Summary of Evidence Related to Indoor Ventilation to Reduce SARS-CoV-2 Transmission

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COVID-19 Literature Report Team:

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Mitigation of SARS-CoV-2 transmission in indoor spaces is crucial, especially during the winter season when activities are mostly held in enclosed indoor environments. Understanding SARS-CoV-2 transmission mechanisms relating to ventilation of indoor air and what evidence-based environmental measures are available will be key to infection control. **This document is a brief summary of published evidence on SARS-CoV-2 transmission mechanisms that relate to ventilation of indoor spaces and ventilation standards/best practices for minimizing spread.** References are mainly drawn from the COVID-19 Literature Report (Lit Rep) team database and guidelines published by the CDC. **References that appeared in the daily Lit Rep are marked with an asterisk*,** and the summary is shown in the annotated bibliography below.

Executive Summary of Ventilation and SARS-CoV-2

- **While evidence suggests that SARS-CoV-2 is commonly transmitted through close contact and respiratory droplets, updated definitions of aerosols show that larger respiratory particles (<100 µm) can remain airborne for extended periods. In enclosed areas with poor ventilation, these aerosols containing infectious SARS-CoV-2 can spread beyond 6 feet and build up in a room. A small number of studies have isolated viable virus from air samples in lab and clinical settings and SARS-CoV-2 airborne transmission beyond 6 feet has been observed in poorly ventilated and crowded indoor spaces.**
- **An expert panel assembled by the National Academies of Sciences, Engineering, and Medicine concluded that aerosols represent an important potential transmission pathway for SARS-CoV-2 based on multiple lines of evidence, but concluded that additional research is needed to definitively prove and quantify the role of the aerosol transmission pathway.**
- **While SARS-CoV-2 RNA has been detected in heating, ventilation, and air conditioning (HVAC) systems, viable virus was not isolated. There has been no documented evidence of SARS-CoV-2 transmission occurring through HVAC systems.**
- **Ventilation standards/best practices to reduce risk of SARS-CoV-2 transmission primarily include methods to decrease concentrations of aerosols that may carry infectious virus either through filtration of indoor air or circulation of cleaner air from outside.**
- **Ventilation standards/best practices alone are not enough to mitigate SARS-CoV-2 transmission. They should be implemented in conjunction with infection control measures that more directly address SARS-CoV-2 primary modes of transmission, such as reducing building occupancy to facilitate physical distancing, mask wearing, surface disinfection, and handwashing.**

SARS-CoV-2 Transmission related to Ventilation

Note: Some of the evidence covered here can also be found in the CDC brief on SARS-CoV-2 and Potential Airborne Transmission and the proceedings of the National Academies of Sciences, Engineering, and Medicine Workshop on Airborne Transmission of SARS-CoV-2.

Aerosol Transmission

- Particles ejected when an infectious person sneezes, coughs, sings, or breathes form a spectrum of respiratory droplets and aerosols.
  - Respiratory droplets are large droplets that settle more quickly on surrounding surfaces. They are responsible for **droplet transmission,** which occurs when a person in close contact (within about 6 feet) inhales these droplets or through exposure via eyes, nose, or mouth.
  - Aerosols tend to be smaller, lighter particles that can remain airborne for much longer and can be carried farther by airflow and wind currents. They are responsible for **airborne transmission**, which occurs when a person inhales these particles. While aerosols have been traditionally defined as <5 µm in diameter, updated descriptions based on aerosol science indicate that aerosols can be up to 100 µm in diameter and remain suspended in the air for extended periods. While concentrations are highest near the source, aerosols can travel more than 6 feet from the source and build up over time, particularly in enclosed spaces with poor ventilation.[1,2]
- The SARS-CoV-2 virus, which is around 0.1 µm, generally does not travel through the air by itself. Potentially infectious virus (based on replication in cell culture) has been isolated from air samples as well as from surfaces on which respiratory droplets have deposited,[3,4]* indicating that particles of varying size can carry infectious virus.
- While other coronaviruses are more likely to be present in aerosols than in larger respiratory droplets,[5] the exact distribution of the SARS-CoV-2 across the range of different-sized particles is unknown.
- **The half-life of SARS-CoV-2 in aerosol is estimated to be approximately 1.1 hours**, based on experimental evidence using a Goldberg drum to keep artificially generated aerosols in suspension.[3] Infectious aerosols generated under experimental conditions have been found after 16 hours.[6]
- **UV light greatly decreases virus stability in droplets and aerosols**,[7] while lower temperatures and humidity may increase stability.[8]
- An expert panel assembled by the National Academies of Sciences, Engineering, and Medicine concluded that **aerosols represent an important potential transmission pathway for SARS-CoV-2** based on multiple lines of evidence:[1]
  - Aerosols have been shown to contain infectious SARS-CoV-2 and can remain suspended in air for hours.
  - Asymptomatic individuals emit mostly aerosols with sizes <10 µm and produce very few droplets.
  - Super-spreading events are more readily explained by aerosol transmission.[9]
  - Aerosols are more concentrated at close range and can spread and accumulate in a room.
  - Transmission in outdoor settings has been much less common than indoors.

