at Huoshenshan Hospital in Wuhan, China (Guo et al., 2020). Thirty-five percent (14/40) of the samples collected from the ICU and 12.5% (2/16) of the general ward samples were positive. Air outlet swab samples also yielded positive test results, with positive rates of 66.7% (8/12) of ICUs and 8.3% (1/12) for general wards. Rates of positivity differed by air sampling site with 44.4% (8/18) samples in patients' rooms, 35.7% (5/14) near air outlets and 12.5% (1/8) in the doctors' office area. The authors indicate that virus-laden aerosols were mainly concentrated near and downstream from the patients, with a maximum transmission distance of 4m. The air sampling sites in the general ward were distributed in different regions around the patient, under the air inlet, and in the patient corridor. Only air samples around the patient were positive. One of their conclusions was that SARS-CoV-2 was widely distributed in the air and on surfaces but did not associate this with HVAC systems (Guo et al., 2020). Both this and the Liu et al. (2020) study noted above are limited by the lack of viable virus testing. It is unclear whether environmental contamination with viral RNA contributes to clinical infection.

Ong et al. (2020) collected surface environmental samples at 26 sites from three airborne infection isolation rooms (12 air exchanges per hour) with anterooms and bathrooms in the dedicated SARS-CoV-2 outbreak center in Singapore between January 24 and February 4, 2020. Note: viral culture was not done to demonstrate viability. There was extensive environmental contamination by one SARS-CoV-2 patient with mild upper respiratory tract involvement. Toilet bowl and sink samples were positive, suggesting that viral shedding in stool[5] could be a potential route of transmission. Post-cleaning samples were negative, suggesting that current decontamination measures are sufficient. Air samples were negative despite the extent of environmental contamination. Two of the three swabs taken from the air exhaust outlets tested positive, suggesting that small virus-laden droplets may be displaced by airflows and deposited on equipment such as vents. The authors conclude the environment is a potential medium of transmission and supports the need for strict adherence to environmental and hand hygiene.

No viral culture was done to demonstrate viability, methodology was inconsistent and sample size was small(Ong et al., 2020).

Santarpia et al. (2020) from the University of Nebraska Medical Center and its clinical partner Nebraska Medicine, monitored and cared for 13 individuals with confirmed SARS-CoV-2 infections (Santarpia et al., 2020). These patients were managed in the Nebraska Biocontainment Unit (NBU) for individuals requiring hospital care and the National Quarantine Unit (NQU) for isolation of asymptomatic or mildly ill patients not requiring hospital care. All the rooms had private bathrooms and were negative pressure equipped. They obtained surface samples, high volume air samples and low volume personal air samples in two NBU and nine NQU rooms where patients who tested positive for SARS-CoV-2 were being monitored. Room surfaces included ventilation grates, tabletops and window ledges. Air samples were collected in the rooms while patients were present. Surface and aerosol samples were analyzed by RT-PCR. Of the 163 samples collected, 77.3% were positive for SARS-CoV-2. Viral gene copy concentrations recovered from each sample were generally low and highly variable ranging from 0 to 1.75 copies/µL. The highest concentration recovered was from an air handling grate in the NBU. No air samples that were positive by RT-PCR demonstrated viral propagation or viral replication using relevant methods. The authors note the presence of viral RNA on the floor under the bed and on the window ledges and suggest that airflow may have played a role. In the NBU suite, airflow enters from the top centre of the room and exits at grates near the head of the patient's bed on either side of the room. They reference airflow modelling suggesting that turbulent eddies may form under the patient's bed causing contamination under the bed, while the dominant airflow likely carried particles away from the bed towards the edges of the room, likely depositing particles by the windows. However, these researchers did not conduct aerodynamic or computational modeling to support this hypothesis in this context.

