Emerging Evidence on COVID-19

Evidence Brief on SARS-CoV-2 Aerosol Transmission

Introduction

What is the existing evidence implicating aerosol transmission of SARS-CoV-2 within the emerging literature?

Many experts maintain expelled respiratory particles containing infectious pathogens can occur in a continuum of sizes, and smaller respiratory particles (often termed aerosols) can remain suspended in air and disperse further distances than large respiratory droplets (1-5). It has been established that other pathogens that are transmitted through large droplets (e.g., Influenza, SARS-CoV-1, streptococcus pneumonia, and legionella) can also spread by aerosols in some settings and conditions (1, 2, 5-7). As such, virus particles in aerosols may play a role in SARS-CoV-2 infection transmission. This evidence brief summarizes studies providing evidence of potential aerosol transmission of SARS-CoV-2 published up to November 6, 2020.

This evidence brief is organized into five sections:

1) SARS-CoV-2 cluster or outbreak investigations and laboratory animal experiments that provide evidence consistent with aerosol transmission
2) Experimental evidence confirming SARS-CoV-2 virus viability (and infectiousness) in aerosols
3) Biological monitoring studies investigating SARS-CoV-2 RNA within exhaled breath and environmental air samples
4) Models on SARS-CoV-2 viral loads within respiratory particles
5) Fluid dynamics studies estimating particle dispersion and suspension, in the context of SARS-CoV-2

Key Points

- The summarized evidence was identified in published and pre-published literature (n=58) from multiple disciplines. Outbreak and cluster investigations suggest aerosol transmission of SARS-CoV-2 may have occurred in some settings. Emerging experimental evidence indicates aerosols containing SARS-CoV-2 virus can be dispersed beyond two meters and can remain suspended in air for prolonged periods. Fluid dynamics evidence, derived from mathematical models and experimental simulations, provide indirect evidence that SARS-CoV-2 infection from aerosol transmission is possible under some contexts.
- Recent reports show respiratory droplets and aerosols more frequently contain virus particles when an individual's viral load is high, some individuals expel more respiratory droplets and aerosols than

others, and the amount of respiratory droplets and aerosols produced depends on the activity. However, the infectious dose for SARS-CoV-2 has not been established.

- The potential for infection transmission by aerosols appears to be amplified in some settings, such as poorly ventilated and crowded indoor spaces. For example, air currents can circulate respiratory particles over large distances and an insufficient number of air changes can cause aerosols to remain in the indoor air space for long periods of time. The impacts of other environmental factors such as temperature and humidity on aerosol transmission are not well understood.
- Analysis of epidemiological data from nine COVID-19 clusters in different real-world settings (e.g., meat processing plants, indoor choir practice, restaurant, cruise ship, passenger bus, fitness facilities, high-rise apartment building and shopping mall) and some experimental studies using animal models have attributed infection transmission, at least partially, to aerosols (Table 1 & 2).
- Four studies point to the stability of SARS-CoV-2 in aerosol particles, and two of these studies have successfully recovered and cultured SARS-CoV-2 virus from aerosols in air sampled from hospital settings (Table 3). Experimental evidence has demonstrated prolonged viability of SARS-CoV-2 virus within aerosols for up to several hours (range 3 to 16 hours).
- Biological monitoring studies have documented viral RNA in exhaled breath condensate and environmental air samples of individuals infected with SARS-CoV-2 (Table 4 & 5).
- A modeling study, informed by a meta-analysis of respiratory viral load data from COVID-19 cases reported the likelihood of viable virus in aerosols expelled by COVID-19 cases varied from ≤ 0.69% for those with the mean viral load to 61.1% among individuals with the highest viral load (Table 6).
- The included fluid dynamic literature published during the pandemic, from experimental simulations and theoretical models, did not specifically study SARS-CoV-2 (Table 7). However, this evidence does indirectly suggest aerosol transmission of SARS-CoV-2 is possible.
    - Experimental simulations that visualize the suspension of fluid emitted during normal speech has shown that these particles can remain suspended in stagnant environments for longer than 8 minutes.
    - A sneeze generates a multiphase respiratory droplet cloud (containing a continuum of droplet sizes) and can spread up to 7-8 meters from the point of origin.
    - The simulation and *in silico* evidence indicate droplet size, airflow, room ventilation, humidity, temperature, and type of activity (e.g., singing, exercise, and breathing) all have the potential to modify aerosol infection transmission risk, however this is not well characterized for SARS-CoV-2.
    - Different fluid dynamic simulations and computational analyses offer a range of estimates on the extent of particle dispersion and duration of suspension in air, under a range of conditions (Table 7).

Overview of the Evidence

The available body of evidence on the potential transmission of SARS-CoV-2 by aerosols, in the published and pre-published literature, is rapidly evolving. This review includes studies accessed up to November 6, 2020 (n=57 studies) and deemed relevant by a single reviewer. The overall quality of the evidence reviewed is broadly described below for each outcome based on study design, quantity, and consistency of the presented data. Briefly, the hierarchy of evidence and general quality ratings considers well-conducted randomized controlled trials to be high quality due to their low risk of bias. Other experimental designs may be considered moderate quality, but may also be downgraded due to power or conduct issues. Experiments using animal models are considered low quality evidence. Similarly, observational studies are generally considered to be at high risk of bias and thus low quality, however some large, well-conducted, prospective cohort studies may be assessed to be of moderate or low risk of bias and thus of higher quality.