No substantial direct evidence of classical long-range airborne transmission

- Currently, there is no substantial evidence that SARS-CoV-2 can be transmitted efficiently over long distances through airborne transmission like other pathogens such as TB, measles, or varicella (chickenpox).[10]
- Though aerosolized SARS-CoV-2 has been shown to be stable in aerosols for 3-16 hours in laboratory settings,[3,6] real-world factors such as UV exposure from sunlight, temperature and relative humidity affect the stability of the virus, while ventilation and exhaled viral load affect the concentration necessary to infect others.
- Given the significant proportion of infections caused by persons with asymptomatic SARS-CoV-2 infection, it is estimated that global spread would have occurred much more rapidly if SARS-CoV-2 spread primarily through long-range airborne transmission.[11]

Evidence of short-range airborne transmission in certain conditions

Several instances of "short-range" airborne transmission beyond what could be attributed to droplet transmission alone have been documented. These events are associated with enclosed, indoor settings with poor or improper ventilation, prolonged exposure to infectious persons, and activities that increase the rate of droplet and aerosol generation:

- An outbreak occurred in a restaurant in which directional airflow from an air conditioner is suspected to have transmitted infected aerosols from the table of the index patient to adjacent tables.[12]*
- An outbreak during a 2.5-hour choir practice with an attack rate of 53-87% occurred, with indoor transmission likely augmented by singing.[13]
- An outbreak involving two 50-minute rides inside a bus with recirculating air occurred, with secondary individuals sitting closer to the index case being no more likely to get infected than those sitting farther, indicating an extended range of transmission.[14]*
- In an outbreak in 1 out of 7 wards of a nursing home during a period of low community incidence occurred, the ward experiencing the outbreak had recently installed demand-controlled ventilation that only circulated outside air based on indoor CO_2 levels.[15]*
- A cluster of cases were associated with a shopping mall, where possible virus aerosolization occurring in confined spaces such as elevators and restrooms and contributed to indirect transmission.[16]
- A cluster of cases associated with a squash court occurred, with individuals who played in the same squash hall as the index case at least 45 minutes later were infected, possibly from aerosols.[17]
- An outbreak at a nightclub occurred in which infected staff likely caused multiple infections across three different events.[18]
- An outbreak of 112 cases occurred in 12 sports facilities over 24 days, where asymptomatic and pre-symptomatic instructors taught fitness dance classes to 5–22 students in a room approximately 60 m^2 for 50 minutes of intense exercise.[19]

Indoor Transmission through HVAC systems

We found no reported evidence of SARS-CoV-2 transmission occurring through heating, ventilation, and air conditioning (HVAC) systems. SARS-CoV-2 RNA has been detected in multiple parts of HVAC systems, though viable virus was not isolated. However, a potential limitation of available evidence is that the sampling timeframe may not have captured the virus when it was infectious.

- Positive samples (swab and cell media) for SARS-CoV-2 RNA were found in the HVAC system of COVID-19 wards and in the central HVAC system, which was located 5 floors above. Viral culture was unable to detect viable virus in samples.[20]*
- Tests for SARS-CoV-2 RNA were negative for swabs and air samples collected from the Diamond Princess cruise ship in cabins with no COVID-19 cases, but that shared air circulation with COVID-19 cabins via the HVAC system.[21]*
- Presence of SAR-CoV-2 RNA was detected in 25% of samples collected in 9 locations of the HVAC system of a university hospital in Oregon. These samples were not evaluated for viral infectiousness.[22]

Ventilation Standards/Best Practices

Note: Some of the guidelines covered here can also be found in the Washington Department of Health ventilation guidance and CDC ventilation guidance.