SARS-CoV-2 & HVAC Systems in Non-Healthcare Settings

Much of the discussion surrounding the role of HVAC systems have stemmed from the report by **Lu et al. (2020)** (Lu et al., 2020)**.** They reported an outbreak of COVID-19 in an air-conditioned restaurant in Guangzhou, China, that involved three family clusters. The distance between each table at the restaurant was about 1 m and Families A and B and Families A and C were each seated for an overlapping period of time ranging from 53 minutes to 73 minutes, respectively. The air outlet and return air inlet for the central air conditioner were located above the table with Family C. On this same day, a total of 83 people had eaten in the same dining area and 10 became ill with COVID-19, the remaining 73 were close contacts and quarantined for 14 days. None of these 73 contacts developed symptoms, throat swab samples were negative, and 6 smear samples from the air conditioner were negative for SARS-CoV-2 by RT-PCR. The authors concluded that the most likely cause of the outbreak was droplet transmission and that the transmission was prompted by air-conditioned ventilation as a result of the direction of airflow. However, they do note that the negative smear samples from the air conditioner is less consistent with aerosol transmission. The authors recommended strengthening temperature-monitoring surveillance, increasing the distance between tables, and improving ventilation; however, with respect to ventilation the author did not provide specific direction or guidance.

A review and commentary of this report by **Public Health Ontario (2020)** highlights that only contacts seated within the closest tables along airflow lines became infected, which provides evidence of droplet transmission (PHO, 2020). It does not definitively establish the route of transmission; however, the finding that no other patrons or staff were infected aside from those seated at neighbouring tables, suggests lack of airborne transmission. A weakness is that the authors did not conduct any aerodynamic testing to support their hypothesis. The authors focused on potential droplet transmission at the restaurant and did not explore other possibilities, such as indirect transmission of fomites (PHO, 2020).

Li et al. (2020) go further to describe the restaurant outbreak and investigated the possibility of aerosol transmission of SARS-CoV-2 using spatial distribution data from the outbreak, computer models and experiments based on airflow dynamics (Y. Li et al., 2020). The authors collected epidemiological data, obtained a video record and patron-seating arrangement from the restaurant and measured the dispersion of a warm air tracer gas as a surrogate for exhaled droplets from the suspected index patient. Computer simulations were performed to simulate the spread of fine exhaled droplets. They compared the in-room location of subsequently infected cases and spread of the simulated virus-laden aerosol tracer. No patrons were infected in the non-ABC zone and based on available video records no evidence was identified to support exposure to SARS-CoV-2 occurring via fomite or close contact routes. Their prediction showed that a contaminated recirculation envelope was created in the ABC zone, which thus sustained a higher concentration of exhaled droplet nuclei from the index patient. The period of overlap between families A and C and A and B allowed enough exposure time to the exhaled droplets; whereas none of the waiters were infected may be contributed to their short exposure time to exhaled droplets. The authors identify that the formation of a contaminated recirculation envelope in the ABC zone cannot explain the outbreak alone. The space had low ventilation rates from the lack of outdoor air supply since the exhaust fans in the walls were turned off and sealed. The measured airflows of 1.04 L/s and 0.75 L/s per patron in the non-ABC and ABC zones respectively were considerably lower than the 8-10 L/s required by most authorities or professional societies. The restaurant was also crowded, with extra tables added to accommodate extra customers celebrating Chinese New Year's Eve. The authors indicate that their results do not show that long-range aerosol transmission of SARS-CoV-2 can occur in any indoor space, but that transmission may occur in a crowded and poorly ventilated space. The authors consider instead that in theory, even if an infectious agent is not typically (i.e. under adequate ventilation) transmitted by a long-range aerosol mechanism (i.e. airborne), the spatial extent of transmission increases if the ventilation rate is very low and they refer to this as an extended short-range aerosol mechanism, which may occur in crowded poorly ventilated spaces (Y. Li et al., 2020).

Qian et al. (2020) identified outbreaks from case reports from local Municipal Health Commissions of 320 prefectural cities in China, not including Hubei province, between 4 January and 11 February 2020 and reviewed major characteristics of the enclosed areas the outbreaks were determined to have occurred and associated indoor environment issues. The authors were not able to identify exact transmission routes from these identified outbreaks; however, the authors comment on the standards of thermal and ventilation conditions for the indoor venues assessed but could not comment on the specifics of the venues identified in these outbreaks (Qian, Miao, Zheng, Luo, & Li, 2020).