Empirical evidence on aerosol transmission of SARS-CoV-2 stem from cluster investigations of human outbreaks (Table 1), are retrospective observational studies at risk of numerous biases. The retrospective nature of these investigations also mean that inferences about aerosol transmission being the attributed mode of infection are limited to circumstantial evidence. Thus, cluster investigations offer low quality evidence of potential aerosol transmission occurring in real life settings.

Four challenge trials using animal models (Table 2) provide additional empirical evidence of indirect transmission among animals housed in separate cages, or artificially exposed to SARS-CoV-2 by aerosols and resulted in infection. However, some of these studies did not provide sufficient details (e.g., types of separations between cages, distances of animal hosts) to completely rule out short-range transmission. Overall, animal models of transmission offer low quality of evidence for aerosol transmission.

Biological monitoring studies that collect exhaled breath (Table 4) and environmental air samples (Table 5) provide moderate quality evidence that SARS-CoV-2 viral RNA can be identified at a point in time in the environments from which the sample was collected. However, low sample size and variability in how samples were collected across studies, limit the generalizability of the data and is considered low quality evidence overall. Additional research is needed, to confirm the infectiousness and viability of SARS-CoV-2 within air samples which may address some knowledge gaps on aerosol transmission of SARS-CoV-2.

The analysis of fluid dynamics is a field of study that preceded the emergence of COVID-19, and studies the movement of expelled respiratory droplets through laboratory simulations and/or computer models (i.e. *in silico*). As such our review of relevant fluid dynamic literature published since the beginning of the current pandemic (Table 7) does not capture all key evidence on this topic. Several fluid dynamic simulations and analyses, measuring dispersion and suspension under a variety of conditions and activities provided indirect evidence that aerosol transmission is possible. These studies provide data on the physics of respiratory particle flow in air that can be used to understand potential risks and effective risk mitigation strategies under different circumstances. Overall, the studies appear to have been conducted and reported well, but study findings should be interpreted with caution due to limited

generalizability within real-world settings. Due to the variability across studies in terms of applied conditions, assumptions, and simulated or modelled parameters, study findings were not directly compared.

The evidence summarized in this rapid review point to the potential aerosol transmission of SARS-CoV-2 in some settings and/or conditions. Additional evidence will help close knowledge gaps related to:

1) The infectious dose of SARS-CoV-2.

2) The characterization of the conditions (case attributes, environmental conditions) under which viable virus is likely to be present in air and breath samples.

3) Modes of SARS-CoV-2 infection transmission in animal models and humans.

4) The role of aerosol transmission in SARS-CoV-2 clusters and super spreading events.

A review of the available fluid dynamic literature, independent of SARS-CoV-2, may also provide insight into the conditions and activities that can increase or decrease production or release of respiratory aerosols and how this may change the potential SARS-CoV-2 infection transmission risk of different circumstances.

CONTENTS

CLUSTER INVESTIGATIONS/OUTBREAKS AND ANIMAL EXPERIMENTS

This section provides a summary of the empirical evidence on potential aerosol transmission of SARS-CoV-2 from cluster investigations of human outbreaks (Table 1) and experimental transmission studies in animal models (Table 2). Aerosol transmission of SARS-CoV-2 has been implicated in nine COVID-19 cluster/outbreak investigations including a: meat processing plant, dine-in restaurant, choir practice, cruise ship, passenger bus, fitness class, a squash court, and a high-rise apartment building. Investigators of these clusters/outbreaks have provided evidence supporting indirect and/or long-range SARS-CoV-2 transmission via aerosols, and based on results presented other modes of infection transmission (e.g., direct contact or transmission from fomites) were less likely. A common characteristic of all clusters is that the suspect SARS-CoV-2 aerosol transmission events took place within closed indoor settings and the index case(s) and subsequent cases occupied same or nearby closed indoor space for an extended

duration of time. Additionally, suboptimal ventilation, lack of air circulation, and indoor air currents (generated by air conditioners, vertical sewer drainage stacks or fans) may have dispersed infectious particles from the index case to others occupying the same indoor space over distances greater than 2 meters.

Table 1: SARS-CoV-2 clusters and outbreak investigations consistent with aerosol transmission (n=15)

STUDY	METHOD	KEY OUTCOMES
Cluster and outbreak investigations		
Shen (2020) (8) Cluster Investigation China Jan 2020	A COVID-19 outbreak among 128 people driven to a worship event in Eastern China on two separate buses. Round trip was 100 minutes on the bus. Attack rates were measured for Bus 1 vs. Bus 2 that had the index case. Air conditioning systems of both buses were on recirculation mode. Spatial analysis of passenger seating was estimated.	None of the passengers on Bus 1 were infected, 24 of the 68 passengers on Bus 2 developed COVID-19. Passengers riding Bus 2 with the index case had an attack rate of 34.3% (95% CI, 24.1%-46.3%), compared to passengers on bus 1. Although sitting near bus windows and doors appeared to have had a protective effect on infection transmission, the authors conclude, the lack of a significant increase in infection risk between individuals sitting in high risk zones (i.e. closer to the index case) and low risk zones, and elevated attack rates among bus passengers riding with the index case, to be partially explained by aerosol transmission of infection.
Guenther (2020) (9) *preprint* Cluster Investigation Germany Spring 2020*	Investigation of a super-spreader event among meat processing plant workers that included: possible routes of transmission, spatial relationship between workers, climate/ventilation conditions, sharing of living quarters and transportation, and genetic typing of	The analysis of index cases (flatmates) and 18 co-worker cases suggest working the early morning shift (140 early shift workers) to be the common source of infection. Statistically significant infection rates were observed for workers working within an 8-meter radius of the suspect index case. Authors conclude indoor confined settings, demanding physical work, and the facility's environmental conditions (i.e. air being constantly re-circulated and cooled to 10°C, with low air