As respiratory droplets and aerosols can contain SARS-CoV-2, a layered prevention approach is recommended to include ventilation measures along with personal protective equipment, mask use, surface disinfection, and personal hygiene. **Implementation of some ventilation measures outlined here require technical expertise, and consultation with an HVAC specialist or professional engineer is recommended.**

Ventilation measures reduce the risk of SARS-CoV-2 transmission by diluting the concentration of infectious aerosols in the environment. This is primarily achieved by filtration of indoor air or circulation of cleaner air from the outside, either through 1) a central HVAC system, or 2) non-HVAC measures. Ventilation measures affect the air exchange rate per hour (ACH), which is defined as the number of times the air occupying the volume of a given space is exchanged with cleaner air.

HVAC Measures

- The CDC recommends installing filters in the HVAC system with the highest performance that the system can handle. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) recommends installing filters with at least Minimum Efficiency Reporting Value (MERV) of 13, provided there is no substantial impact on HVAC performance or occupant comfort.
  - MERV values range from 1 to 16, with higher values corresponding to better efficiency. MERV 13 filters are at least 50% efficient at capturing particles in the 0.3 µm to 1.0 µm size range and 85% efficient at capturing particles in the 1 µm to 3 µm size range (more information on MERV standards can be found here.
  - Higher MERV values can cause a drop in air pressure as more air is filtered, but provide cleaner air with which to exchange the existing air in an enclosed space.
- Turn off demand-controlled ventilation, which automatically circulates outside air based on temperature, humidity, or CO_2 concentrations, to avoid build-up of indoor air
- Allow for HVAC systems to circulate outside air. Run HVAC systems on maximum to flush indoor air 2 hours before and after occupancy.
  - The CDC has guidelines for how long a system performing at certain ACH must be run in order to remove the recommended 99% of airborne contaminants.

- Open outdoor air dampers to reduce or eliminate HVAC indoor air recirculation (this may be difficult in hot or humid weather)
- Maintain relative humidity at 40-60% and temperature within 68-78F (ASHRAE guidance for residential)
    - Ecological studies have found higher transmission rates in geographical regions with colder and dryer air; however, there is considerable potential for confounding in these comparisons, and the role of temperature and humidity in SARS-CoV-2 infectiousness is not clearly established.[23]
    - Surface stability of SARS-CoV-2 has been found to decrease with increasing temperature and humidity.[24]*
- Ensure that minimum rates for outdoor air circulation are met or exceeded.
    - These minimum rates not only depend upon the room size, but also the number of occupants, typical activities conducted within the room, and other environmental factors. In general, doubling the occupancy will double the minimum required rate. For more comprehensive standards and calculations for a wide variety of settings, **see Equation 6-1 and Table 6-1 of ASHRAE 62.1 (2019)**

Non-HVAC Measures

These measures are best used to augment HVAC measures and are best implemented in settings with limited or nonexistent HVAC systems.

- Place portable High Efficiency Particulate (HEPA) filter-equipped systems in critical areas.
    - High Efficiency Particulate (HEPA) filters are at least 99.97% efficient in capturing particles 0.3 µm in size and are even more efficient in capturing particles that are both smaller and larger.
    - As particles increase in size from 0.3 µm, they are more likely to be strained or blocked since they cannot pass through the tightly woven fiber mesh of the filter. As particles decrease in size from 0.3µm, their movement is increasingly dictated by random diffusional collisions with other molecules rather than the airflow, and thus have increasing probability to collide with the large combined surface area of every fiber in the filter (see page 3 and page 7 of this NASA report for a more detailed explanation).
    - Portable HEPA-equipped systems have a Clean Air Delivery Rate (CADR) measured in cubic feet per minute (cfm), which dictates how quickly they can remove particles in the air of a room of a given size. Bigger rooms require systems with higher CADR.

Table: Portable Air Cleaner Size for Particle Removal (EPA)

Room area (ft2)	100	200	300	400	500	600
Minimum CADR (cfm)	65	130	195	260	325	390

For estimation purposes in a home setting. CADRs are calculated based on an 8 ft. ceiling and an ACH of 4.875.