Park et al. (2020) describe the epidemiology of a COVID-19 outbreak in a call centre located in a commercial-residential mixed-use building in Seoul, South Korea (Park et al., 2020). Of the 1,145 persons under investigation in the building, 99.8% were tested and 97 (8.5%, 95% CI 7.0-10.3) were confirmed case-patients. Most (94, 96.9%) of the confirmed case-patients were working on the 11th floor call-center, which had a total of 216 employees (43.5% attack rate). Case-patients on the 11th floor were mostly on the same side of the building. Residents and employees had frequent contact in the lobby or elevators. The authors comment that the magnitude of the outbreak illustrates how a high-density work environment can become a high-risk site for the spread of COVID-19 and potentially a source of further transmission. Despite considerable interactions between workers on different floors in elevators and the lobby, the outbreak was mostly on the 11th floor indicating that the duration of interaction (or contact) was likely the main facilitator for further spreading of SARS-CoV-2 (Park et al., 2020). The authors do not comment on the role the HVAC system may have played in the transmission of SARS-CoV-2; however, on their epidemic curve it indicates that on March 13 (after the peak of the outbreak) the ventilation system was evaluated. Currently, there is no information available on the results of that evaluation; however, Dr. MacKay has contacted the authors for this information.

Dai & Zhao (2020) employed the Wells–Riley equation to estimate the association between infected probability and ventilation rate (Dai & Zhao, 2020). Their model assumed droplet nuclei are evenly distributed in space, which means the infection risk predicted by this equation is uniform within the space, and it neglects viability and infectivity of the pathogen. To ensure infected probability less than 1%, ventilation rate larger than common values (100-350 m3/h and 1200-4000 m3/h for 15 minutes and 3 hours exposure, respectively) is required. If both the infector and susceptible individuals wear masks, the ventilation rate ensuring less than 1% infected probability is reduced to 50-180 m3/h and 600-2000 m3/h correspondingly, which is easier to be achieved by normal ventilation mode applied in some typical scenarios, including offices, classrooms, buses and aircraft cabins. Wearing an ordinary medical surgical mask is effective, thus it is important to educate people wearing mask when they enter or stay in confined spaces (Dai & Zhao, 2020).

Buonanno et al. (2020) estimate the SARS-CoV-2 viral load emitted by a contagious subject on the basis of the viral load in the mouth, the type of respiratory activity (e.g. breathing, speaking), respiratory physiological parameters (e.g. inhalation rate), and activity level (e.g. resting, standing, light exercise). The authors conclude that the results obtained from the simulations highlight that a key role is played by proper ventilation in containment of the virus in indoor environments (Buonanno, Stabile, & Morawska, 2020).

Dbouk and Drikakis (2020) used computational multiphase fluid dynamics and heat transfer to investigate the transport, dispersion, and evaporation of saliva particles arising from a human cough (Dbouk & Drikakis, 2020). An ejection process of saliva droplets in air was applied to mimic the real event of a human cough. Their model took into account relative humidity, turbulent dispersion forces, droplet phase-change, evaporation, and breakup in addition to the droplet-droplet and droplet-air interactions. The authors further investigated the effect of wind speed on social distancing. For a mild human cough in air at 20 °C and 50% relative humidity, human saliva-disease-carrier droplets may travel up to unexpected considerable distances depending on the wind speed. When the wind speed was approximately zero, the saliva droplets did not travel 2 m, which is within the social distancing recommendations. However, at wind speeds varying from 4 km/h to 15 km/h, the saliva droplets can travel up to 6 m with a decrease in the concentration and liquid droplet size in the wind direction. The findings imply that considering the environmental conditions, the 2 m social distance may not be sufficient. Further research is required to quantify the influence of parameters such as the environment's relative humidity and temperature among others. The authors further highlight that further research is required to assess the probability of viral transmission and that a holistic approach to address these questions is needed. This would require closer interactions between individuals in medicine, biology, engineering fluid physics and social sciences.

Morawska and Cao (2020) stated that based on the trend in the increase of infections, and understanding the basic science of viral infection spread, they strongly believe that the SARS-Cov-2 virus is likely to be spreading through the air and that it will take several months for this to be confirmed by science. The authors recommend all possible precautions against airborne transmission of SARS-CoV-2 virus in indoor scenarios be taken and that these precautions include increased ventilation rate, using natural ventilation, avoiding air recirculation, avoiding staying in another person's direct air flow, and minimizing the number of people sharing the same environment based on Qian & Zeng (2018). Morawska & Cao (2020) also recommend personal protective equipment, in particular masks and respirators should be recommended, to be used in public places where density of people is high and ventilation potentially inadequate, as they can protect against infection (by infected individuals) and infecting others (L. Morawska & Cao, 2020).