	oropharyngeal swab samples.	exchange rates) all created conditions for aerosol transmission. Note: quantitative risk estimates were not provided.
Lu 2020 (10) Cluster Investigation China Jan-Feb 2020	Analysis of a COVID-19 cluster among restaurant lunch diners. The investigation included a spatial analysis of restaurant table arrangement and where cases were seated.	An outbreak among 91 individuals at a restaurant, 83 had dined at 15 tables, and the remaining 8 individuals were staff. A single asymptomatic case led to 9 COVID-19 infections among diners from families A, B, and C. None of the families had met previously and did not have any close contact during lunch. No additional cases were identified during the 14 days quarantine of the remaining diners. Spatial analysis of case tables during lunch (i.e. exposure event reveal) found the affected tables had been arranged in line with airflow from an air conditioning unit. Authors suggest infection transmission could not be explained by droplets alone, and aerosols travelling with air flow may have contributed to infection transmission.
Li (2020) (11) *preprint* *In silico* study China Feb 2020 Note: See also a separate analysis of the cluster described by Lu (2020).	An investigation and analysis of a COVID-19 cluster among 3 families who ate at the same restaurant. The analysis included: epidemiological data, spatial analysis of restaurant table arrangement, video surveillance data, and computer fluid dynamic and tracer gas simulations of event's fine droplet spread.	10 people from three different families seated at different tables were found to have been infected with SARS-CoV-2 following a Chinese New Year's Eve (January 24, 2020) lunch. None of the waiters or patrons at the remaining tables became infected. Ventilation rate was estimated to be 0.75-1.04 L/s per person. No close contact or fomite contact was observed among cases, aside from back-to-back sitting by some patrons. Using computer simulations the authors demonstrate infection distribution to be consistent with the spread pattern of exhaled virus aerosols. Poor ventilation in the restaurant may have also contributed to infection spread.
Hamner (2020) (12)	An epidemiologic investigation of a case	Among the 61 choir members attending the practice, at least one singer was known to be a

Cluster Investigation USA Mar 2020 Note: See also a separate analysis of the cluster described by Miller (2020).	cluster linked to a choir practice, in Skagit County, Washington. The practice lasted for 2.5h. During practice people were singing and seated 6-10 inches apart, socializing with communal snacks, and stacking chairs. None of the attendees reported physical contact.	symptomatic COVID-19 case. The epidemiological investigation reported 53 cases (33 confirmed, 20 probable cases). Secondary attack rates were 53.3% among confirmed cases and 86.7% among all cases. The odds of infection were 125.7 (95% CI: 31.7-498.9) times greater among members who attended the March 10 practice (assumed exposure event). The investigators introduce the potential for aerosol emission and COVID-19 transmission during singing in the COVID-19 literature.
Miller (2020) (13) *In silico* study USA Mar 2020 Note: See also a separate analysis of the cluster described by Hamner (2020).	Monte Carlo simulations and mathematical modeling were used to estimate aerosol emission rates in the outbreak linked to a choir practice, in Skagit County. The applied model assumes infection transmission during the outbreak was dominated by inhalation of respiratory aerosols in a well mixed indoor environment (i.e. the aerosols were evenly distributed in the air). The viral load emitted was expressed as quanta emission rate (quanta per hour) where a quantum was defined as the dose of aerosol droplet nuclei required to cause infection in 63% of susceptible persons.	*In silico* analysis supported aerosol transmission from respiratory aerosols based on assumption that high emission rates occurred given the high attack rate (53-87%), which was higher than would be expected if the transmission was due to fomites or large respiratory droplets. The model estimates the mean respiratory aerosol emission rate for a single infected case at the exposure event to be 970 [IQR 680-1190] quanta per hour. Note: Study findings are in agreement with results from Buonanno, 2020).