- A study (pre-print, not peer reviewed) found that HEPA filters installed in a poorly-ventilated classroom setting with a combined ACH of 5.7 could reduce the inhaled viral dose from a super-spreader in a room by a factor of 6.[25]*

- Open windows and doors to outside air. Use caution if outdoor air quality is poorer or not ideal for occupant comfort (e.g. high pollution, colder outdoor weather).
- Use indoor fans to facilitate airflow following a clean-to-less-clean air pattern and blowing away from people
    - Place fans near windows or doors to blow out indoor air
    - Reverse direction of ceiling fans to pull air up
- Reduce occupancy as much as possible to allow for physical distancing, and avoid occupant activities that cause higher rates of emitting respiratory droplets and aerosols (e.g., singing, shouting, cheering)
- Use faces coverings
    - Face masks or other face coverings function as filters that are closest to the source of infectious aerosols and can drastically reduce the concentration of viral particles in indoor environments.
    - Hospital rooms with unmasked COVID-19 patients, despite extensive ventilation measures, were found to contain RNA-positive surface samples[26] and air samples with viable virus.[4*]
    - Air samples collected in indoor spaces (hotel room, car) where an individual who had either confirmed influenza or suspected COVID-19 wore a cotton/surgical mask showed a substantial decrease in aerosol concentration.[27*]
    - A modeling study exploring risk of transmission from super-spreaders in various indoor settings (e.g. schools, offices) found that active ventilation combined with mask use outperformed portable HEPA filtration with up to 9 ACH in all scenarios.[28]

Ventilation Considerations for Special Settings: Schools

- HVAC and non-HVAC measures summarized here can be applied to a wide variety of contexts. For example, in schools, the CDC ventilation guidance recommends increasing outdoor ventilation by opening windows and using fans, improving central air filtration, and using portable HEPA filtration systems in high-risk areas such as nurses offices.
- Maintain temperature and relative humidity at 72°F and 40-50% (ASHRAE winter classroom guidelines).

Other Measures

- Germicidal Ultraviolet Irradiation (GUVI)
    - GUVI, which employs UV-C to inactivate fungal, bacterial, and viral pathogens, can be installed in ducts or as ceiling fixtures to disinfect indoor air (see ASHRAE guidelines)
    - GUVI can be costly (can be upwards of $1,500) and potentially harmful to occupants, thus they are typically only used in high-risk settings such as TB wards.
    - A modeling study estimates that installation of safer far-UVC in populated rooms could increase SARS-CoV-2 disinfection rates by 50-85%.[29]

Table of key studies

Study Name	Pub Date	Location	Setting	Ventilation Setting	Sampling Technique	Outcomes
Dumont-Leblond et al.	11/19/2020	Quebec, Canada	Hospital, acute COVID-19 care rooms	Negative pressure rooms with mean ACH of 4.85	100 air samples in the rooms of 22 patients over their course of hospitalization	11 positive out of 100, no live virus isolated
Nissen et al.	11/11/2020	Uppsala, Sweden	Hospital, multiple COVID-19 wards	Central HVAC System, ventilation opening in one ward and central ducts expelling indoor air from three other COVID-19 wards. Central ventilation HEPA filters several stories above wards. Rooms had 1.7-3 ACH	Swab samples of vent openings and central air ducts. Fluid samples near air entrances and exits (10cm petri dishes with cell medium)	7/19 positive swab samples in vent openings at timepoint 1 4/19 positive swab samples in vent openings at timepoint 2 (11 days later) 3/3 pooled fluid samples positive 8/9 main exhaust filters for COVID-19 wards positive No positive samples from central ventilation channels No live virus isolated
Curtius et al.	10/6/2020	Germany	2 classrooms with total volume 186.4 m^3, windows and door open for venting	3-4 portable HEPA filters with 5.7 ACH (1 room with no filters)	Sensors to measure aerosol concentration and CO_2 levels	Room with air filters show a dramatic decrease in aerosol concentration (95% decrease within 37 mins) Applying a scenario of airborne virus transmission, inhaled dose after 2 hours is 11 particles compared to 68 particles
Shen et al.	9/1/2020	Zhejiang Province, China	Bus	Recirculating AC, windows. 100 minute ride duration	PCR testing of passengers	23 passengers infected in bus with index patient. Passengers who were within 2m of index patients were not an increased risk of infection compared to passengers farther away. Passengers close to a window or the bus door were less likely to get infected
de Man et al.	8/21/2020	Netherlands	Nursing home with psychogeriatric residents.	1 out of 7 wards recently upgraded with demand controlled ventilation, the rest ventilated with outside air.	PCR testing of residents and staff, dust filters from AC units, ventilation cabinet dust filters	81% of residents and 50% of staff of DCV ward infected, other wards had no infection. 1/2 dust filters positive for RNA 3/8 ventilation cabinet samples positive for RNA
Lednicky et al.	9/15/2020	Gainesville, FL	Hospital room with 2 patients with positive PCR on admission. Patient 2 was PCR negative at beginning of study	6 ACH, MERV 14, coil condensation, and UV-C irradiation	2 air samplers located ≥2m from patients' heads, using a water vapor condensation method to preserve virus viability. Serial sampling per hour for 3 hrs, with HEPA filter for the second sampling	All samples without HEPA filter detected RNA and live virus
Lu et al.	6/18/2020	Guangzhou, China	Restaurant	indoor, poor ventilation, air conditioning blowing across tables	PCR testing, swab samples of air conditioner	Confirmed COVID-19 in 3 family clusters sitting at different tables, but in the same path as air conditioner-directed airflow. Swab samples were RNA-negative
Hamner et al.	5/15/2020	Skagit County, WA	Church	2.5 hours of singing	PCR testing	32 confirmed and 20 probable secondary COVID-19 cases from a single symptomatic index patient
van Doremalen et al.	3/17/2020	n/a	Laboratory setting	NA	NA	SARS-CoV-2 virus stable for up to 3 hours in aerosol state