Other Viruses & HVAC Systems in Healthcare Settings

Li et al. (2004) presented a detailed air distribution study of a hospital ward during a major nosocomial outbreak of SARS-CoV in Hong Kong in March 2003 (Y. Li, Huang, Yu, Wong, & Qian, 2004). Retrospective on-site inspections and measurements of the ventilation design and air distribution system, three months after the outbreak, showed that the flow rates in the supply diffusers and exhaust grilles were not balanced. Measurements performed using bio-aerosol generator (with diameters between 0.1 and 10um) placed in one of the beds next to the index patient's bed (since it was occupied). At a height of 1.1m, concentration decreased as the virus laden bio-aerosols moved away from the index patient's cubicle. The concentrations at the doorstep of patient's toilet and store/clean room were relatively high – so risk if other patients in distant cubicles visited the toilets. Extraction fans in the store/cleaning room and in the patient's toilet seems to have also contributed to spread of bio-aerosols from index patient's cubicle to corridor and nurses station. Using their simulations and measurements, the predicted bio-aerosol concentration agreed with the spatial infection pattern which the authors indicated it suggested a probable airborne transmission route, in addition to the commonly accepted large droplet and close personal contact transmission (Y. Li et al., 2004).

Yu et al. (2005) conducted a retrospective cohort study of the SARS-CoV outbreak, noted above, on a hospital ward at the Prince of Wales Hospital, China (Yu, Wong, Chiu, Lee, & Li, 2005). Information on roles of healthcare workers and the ventilation system (location and size of supply diffusers, exhaust grills, supply air temperature, and the air-flow rate through each supply diffuser, exhaust grille and exhaust fan) were collected. Dispersion of hypothetical virus-laden aerosols, originated from the index case patient's bed, through the entire ward was analyzed by computational fluid dynamics method. Sixty-five percent of the 20 subjects in the same bay developed SARS-CoV, 52.4% in the adjacent bay, and 18.2% in the distant bays. All 14/15 nurses were infected with SARS and had direct contacts with the index case patient except the ward manager and most reported washing their hands after caring the index patient. The CFD model corresponded well to the spatial distribution of the infected patients and interpreted this to suggest airborne transmission probably played a role in the outbreak. The authors consider alternative explanations for the pattern but rule them out as explanations: for example no particular high risk patient characteristics were identified to suggest that more susceptible individuals were grouped in certain bays, the index patient was very ill during the first week of hospitalization and was bed-bound, other patients were ambulatory but unlikely to have come in direct contact with index patient, patient transfers of patients with SARS-CoV did not occur after the onset of fever. The authors consider patients getting infected in common areas, such as the toilets and that the probability of getting infection would not differ given that they were not more or less likely to be bed bound or ambulatory. With 14/15 nurses contracting SARS-CoV, it was possible that it was spread indirectly through fomites or HCWs as mechanical carriers. All nurses served patients in all 4 bays, physicians visited different inpatients in all four bays. The authors rule out healthcare workers as potential source based on the assumption that every nurse had a chance of contacting different inpatients in the different bays, and that the risk of infection should be distributed more evenly among the different bays (however this assumes that the interactions between nurses and patients were evenly distributed and that nurses visited each patient similarly, which seems unlikely). A limitation of their study was that they were not able to document existence of the infective agent in aerosols (Yu et al., 2005).

Satheesan et al. (2020) investigated the transport mechanisms and deposition patterns of MERS-CoV within a typical six bedded general inpatient ward cubicle through numerical simulation. The authors concluded that air change and exhaust airflow rates have significant effects on not only the airflow but also the particle distribution within a mechanically vented space. The authors recommended exhaust grilles near a patient, preferably above each patient's bed, and high exhaust airflow rate (Satheesan, Mui, & Wong, 2020).