Buonanno (2020) (14) *In silico* study China and US (sites of applied outbreaks) Feb-Mar 2020 Note: A different analysis of restaurant and choir practice outbreaks described above.	This is an emission and exposure model that used a step-wise approach to quantify individual infection risk among susceptible subjects exposed to an asymptomatic/mildly symptomatic case in choir practice and dine-in restaurant. Also used Monte Carlo method; individual infection risks were calculated as a function of quanta emission characteristics.	The model illustrated individual infection risk increased based on ventilation rates, activities and amount of virus exhaled. For instance, sedentary activities for 1 hour may have an infection risk of 2.1%, which can increase to 27% with higher emission rates. Based on risk assessment approach and available data, quanta emission rates were estimated to be 61 quanta per hour for the restaurant and 341 quanta per hour for the Skagit Valley choir practice. In both of the examples, varying the ventilation would not have achieved an individual risk <0.1. The authors concluded aerosol transmission represents the main route of transmission for both outbreaks.
Kriegel (2020) (15) *In silico* study Germany, China, USA, (sites of applied outbreaks) Feb-Mar 2020 Note: Included the following clusters: Meat Processing plant- Guenther (2020), Choir Practice- Hamner (2020), Bus Passengers – Shen (2020), and Restaurant – Lu (2020).	An extension of the Wells-Riley equation was used to estimate predicted infection risk via aerosols in twelve published and unpublished COVID-19 outbreaks. Predicted infection risks were compared to observed attack rates in each event. To estimate a "credible interval" for model predicted infection risks, the quanta emission rate, the respiratory rate as well as the air volume flows were varied. The analysis assumes long range aerosol transmission in an ideally mixed environment.	In nine out of the twelve outbreaks the observed attack rates were in range with the predicted infection risk via aerosols and the corresponding ranges (with the variation of the boundary conditions). Predicted Infection Risk via Aerosols (PIRA)/attack rate (AR) Meat processing plant: 25% (17-35)/ 26% Choir: 97% (88-99)/ 87% Restaurant: 40% (35-56)/ 45% Bus tour: 35% (19-58)/ 34% The attack rates from all these outbreaks are reported to be in-line with estimated infection risk via aerosols.

Azimi 2020 (16) *preprint* *In silico* study Cruise ship Jan-Feb 2020 Note: Same outbreak described by Almilaji (2020) and Xu (2020).	Analysis of case data from the Diamond Princess outbreak using a framework that applies stochastic Markov chain and negative exponential dose-response modeling with empirical data, to inform a modified version of the Reed-Frost epidemic model, to predict case count rates. Effective incubation period was estimated to be 6-15 days, and considered different modes of transmission. Note: Case data from January 20 to February 24, 2020 were included in the analysis.	There were 712 COVID-19 cases among 3711 passengers and crew members (attack rate of 19%). Mean contributions of short-range droplets and aerosols (35%), long-range aerosols (35%), and fomite (30%) modes of infection transmission aboard the ship were estimated, as were the contributions of large respiratory droplets (41%) and small respiratory aerosols (59%). Based on the modeled analysis estimates, the authors conclude short-range and long-range aerosol transmissions to be the dominant modes of infection transmission in the outbreak. Quarantining passengers to their cabins dropped the Rt value to almost zero. Authors suggest that on the cruise ship aerosol transmission was the dominant mode of transmission (>70% of cases) despite the high ventilation rates (9-12 air changes per hour) with no air recirculation.
Almilaji (2020) (17) *preprint* Cluster Investigation Cruise ship Jan-Feb 2020 Note: Same outbreak described by Azimi (2020) and Xu (2020).	Analysis of clinical and case count data from Diamond Princess cruise ship outbreak. Post quarantine symptomatic infection onset rates (SIRR) among lab confirmed cases were examined and the design of the cruise ship's air conditioning system was considered. Note: Case data up to February 20, 2020 were included in the analysis.	Rates among passengers in cabins without infected cases was 5.4%, which was higher than rates among passengers in cabins with confirmed cases 2.4%. Difference in rates was -3.1% (95% CI_{upper} 9.1%). Based on this difference, the authors suggest aerosol transmission of SARS-CoV-2 through the cruise ship's ventilation system may have contributed to the outbreak. Note: All cases in both room types occurred within 10 days of the start of quarantine on the ship. The use of a 6-day incubation period cut-off by the author led to the results above.
Xu (2020) (18) *preprint*	Analysis of COVID-19 case data from the Diamond Princess cruise ship	Daily infection rates for passenger cases (n=146) were predicted based on close contact vs. non-

Cluster Investigation Cruise ship Jan-Feb 2020 Note: A different analysis of the cluster described by Azimi (2020) and Almilaji (2020).	outbreak was analyzed based on individual risk factors, stateroom occupancy and the air conditioning (i.e. HVAC) system of the ship to explore the most plausible modes of transmission. Case data from January 20 to February 18, 2020 were included in this analysis.	close contact status, and pre- and post-quarantine data (February 5 was the start of quarantine). The investigators concluded most passenger cases were likely exposed before the passengers were quarantined and the cruise ship's air conditioning system did not play a role in long-range aerosol transmission of COVID-19.
Jang (2020) (19) Cluster Investigation South Korea Feb-Mar 2020	Investigation of a COVID-19 outbreak associated with Zumba classes at 12 different fitness sports facility locations following an instructor workshop in Cheonan, South Korea.	The initial transmission event is assumed to have occurred among instructors at a 4-hour workshop where 8 of the 27 attendees tested positive for SARS-CoV-2. In the following weeks case counts associated with infected instructors grew to 112 cases across multiple fitness facilities. The workshop attack rate was 26.3% (95% CI 20.9%–32.5%) and the secondary attack rate from 8 instructors was 4.10% (95% CI 2.95%–5.67%, 830 close contacts). The investigators state approximately half of identified cases (50.9%) were due to transmission from instructors to fitness class participants; 38 cases (33.9%) were in-family transmission from instructors and students; and 17 cases (15.2%) were from transmission during meetings with coworkers or acquaintances. No secondary cases were observed among Pilates and yoga class students, led by an infected instructor. Authors state intense physical activity, large number of participants in a fitness class (i.e. crowded space), and the moist warm atmosphere of the sports facility may have contributed to high rates of infection in the outbreak.