Annotated Bibliography

1. National Academies of Sciences, Engineering, and Medicine. (Oct 22, 2020). Airborne Transmission of SARS-CoV-2: Proceedings of a Workshop in Brief (2020). In: Airborne Transmission of SARS-CoV-2. National Academies Press. https://doi.org/10.17226/25958

2. Prather et al. (Oct 16, 2020). Airborne Transmission of SARS-CoV-2. Science. https://doi.org/10.1126/science.abf0521

3. van Doremalen et al. (Apr 16, 2020). Aerosol and Surface Stability of SARS-CoV-2 as Compared with SARS-CoV-1. New England Journal of Medicine. https://doi.org/10.1056/NEJMc2004973

4. Lednicky et al. (Sept 15, 2020). Viable SARS-CoV-2 in the Air of a Hospital Room with COVID-19 Patients. International Journal of Infectious Diseases. https://doi.org/10.1016/j.ijid.2020.09.025

    - Lednicky et al. reported the detection of viable SARS-CoV-2 in air samples collected 2 to 4.8 m away from 2 hospitalized patients with COVID-19. The genome sequence of the SARS-CoV-2 strain isolated from air samplers was identical to that isolated from the newly admitted patient. The authors conclude that aerosols generated by patients with respiratory manifestations of COVID-19 may serve as a source of SARS-CoV-2 transmission.

5. Leung et al. (April 3, 2020). Respiratory Virus Shedding in Exhaled Breath and Efficacy of Face Masks. Nature Medicine. https://doi.org/10.1038/s41591-020-0843-2

6. Fears et al. (Aug 19, 2020). Persistence of Severe Acute Respiratory Syndrome Coronavirus 2 in Aerosol Suspensions. Emerging Infectious Diseases. https://doi.org/10.3201/eid2609.201806

7. Schuit M, Ratnesar-Shumate S, Yolitz J, et al. (Aug 1, 2020). Airborne SARS-CoV-2 is rapidly inactivated by simulated sunlight. Journal of Infectious Diseases. https://doi.org/10.1093/infdis/jiaa334

8. Morris DH, Yinda KCH, Gamble A, et al. (Dec 18, 2020). Mechanistic theory predicts the effects of temperature and humidity on inactivation of SARS-CoV-2 and other enveloped viruses. bioRxiv. https://doi.org/10.1101/2020.10.16.341883

9. Miller SL, Nazaroff WW, Jimenez JL, et al. (Sep 26, 2020) Transmission of SARS-CoV-2 by inhalation of respiratory aerosol in the Skagit Valley Chorale superspreading event. Indoor Air. https://doi.org/doi:10.1111/ina.12751