Sung et al. (2018) aimed to identify the airflow as a possible infection routes of secondary infected patients, for whom close contact was not identified, using spatial and environmental analysis of Pyeongtaek St. Mary's Hospital, in which the initial MERS-CoV patient directly and indirectly infected 38 people after being admitted to the hospital on 15 May 2015, for two nights and three days. The tracer gas was continuously generated on the bed in the room of the initial patient, at a rate of 1L/min. The concentration of the tracer gas was measured at a height of 1.2 m at the centers of room 8104 (index room), rooms 8103, 8106 (adjacent rooms), rooms 8110 and 8113 (across the corridor), and room 8218 (single patient room).The experiment with an external wind direction and speed like those during the hospitalization of the initial patient revealed that the air change rate was 17–20 air changes per hour, with air introduced through the window in the room of the infected patient (room 8104). The tracer gas concentration of room 8110, which was the farthest room, was 7.56% of room 8104, indicating that a high concentration of gas has spread from room 8104 to rooms across the corridor. In contrast, the tracer gas was barely detected in a maternity ward to the south of room 8104, where there were no secondary infected patients. The authors concluded that the tracer gas from room 8104, in which the initial patient (super-spreader) was hospitalized, was confirmed to spread over long distances to patient rooms across the corridor. This indicates the significant effect of the outdoor wind entering through the window. The high concentration in room 8104 was probably spread to the corridor and rooms on the opposite side due to the strong airflow entering from the outside. The results indicate that cross ventilation by outdoor wind in the central corridor inpatient ward could cause dispersion of infectious aerosols to indoor through airflow. Although there were limitations in confirming the infectivity of propagated airborne particles, the possibility of the spread of infections by airflow was presented for the analysis of relatively long-distance infection cases, for which the close-contact infection route by droplets could not be identified from epidemiologic investigations (Sung et al., 2018).

Brankston et al. (2007) conducted a systematic review of the experimental and epidemiological literature on how influenza is transmitted (Brankston, Gitterman, Hirji, Lemieux, & Gardam, 2007). Of the nine observational studies of natural influenza in human beings, three are frequently cited as evidence for airborne transmission of influenza and the relationship between HVAC systems. McLean reported an observational account of the 1957 influenza pandemic in a California veteran's hospital housing TB patients. The proportion of individuals infected with influenza over two successive outbreaks was substantially lower in the hospital department in which upper air UV disinfection had been installed vs. another department in which it had not been installed (2 vs 19%). Another observational study suggested airborne transmission based on an association between influenza infection and ventilation system design in different buildings of a long-term care facility. In the newest building, with a ventilation system that provided 100% outside air, 1.6% of patients were infected. In two buildings that provided 70% outside air, 15.8% and 9.3% of patients were infected, whereas an older building that provided 30% outside air had an infected proportion of 13.8%. No measurement of any HVAC parameters were conducted and these authors negated this study after five subsequent years of sampling and found no clear associations (Luongo et al., 2016).

Other Viruses & HVAC Systems in Non-Healthcare Settings

Yu et al. (2004) analyzed the temporal and spatial distributions of cases in a large community outbreak of SARS-CoV in Hong Kong (Yu et al., 2004). The authors studied the association between the location (building, floor and direction the apartment unit faced) of the Amoy Gardens housing complex and the probability of infection using logistic regression. The spread of the airborne, virus-laden aerosols generated by the index patient was modeled with the use of airflow-dynamics studies, including studies performed with the use of computational fluid-dynamics and multizone modeling. Residents of the floors at the middle and upper levels in building E (where index patient lived) were at a significantly higher risk than residents on lower floors, consistent with a rising plume of contaminated warm air in the air shaft generated from a middle-level apartment unit. The risks for the different units matched the virus concentrations predicted with the use of multizone modeling. The distribution of risk in buildings B, C and D corresponding well with the three-dimensional spread of virus-laden aerosols predicted with the use of computational fluid-dynamics modeling. Members of the management and security staff of the buildings had frequent person-to-person contact with the residents, but none became infected. No cases were identified in the shopping centre of the Amoy Gardens estate.