Brlek (2020) (20) Cluster Investigation Slovenia Feb-Mar 2020	Investigation of a SARS-CoV-2 cluster linked with a squash court.	The cluster involved 6 cases assumed to be linked through indirect transmission of infection. Epidemiological investigation indicated the index case developed symptoms during the game of squash, and four confirmed and one suspect case were linked to the same squash hall and potentially the same change rooms. None of the cases shared sports equipment or had contact with the facility staff. No additional cases were identified. Authors suggest the infection transmission within the cluster likely occurred due to aerosolization of virus in the indoor setting including small confined space, inadequate ventilation and strenuous physical activity.
Cai 2020 (21) Cluster Investigation China Jan 2020	Investigation of a SARS-CoV-2 cluster linked to a shopping mall. Clinical, epidemiological and laboratory (RT-PCR) data of cases was analyzed to assess possible modes of infection transmission.	Two shopping mall co-workers were the index cases: this was associated with 7 infections among co-workers on the same floor, 7 mall staff from other floors, 10 mall shoppers, and 2 close case contacts outside of the mall. Shoppers and co-workers from other floors denied close contact with the index cases. Based on the available data the authors suggest infection spread could have resulted from spread via fomites or virus aerosolization in a confined public space (e.g., restrooms or elevators).
Kang 2020 (22) China Cluster Investigation Jan – Feb 2020	Investigate infection transmission between nine cases from three families living in the same high-rise apartment building. Use ethane as a tracer gas surrogate for gas in the buildings drainage system and computational fluid dynamics to investigate possible sources of	The index family reported travel related to exposure in Wuhan, but the two other families with subsequent cases did not. All three families lived in vertically aligned flats that were connected by drainage pipes in the master bathrooms. No exposure from the building's elevators were identified, and viral RNA was not detected on elevator buttons or air vent surfaces. Based on the epidemiological and *in silico* analyses it is assumed infection transmission from the index family to the other two families likely occurred

	infection and transmission among families.	through fecal aerosols traveling within vertical drainage stacks.

Four experimental studies using animal models assessed the possibility of indirect and aerosol transmission. These included ferrets (n=2) separated by a permeable partition and a duct system, golden hamsters in adjacent stainless steel cages, and non-human primates exposed to SARS-CoV-2 laden aerosols. This evidence implies indirect transmission by aerosols can occur.

Table 2: laboratory animal experiments consistent with SARS-CoV-2 aerosol transmission (n=4)

STUDY	METHOD	KEY OUTCOMES
Laboratory animal experiments		
Edwards (2020) (23) *Preprint* Simulation experiment USA Oct 2020* Note: Additional results on aerosols emission are summarized in Table 7.	Eight non-human primates (Macaca mulatta (rhesus macaque) and Chlorocebus aethiops (African green monkey)) were infected with aerosols (≈2 µm) containing SARS-CoV-2 (~$2.5x10^3$ TCID50) using a laboratory inhalation system.	Mucosal sampling by nasal swabs showed viral RNA detected as early as +1 day post infectious aerosol exposure. Exhaled breath particle production started 3 days post infection rose to day 7 and decreased to baseline by day 14 in primates. There was a significant association between exhaled breath particles and viral load in most primates and correlated with viral kinetics. Viral RNA was undetectable in nasal swab samples of infected primates by day 28 post-infection.
Kim (2020) (24) *In Vivo Study* South Korea* May 2020*	An experimental study of ferret to ferret transmission of SARS-CoV-2 in laboratory settings. Indirect contact of ferrets was achieved by a permeable partition between cages to separate susceptible and infected ferrets.	Two out of six indirect contact ferrets were positive for viral RNA in nasal washes and fecal specimens. Authors suggest aerosol transmission to have occurred among indirect contact ferrets.
Kutter (2020) (25) *Preprint*	An experimental study set-up in which four donor and indirect recipient	Indirect transmission of SARS-CoV-2 between two ferrets more than 1 meter away was confirmed in two of four independent transmission pairs.

In Vivo Study Netherlands* Oct 2020*	pairs' cages were connected through a hard duct system consisting of horizontal and vertical pipes with multiple turns. Airflow was directed upwards from the donor to indirect recipient animals. Air travelled an average of 118 cm through the tube systems.	Infection was confirmed through the detection of viral RNA in throat and nose swabs.
Sia (2020) (26) *In Vivo* Study Hong Kong* May 2020*	Experimental study to investigate SARS-CoV-2 infection transmission via aerosols. Infected and susceptible golden hamsters were housed in adjacent wire cages placed 1.8 cm away from one another (3 different pairs) were exposed to one another for 8 hours.	Efficient indirect transmission of infection to susceptible hamsters occurred for all three pairs in experimental settings. Peak viral load in aerosol exposed hamster was at 3 days post contact.

*Estimated based on author affiliations and publication date.

SARS-COV-2 VIABILITY IN AEROSOLS

Four studies point to the stability of SARS-CoV-2 in aerosol particles, while three of these studies measured the potential infectiousness of virus in aerosols. Two experimental investigations demonstrated SARS-CoV-2 viral titers can remain stable in artificially created aerosols up to 3 hours and 16 hours, respectively (27, 28). The infectiousness of virus within aerosols from hospital environments with SARS-CoV-2 patients were measured using cell culture, while the infectiousness of virus within aerosols artificially suspended for up to 16 hours in a laboratory was quantified via plaque assay (29-31).