10. Tang et al. (Oct 1, 2006). Factors Involved in the Aerosol Transmission of Infection and Control of Ventilation in Healthcare Premises. Journal of Hospital Infection. https://doi.org/10.1016/j.jhin.2006.05.022

11. Klompas et al. (Aug 4, 2020). Airborne Transmission of SARS-CoV-2. JAMA. https://doi.org/10.1001/jama.2020.12458

12. Lu et al. (July 2, 2020). COVID-19 Outbreak Associated with Air Conditioning in Restaurant, Guangzhou, China, 2020. Emerging Infectious Diseases. https://doi.org/10.3201/eid2607.200764

    - An outbreak of SARS-CoV-2 among 10 people from 3 family units was linked to an indoor air-conditioned restaurant in Guangzhou, China. Examination of the potential routes of transmission suggest that the most likely cause of this outbreak was droplet transmission from one asymptomatic index patient. The authors recommend increasing the distance between tables and improving ventilation to prevent the spread of SARS-CoV-2 transmission.

13. Hamner et al. (May 15, 2020). High SARS-CoV-2 Attack Rate Following Exposure at a Choir Practice - Skagit County, Washington, March 2020. MMWR. Morbidity and Mortality Weekly Report. https://doi.org/10.15585/mmwr.mm6919e6

14. Shen et al. (Sept 1, 2020). Community Outbreak Investigation of SARS-CoV-2 Transmission Among Bus Riders in Eastern China. JAMA Internal Medicine. https://doi.org/10.1001/jamainternmed.2020.5225

    - In a community outbreak involving two buses with indoor air recirculation on a 100-minute roundtrip to attend a worship event in Zhejiang province, passengers in the bus that had the index case had a 34% higher risk of getting COVID-19 compared to the other bus. Dividing seats on the exposed bus into high- and low-risk zones based on proximity from the index case, individuals in high-risk zones had moderately (but nonsignificantly) higher risk for COVID-19 compared with individuals in low-risk zones.

15. de Man et al. (Aug 28, 2020). Outbreak of COVID-19 in a Nursing Home Associated with Aerosol Transmission as a Result of Inadequate Ventilation. Clinical Infectious Diseases. https://doi.org/10.1093/cid/ciaa1270

    - Inadequate ventilation may promote aerosol transmission, as suggested by an outbreak in one of the wards of a Dutch nursing home that was recently renovated with a ventilation system that only circulates outside air when the indoor CO2 concentration is below a certain concentration. Over 6 days, this ward reported 17 (81%) residents and 17 (50%) mask-equipped healthcare workers were positive for COVID-19, while all 106 healthcare workers and 95 residents of the other 6 wards that were ventilated with outside air tested negative (compared to a national weekly prevalence of 0.8%).

16. Cai et al. (May 19, 2020). Indirect Virus Transmission in Cluster of COVID-19 Cases, Wenzhou, China, 2020. Emerging Infectious Diseases. https://doi.org/10.3201/eid2606.200412

17. Brlek et al. (June 19, 2020). Possible Indirect Transmission of COVID-19 at a Squash Court, Slovenia, March 2020: Case Report. Epidemiology and Infection. https://doi.org/10.1017/S0950268820001326

18. Muller et al. (Dec 2, 2020). Severe Acute Respiratory Syndrome Coronavirus 2 Outbreak Related to a Nightclub, Germany, 2020. Emerging Infectious Diseases. https://doi.org/10.3201/eid2702.204443

19. Jang et al. (July 19, 2020). Cluster of Coronavirus Disease Associated with Fitness Dance Classes, South Korea. Emerging Infectious Diseases. https://doi.org/10.3201/eid2608.200633

20. Nissen et al. (Dec 11, 2020). Long-Distance Airborne Dispersal of SARS-CoV-2 in COVID-19 Wards. Scientific Reports. https://doi.org/10.1038/s41598-020-76442-2

    - Detection of SARS-CoV-2 in the ventilation system of 3 linked COVID-19 wards in a Swedish hospital suggests long-distance airborne dispersal beyond droplet transmission. SARS-CoV-2 genetic material was detected in 7 of 19 vent openings within wards, while 8 of 9 samples obtained from HEPA exhaust filters located several floors above the wards were also positive for genetic material. Inoculation of susceptible cell cultures with the samples did not demonstrate infectious virus at the time of sampling.