In a hypothesis report published in the Lancet it was posited that an animal vector, such as roof rats, that was infected by the index patient could have contributed to the outbreak in the Amoy Gardens complex (Ng, 2003). The circumstantial evidence they provide include that the SARS-CoV virus can probably survive and infect animals as well as humans since it's suspected that the SARS-CoV coronavirus originate from animals; viral remnants were detected in four of eight rat droppings found around the Amoy Gardens and in throat or rectal swabs of five housecats, one dog, and at least one rat; the housing complex is located in one of the most densely populated areas in Hong Kong, known for poor hygiene and rat infestation; rats are territorial, mobile and can reach high floors through external pipes; and viral footprints were found around toilet bowls, kitchen sinks and kitchen floors in block E but not in bedrooms which is an unlikely pattern if contamination caused by man. Yu et al. (2004) rejected the hypothesis that roof rats could have been carriers and distributors of SARS-CoV, given that they are territorial and so could not be responsible for the spread to other buildings. There was no sudden disappearance or deaths of roof rats that could explain the steep decline in the epidemic curve after the peak (Yu et al., 2004).

Li, Duan, et al. (2004) studied the spread of SARS-CoV in Amoy Gardens housing estate in Hong Kong, where the infection of over 300 people from over 150 apartments in 15 blocks was linked to one index case visiting one of the apartments. Retrospective research suggested that atomized sewage containing faeces from the infection person in Blok E of the estate was sucked from the downpipe through a dry floor waste and ejected from the building through a bathroom exhaust fan. Virus-laden particles then entered the re-entrant and upper story faults through open windows (Y. Li, Duan, Yu, & Wong, 2004).

Moser and colleagues describe an influenza outbreak that occurred on an Alaskan Airlines flight. A passenger became acutely ill with laboratory-confirmed influenza A during a stop-over for which the aircraft ventilation was shut down for 3h. Of the passengers confined to the aircraft during the stop-over 72% became infected with influenza. Passengers were able to move freely in the cabin during this period and occurrence of infection increased with increasing time spent on the aircraft. The authors conceded that because of the free movement of passengers, close range transmission of influenza through droplet or direct contact could not be ruled out (Brankston et al., 2007).

In contrast, an influenza outbreak on a naval base was associated with recent airplane travel. 56% of people became ill within 72h of being on one of two aircraft with 11 ill squadron mates. Both aircraft had fully functioning ventilation systems designed to completely exchange the volume of air in the passenger cabin with 100% fresh air every 4 min (15 air exchanges per hour). Given that proper ventilation is the most important factor to influence airborne transmission rates, if influenza is transmitted mainly by the airborne route, then one might have expected a very low proportion infected in this study given that the air exchange rate on the aircraft was similar to that required for an airborne isolation room (Brankston et al., 2007).

Withers & Christopher (2002) concluded that under normal operating conditions, modem civil airliners and military transport aircraft do not provide a venue for infectious disease transmission at higher rates than in other crowded places. Although not proved, the risk in them may be much lower than in other common public enclosures. Under abnormal operating conditions-namely, when the ventilation system is not functioning-these same aircraft can be venues for unusually high attack rates for airborne viruses such as measles and influenza (Withers & Christopher, 2000).

Evolving Evidence

The role of HVAC systems in the transmission of SARS-CoV-2 and other similar viruses needs to be studied with rigorous epidemiologic, engineering, infectious disease modeling and microbiological methods that complement each other. If the evidence evolves on the transmission routes of SARS-CoV-2, particularly related to short-range aerosols and the role that HVAC systems may play, these groups need to jointly evaluate the quality of methods and reporting of these studies.

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Date report submitted to committee: 20 May 2020

Date of first assessment: 5 June 2020

(If applicable) Date of re-assessment:

Authorship and Committee Members

This review was written by Jenine Leal and assisted by Heather Gagnon, and scientifically reviewed by Elizabeth MacKay, Karin Fluet (external reviewer), Dean Olmstead (external reviewer), Steve Rees (external reviewer), Brandie Walker, John Conly, Joseph Kim (external reviewer), Karen Hope (external reviewer), Sharon Wilson (external reviewer), Bev Knudtson (external reviewer), and Byron Berenger (external reviewer). The full Scientific Advisory Group was involved in discussion and revision of the document: Braden Manns (co-chair), Lynora Saxinger (co-chair), Alexander Doroshenko, Shelley Duggan, Andrew McRae, Nelson Lee, Jeremy Slobodan, James Talbot, and Nathan Zelyas.