Table 3: Experimental evidence confirming SARS-CoV-2 virus viability (and infectiousness) in aerosols (n=4)

STUDY	METHOD	KEY OUTCOMES
Fears 2020 (31) Simulation experiments	The long-term persistence of artificially generated viral aerosol suspensions of SARS-	Infectious SARS-CoV-2 was detected at 10 minutes, 30 minutes, 2, 4, and 16 hours

USA* Spring 2020*	CoV-2 was measured at different time intervals. Viral contents were quantified by RT-PCR, and infectiousness of virus was measured by plague assay. Samples were qualitatively assessed by electron microscopy.	during the aerosol suspension stability experiment. A minimal reduction in viral genome copies in aerosol samples (as measured by RT-PCR) was noted for the measured time points. A minor but constant fraction of the SARS-CoV-2 virus in aerosols maintained replication-competence at all measured time points, including at 16 hours. Qualitative assessment of virion integrity revealed virions were either ovoid or spherical in shape, and maintained the expected morphologies up to 16 hours in aerosol suspension.
Santarpia (2020) (30) *Preprint* Biological monitoring study USA* Apr 2020* Note: Additional results on viral RNA in environmental air samples are summarized in Table 5.	Patient generated aerosols in hospital settings were collected using a NIOSH BC251 aerosol sampler at the foot of COVID-19 patient beds (n=6). Aerosol sizes and concentrations were measured during sample collection using an Aerodynamic Particle Sizer Spectrometer. Aerosols were distinguished by the proportion of different sizes (>4.1 µm, 1-4 µm, and <1 µm) among samples. Presence of the virus in isolated aerosols (<5µm) was measured using RT-PCR, western blot, and transmission electron microscopy and infectiousness of isolated viral particles was examined using cell culture (Vero-E6).	Viral RNA was detected in all collected samples with aerosols in the <1 µm, 1-4 µm, and >4.1µm ranges. Replicating virus in cell culture was observed in most <1 µm aerosol samples, two of the 1-4 µm size aerosol samples and two of the >4.1µm samples. Western blot and TEM analysis of these samples showed evidence of viral proteins and intact virions, which the authors regard as support for virus viability. The authors conclude the infectious nature of the aerosols collected in this study suggests that aerosol transmission of COVID-19 is possible.

Lednicky (2020) (29) Biological monitoring study USA* Nov 2020* Note: Additional results on viral RNA in environmental air samples are summarized in Table 5.	Air samples were collected from hospital rooms of COVID-19 patients in the absence of aerosol generating procedures. Air samples were collected using a VIVAS air sampler 2 to 4.8 meters away from patients. Air samples were collected both with and without a HEPA filter on the air sampler inlet tube. The presence of the virus in isolated air samples was measured using RT-PCR, and infectiousness was measured based on cytopathic effects in cell culture (LLC-MK2 and Vero-E6). The genomes of isolated virus was sequenced.	Viable (infectious) SARS-CoV-2 was found to be present in aerosols sampled from hospital patient rooms by RT-PCR and cell culture. A single nearly complete virus sequence was isolated from the air samplers that collected environmental air. This genetic sequence matched the virus strain isolated from nasopharyngeal sample of one of the two patients who occupied the room during sampling. The matched person was diagnosed with acute infection at the time of air sampling.
Van Doremalen (2020) (28) *Letter to Editor* Simulation experiment USA* Spring 2020*	In this experiment SARS-CoV-2 and SARS-CoV-1 virus titer stability and decay was measured from artificially generated aerosols. Analysis used a Bayesian regression model.	SARS-CoV-2 virus remained viable in experimentally generated aerosols up to 3 hours (duration of the experiment), with a reduction in infectious titer from $10^{3.5}$ to $10^{2.7}$ $TCID_{50}$ per liter of air. In aerosols the half life of SARS-CoV-2 virus was estimated to be 1.1-1.2 with a 95% credible interval of 0.64-2.64.

*Estimated based on author affiliations and publication date.

SARS-COV-2 RNA IN EXHALED BREATH

Three studies that investigated the presence of SARS-CoV-2 RNA in exhaled breath air samples and exhaled breath condensate samples of infected cases were identified. Two studies confirm the presence of SARS-CoV-2 RNA in exhaled breath condensate of COVID-19 patients via RT-PCR (32, 33). However, no exhaled breath samples from SARS-CoV-2 cases in any of the included studies were reported to be positive for viral RNA.

Exhaled breath condensation technique is applied to detect biomarkers (e.g., virus) expelled from the lower respiratory tract, 1-2 ml of condensate is collected by cooling and condensation of aerosols exhaled during quiet breathing (34, 35). Among the included studies exhaled breath samples were collected using different air sampling devices. Although the sensitivity of each method in identifying viral particles in exhaled breath does not appear to be established, relevant literature states both methods are greatly affected by the breathing protocol used, specifically the depth of inhaled and exhaled breath velocities (35).

Some authors reporting negative results in exhaled breath (and environmental air) samples attribute their inability to identify SARS-CoV-2 virus to efficient ventilation and infection control practices in hospital settings, differences in case viral loads, infection progression, and reduced respiratory viral shedding at later stages of infection. The variability in respiratory viral loads during the course of SARS-CoV-2 infection was explored by a systematic review meta-analysis informed *in silico* model of viral load and infectiousness (Table 6) (36).