21. Yamagishi et al. (July 21, 2020). Environmental Sampling for Severe Acute Respiratory Syndrome Coronavirus 2 during COVID-19 Outbreak in the Diamond Princess Cruise Ship. The Journal of Infectious Diseases. https://doi.org/10.1093/infdis/jiaa437

    - After sampling environmental surfaces in the Diamond Princess cruise ship, Yamagishi et al. detected SARS-CoV-2 RNA from 10% of the samples from case-cabins 1-17 days after they were vacated and detected none in non-case-cabins. Asymptomatic and symptomatic case cabins had a similar proportion of detection (21% vs 15%). No viable SARS-CoV-2 virus was isolated from any of the samples.

22. Horve et al. (June 28, 2020). Identification of SARS-CoV-2 RNA in Healthcare Heating Ventilation and Air Conditioning Units. Medrxiv. https://doi.org/10.1101/2020.06.26.20141085

23. Mecenas et al. (Sep 18, 2020). Effects of Temperature and Humidity on the Spread of COVID-19: A Systematic Review. PloS One. https://doi.org/10.1371/journal.pone.0238339

24. Bedrosian et al. (Nov 23, 2020). A Systematic Review of Surface Contamination, Stability, and Disinfection Data on SARS-CoV-2 (Through July 10, 2020). Environmental Science & Technology. https://doi.org/10.1021/acs.est.0c05651

    - A systematic review and meta-analysis (n=78 studies) found that laboratories had the highest proportion of surfaces test positive for SARS-CoV-2 while household surfaces had the lowest. In assessing surface stability using infectivity, half-life of SARS-CoV-2 on stainless steel, plastic, and nitrile was 2.3-17.9 hours, and decreased at higher temperature and humidity. Disinfection studies with SARS-CoV-2 or surrogate viruses indicated that sunlight, ultraviolet light, ethanol, hydrogen peroxide, and hypochlorite can attain 99.9% reduction in infectivity.

25. Curtius et al. (Oct 5, 2020). Testing Mobile Air Purifiers in a School Classroom Reducing the Airborne Transmission Risk for SARS-CoV-2. MedRxiv. https://doi.org/10.1101/2020.10.02.20205633

    - *[Pre-print, not peer reviewed]* Four mobile air purifiers with HEPA filters in a regular high school classroom were able to reduce the concentration of aerosols by more than 90% within less than 30 minutes compared to a neighboring classroom without purifiers. The authors further estimate that the inhaled dose via airborne transmission from staying in the room with a super-infectious person for two hours is reduced by a factor of 6 by the air exchange rate when using the purifiers.

26. Dumont-Leblond et al. (Nov 18, 2020). Low Incidence of Airborne SARS-CoV-2 in Acute Care Hospital Rooms with Optimized Ventilation. Emerging Microbes & Infections. https://doi.org/10.1080/22221751.2020.1850184

    - Out of 100 air samples collected over 2 months in acute care hospital rooms hosting COVID-19 patients, 11 samples were confirmed positive via PCR and 0 samples were infectious via viral cultures. No correlation between patient clinical characteristics (e.g., length of hospital stay) and detection of airborne viral RNA was observed.

27. Ho et al. (May 18, 2020). Medical Mask versus Cotton Mask for Preventing Respiratory Droplet

Transmission in Micro Environments. The Science of the Total Environment. https://doi.org/10.1016/j.scitotenv.2020.139510

- Ho et al. compared performance of medical masks and cotton masks in suppressing respiratory droplets from a coughing infectious person. Particles with size ranging 20-1000 nm (NC0.02-1) were measured for each participant while they were in a bedroom and a car wearing a medical mask and 100% cotton mask. There were no significant differences in NC0.02-1 between participants with medical masks and cotton masks in either environment, suggesting that cotton masks could be an effective substitute for medical masks in curbing transmission in public.

28. Lelieveld et al. (Nov 3, 2020). Model Calculations of Aerosol Transmission and Infection Risk of COVID-19 in Indoor Environments. International Journal of Environmental Research and Public Health. https://doi.org/10.3390/ijerph17218114

29. Buchan et al. (Dec 12, 2020). Predicting Airborne Coronavirus Inactivation by Far-UVC in Populated Rooms Using a High-Fidelity Coupled Radiation-CFD Model. Scientific Reports. https://doi.org/10.1038/s41598-020-76597-y