Appendix

Methods

Literature Search

A literature search was conducted by Rachel Zhao from Knowledge Resources Services (KRS) within the Knowledge Management Department of Alberta Health Services. KRS searched databases for articles published from 1946 to May 11, 2020. The search was conducted in MEDLINE, LitCOVID, TRIP PRO, WHO research on coronavirus disease (COVID-19), MedRxiv and BIORxiv, BMJ Best Practice, CADTH, Cambridge Coronavirus Free Access Collection, Oxford COVID-19 Evidence Service, COVID-19 Primer, National Collaborating Centre for Methods and Tools, NICE Rapid Reviews, Google/Google Scholar. Citation tracking was also used in Google Scholar.

Search Strategy

Ovid MEDLINE(R) and Epub Ahead of Print, In-Process & Other Non-Indexed Citations, Daily and Versions(R) 1946 to May 11, 2020

Searches Results
1 exp Coronavirus/ or exp Coronavirus Infections/ or coronaviru*.mp. or "corona virus*".mp. or ncov*.mp. or n-cov*.mp. or "novel cov".mp. or COVID-19.mp. or COVID19.mp. or COVID-2019.mp. or COVID2019.mp. or SARS-COV-2.mp. or SARSCOV-2.mp. or SARSCOV2.mp. or SARSCOV19.mp. or Sars-Cov-19.mp. or SarsCov-19.mp. or SARSCOV2019.mp. or Sars-Cov-2019.mp. or SarsCov-2019.mp. or "severe acute respiratory syndrome cov 2".mp. or "2019 ncov".mp. or "2019ncov".mp. 30866
2 Ventilation/ 5654
3 Air Pollution, Indoor/ 13403
4 (ventilation* adj5 system*).mp. 3085
5 (HVAC or aircondition* or air condition* or indoor air pollution or indoor air quality).mp. 8105
6 or/2-5 24905
7 1 and 6 47
8 limit 7 to (english language and yr="2020 -Current") 8
9 exp Viruses/ 773845
10 (virus* or viral*).kf,tw. 869016
11 9 or 10 1121892
12 (virus* or viral or arboviruses or bacteriophage* or Herpesvirus* or papillomavirus* or Influenzavirus* or fuselloviridae or guttaviridae or lipothrixviridae or myoviridae or rudiviridae or siphoviridae or bacillus phages or caudovirales or podoviridae or coliphages or leviviridae or allolevivirus or levivirus or t-phages or corticoviridae or inoviridae or inovirus or plectrovirus or microviridae or microvirus or mycobacteriophages or prophages or pseudomonas phages or rna phages or cystoviridae or salmonella phages or staphylococcus phages or streptococcus phages or tectiviridae or adenoviridae or atadenovirus or aviadenovirus or fowl adenovirus a or mastadenovirus or siadenovirus or anelloviridae or ascoviridae or asfarviridae or baculoviridae or granulovirus or nucleopolyhedroviruses or caulimoviridae or badnavirus or caulimovirus or tungrovirus or circoviridae or circovirus or gyrovirus or gammaherpesvirinae or lymphocryptovirus or leporipoxvirus or papillomaviridae or alphapapillomavirus or betapapillomavirus or deltapapillomavirus or gammapapillomavirus or kappapapillomavirus or cottontail rabbit papillomavirus or lambdapapillomavirus or mupapillomavirus or xipapillomavirus or polyomaviridae or polyomavirus or yatapoxvirus or geminiviridae or begomovirus or hepadnaviridae or avihepadnavirus or alphaherpesvirinae or iltovirus or mardivirus or simplexvirus or varicellovirus or betaherpesvirinae or cytomegalovirus or muromegalovirus or roseolovirus or rhadinovirus or ictalurivirus or iridoviridae or iridovirus or ranavirus or mimiviridae or nanoviridae or nanovirus or nimaviridae or nudiviridae or parvoviridae or densovirinae or densovirus or parvovirinae or amdovirus or bocavirus or dependovirus or erythrovirus or parvovirus or phycodnaviridae or polydnaviridae or poxviridae