Table 4: Biological monitoring studies investigating SARS-CoV-2 within exhaled breath (n=3)

STUDY	METHOD	KEY OUTCOMES
Reporting SARS-CoV-2 in some samples		
Feng (2020) (33) Biological monitoring study China Feb-Mar 2020 Note: Additional results on viral RNA in environmental air samples are summarized in Table 5.	Sampled exhaled breath and environmental air of COVID-19 patients using a NIOSH bio-aerosol sampler. Exhaled breath condensate was sampled using a sterile laboratory-made collection system. Air samples were segregated by aerosol size. Samples were collected from COVID-19 patients in the later stages of infection in hospital settings.	SARS-CoV-2 RNA was not detected in any of the patients' expired breath samples (n=0/9). RNA was isolated in exhaled breath condensate (n=2/8), and bedside air samples (n=1/12). The authors attributed minimal contamination of viral RNA in study samples to reduced respiratory viral shedding among patients in later stages of infection.
Ma (2020) (32) *Preprint* Biological monitoring study China	Exhaled breath condensate samples were collected from COVID-19 patients (n=30) using a BioScreen device.	The study confirms the emission of SARS-CoV-2 virus RNA into the air from exhaled breath condensate of infected individuals (16.7% n=5/30). The positive samples were detected either <3 days from symptom onset

Spring 2020* Note: Additional results on viral RNA in environmental air samples are summarized in Table 5.		(n=3) or within 7-14 days from symptom onset (n=2). SARS-CoV-2 levels in exhaled breath were estimated to reach 105-107 copies/m3 if an average breathing rate of 12 L/min is assumed and is highest during early stages of infection.
Reporting NO SARS-CoV-2 in samples		
Ding (2020)(37) *Preprint* Biological monitoring study Hong Kong Feb 2020 Note: Additional results on viral RNA in environmental air samples are summarized in Table 5.	Exhaled condensate samples (n=2) and expired air samples (n=2) were collected from COVID-19 patients housed in airborne infection isolation rooms (AIIR). Multiple devices were used for air sample collection (n=27), which was conducted on different days. Note: sample collection distances from patient(s) are not reported.	All collected exhaled condensate samples and expired air samples were negative for SARS-CoV-2 RNA.

*Estimated based on author affiliations and publication date.

SARS-COV-2 RNA IN ENVIRONMENTAL AIR

There were seventeen biological monitoring studies investigating SARS-CoV-2 RNA in air samples collected from COVID-19 patient care settings. Air sampling methods across included studies were highly variable, some studies used different air sampler models while others used fluid filled petri dishes, gelatin filters, agar plates and novel COVID-traps to capture viral RNA from environmental air. This variability in sampling methodologies may have contributed to the observed differences in viral RNA positivity in collected samples. Thirteen studies noted some degree of SARS-CoV-2 RNA contamination within collected air samples, while four studies did not. Authors reporting no air contamination suggested effective disinfection, high efficiency air ventilation and filtration systems fitted to Airborne Infection Isolation Rooms (AIIR) as possible reasons for negative results (38, 39). This rationale is further supported by one biological monitoring study which was unable to detect viral RNA in collected samples when the air sampler inlet was covered with a HEPA filter(29).

Of the studies reporting SARS-CoV-2 RNA in air samples, seven reported on viral RNA concentrations (29, 32, 33, 40-43), three provided details on aerosol particle size and proportion (33, 43, 44). Sampling distance from COVID-19 patients (i.e. source) were not consistently reported across included studies, but some studies did note collecting positive air samples more than 2 meters away from patients (29, 41, 43, 45-47). Moreover, studies did not consistently report the types of medical procedures taking place at the time of air sample collection, nor the days of illness for patients who were present during sample collection. These data gaps make it difficult to determine the conditions upon which viral RNA in air samples becomes a common occurrence.

Table 5: Biological monitoring studies investigating SARS-CoV-2 within air (n=17)

STUDY	METHOD	KEY OUTCOMES
Reporting SARS-CoV-2 in some samples		
Chia (2020) (44) Biological monitoring study Singapore Spring 2020*	Detection of air contamination by SARS-CoV-2 in airborne infection isolation rooms (AIIR) housing COVID-19 patients, in hospital settings. Air samples were collected, and aerosol sizes were measured by NIOSH BC 251 bio-aerosol samplers. Viral RNA was detected by PCR.	66% (n=2/3) of the air samples collected from AIIR environments were SARS-CoV-2 RNA positive. The smallest aerodynamic size fraction that contained detectable levels of SARS-CoV-2 RNA was 1–4 μm. Total SARS-CoV-2 concentrations in air ranged from 1.84×10^3 to 3.38×10^3 RNA copies per m^3 air sampled. The authors suggest the presence of SARS-CoV-2 in the sampled air is likely highest during the first week of illness, when respiratory viral load is high.
Ding (2020) (37) *Preprint* Biological monitoring study Hong Kong Feb 2020 Note: Additional results on viral RNA in exhaled breath samples are summarized in Table 4.	Air samples (n=46) were collected from airborne infection isolation rooms (AIIR) housing COVID-19 patients, nursing stations, corridor and air-conditioning units at a hospital treating COVID-19 cases. Multiple air samplers were used for sample collection, which was conducted on different days, and RNA was detected by RT-PCR.	A single air sample (n=1/46) from the corridor outside a storage room with a medical waste bin was weakly positive for SARS-CoV-2 RNA. All other tested air samples from patient rooms, washrooms, and air supply inlets were negative. RNA copies for the weakly positive sample was not quantified.