or chordopoxvirinae or avipoxvirus or capripoxvirus or molluscipoxvirus or orthopoxvirus or parapoxvirus or suipoxvirus or entomopoxvirinae or virophages or orthohepadnavirus or hepatovirus or dicistroviridae or nodaviridae or retroviridae or alpharetrovirus or betaretrovirus or jaagsiekte sheep retrovirus or deltaretrovirus or endogenous retroviruses or epsilonretrovirus or gammaretrovirus or bromoviridae or alfamovirus or bromovirus or cucumovirus or ilarvirus or oleavirus or closteroviridae or closterovirus or crinivirus or flexiviridae or carlavirus or potexvirus or luteoviridae or luteovirus or comovirus or potyvirus or tobamovirus or tymovirus or babuvirus or potyviridae or secoviridae or fabavirus or nepovirus or sequiviridae or sequivirus or waikavirus or tenuivirus or tombusviridae or carmovirus or tombusvirus or tospovirus or tymoviridae or proviruses or arenaviridae or arenavirus or astroviridae or avastrovirus or mamastrovirus or birnaviridae or aquabirnavirus or avibirnavirus or entomobirnavirus or bunyaviridae or hantavirus or nairovirus or orthobunyavirus or phlebovirus or caliciviridae or lagovirus or norovirus or sapovirus or vesivirus or flaviviridae or flavivirus or hepevirus or mononegavirales or bornaviridae or filoviridae or ebolavirus or marburgvirus or paramyxoviridae or paramyxovirinae or avulavirus or henipavirus or morbillivirus or respirovirus or rubulavirus or pneumovirinae or metapneumovirus or pneumovirus or rhabdoviridae or ephemerovirus or lyssavirus or novirhabdovirus or vesiculovirus or nidovirales or arteriviridae or arterivirus or equartevirus or coronaviridae or coronavirus or alphacoronavirus or betacoronavirus or gammacoronavirus or torovirus or roniviridae or orthomyxoviridae or isavirus or thogotovirus or picobirnavirus or picornaviridae or aphthovirus or cardiovirus or mengovirus or theilovirus or enterovirus or poliovirus or erbovirus or kobuvirus or parechovirus or rhinovirus or teschovirus or reoviridae or coltivirus or orbivirus or orthoreovirus or rotavirus or lentivirus or retroviruses, simian or spumavirus or togaviridae or alphavirus or rubivirus or totiviridae or giardiavirus or leishmaniavirus or totivirus or virion or nucleocapsid or capsid or viroids).kf,tw. 995335
13 9 or 12 1172809
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15 limit 14 to (english language and (clinical trial, all or clinical trial protocols as topic or clinical trial or meta analysis or observational study or pragmatic clinical trial or randomized controlled trial or "review" or "scientific integrity review" or "systematic review" or systematic reviews as topic)) 48

LitCovid
“ventilation system*” or “heating ventilation and air conditioning” or HVAC or aircondition* or “air condition*” or “indoor air pollution” or “indoor air quality”

TRIP PRO / Google / Google Scholar
Search 1:
(“ventilation system*” or “heating ventilation and air conditioning” or HVAC or aircondition* or “air condition*” or “indoor air pollution” or “indoor air quality”) AND (coronaviru* OR "corona virus" OR ncov* OR n-cov* OR COVID-19 OR COVID19 OR COVID-2019 OR COVID2019 OR SARS-COV-2 OR SARSCOV-2 OR SARSCOV2 OR SARSCOV19 OR SARS-COV-19 OR SARSCOV-19 OR SARSCOV2019 OR SARS-COV-2019 OR SARSCOV-2019 OR "severe acute respiratory syndrome cov 2" OR "severe acute respiratory syndrome coronavirus*" OR "2019 ncov" OR 2019ncov OR Hcov*) from:2020
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(“ventilation system*” or “heating ventilation and air conditioning” or HVAC or aircondition* or “air condition*” or “indoor air pollution” or “indoor air quality”) AND (virus* or viral*)

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WHO research on coronavirus disease (COVID-19)
tw:("hvac") or tw:(“ventilation system*”) or tw:(“heating ventilation and air conditioning”) or tw:(“aircondition*”) or tw:(“air condition*”) or tw:(“indoor air pollution”) or tw:(“indoor air quality”)

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hvac or "ventilation system" or "heating ventilation and air conditioning" or "airconditioning" or "air conditioning" (posted between "01 Jan, 2020 and 12 May, 2020")

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