Feng (2020) (33) Biological monitoring study China Feb-Mar 2020 Note: Additional results on viral RNA in exhaled breath samples are summarized in Table 4.	Environmental air from the rooms of recovering COVID-19 patients in isolation hospital wards and ICU were sampled using a NIOSH sampler. Air samples (n=12) were collected and aerosol size measured. Samplers were also placed on a tripod 1.2 m in height and 0.2 m away from the bed at the side of the patient's head for 30 minutes.	SARS-CoV-2 RNA was detected in a single air sample from SARS-CoV-2 patients. The maximum viral RNA concentrations detected in the positive air sample by particle size was 1112 copies/m^3 (<1 µm) and 745 copies/m^3 (>4 µm). The authors attribute minimal contamination of viral RNA in study samples to reduced respiratory viral shedding among patients in later stages of infection.
Lednicky (2020) (29) Biological monitoring study USA* Nov 2020* Note: Additional results on viral RNA viability in aerosols are summarized in Table 3.	Air samples were collected from hospital rooms of COVID-19 patients in the absence of aerosol generating procedures. Air samples in triplicate were collected using two VIVAS air samplers 2 and 4.8 meters away from patients' heads. Air samples were collected both with and without a HEPA filter on the air sampler inlet tube. The presence of the virus in isolated air samples was measured using RT-PCR, and infectiousness was measured based on cytopathic effects in cell culture (LLC-MK2 and Vero-E6). The genomes of isolated virus was sequenced.	All air samples collected without a HEPA filter was positive for viral RNA. A single nearly complete virus sequence was isolated from the air samples. This genetic sequence matched the virus strain isolated from nasopharyngeal sample of one of the two patients who occupied the room during sampling. The matched patient had an acute infection at the time of air sampling.
Liu (2020) (48) Biological monitoring study China Feb-Mar 2020	SARS-CoV-2 RNA concentration and aerosol size distributions in air samples (n=30) from multiple sites within or near a hospital and field hospital.	SARS-CoV-2 contamination in patient care air samples was low to undetectable. In the field hospital setting, the greatest suspended SARS-CoV-2 RNA in aerosols was identified in a temporary

	All aerosol samples (n=30) were collected on pre-sterilized gelatin filters (Sartorius). Three size-segregated aerosol samples were collected using a miniature cascade impactor (all sampled from staff areas). Viral RNA was detected by RT-PCR.	patient toilet room (1 m^2 area) with low ventilation, likely from the patient breathing or aerosolization of virus from feces and urine of infected patients. Samples from the field hospital staff personal rooms demonstrated the greatest virus concentrations. Aerosols from 0.25 to > 2.5 µm were identified. The authors hypothesize this came from healthcare worker PPE surfaces and apparel. Low but detectable viral RNA concentrations were found at a department store entrance and an outdoor site near the hospital suggesting this may have occurred due to high traffic flow and crowding. Note: The specific concentrations of airborne SARS-CoV-2 in each aerosol sample by site are provided in the publication.
Ma (2020) (32) *Preprint* Biological monitoring study China Spring 2020* Note: Additional results on viral RNA in exhaled breath samples are summarized in Table 4.	Air samples were collected from hospital settings and unventilated quarantine hotel rooms of cases using a robot. RNA was detected by RT-PCR.	A single positive air sample (3.8% n=26) was identified in an unventilated quarantine hotel toilet room.
Guo (2020) (45) Biological monitoring study China	Air samples were collected from hospital ICU (n=40) and general wards housing (n=6) COVID-19 patients, at different distances	SARS-CoV-2 virus particles were identified in 35% of ICU air samples, 12.5% of general ward air samples, and 12.5% of the doctor's office air samples.

Feb-Mar 2020	from patients and the doctors office (n=8). Air samples were collected using a SASS 2300 Wetted Wall Cyclone Sampler.	No SARS-CoV-2 virus were identified in patient corridor air samples. Based on site(s) of positive air sample collection authors conclude virus-laden aerosols to concentrate near and downstream from patients, and the maximum transmission distance of virus laden aerosols to be 4 meters.
Nissen (2020) (46) Biological monitoring study Sweden Spring 2020*	Open liquid containing petri dishes were placed at air entrances to ward rooms and near exhaust filters of a hospital's ventilation system for 24 hrs to collect viable virus. Infectivity was assessed using Vero E6 cell culture.	SARS-CoV-2 RNA was detected in fluid samples placed in the ventilation system, and in 33% of samples (n=1/3) placed near air entrances of wards. Viability of the isolated virus could not be established by cell culture.
Orenes-Piñero (2020) (47) Biological monitoring study Spain Spring 2020*	Investigators develop and apply "COVID traps" to measure the capacity of SARS-CoV-2 aerosol transmission in hospital patient care settings. "COVID traps" were placed 1 meter away from patients in ICU and ward settings. Viral RNA was detected by RT-PCR.	In the ICU, none of the "COVID traps" were positive for COVID-19; all COVID-19 patients were intubated. In the ward setting, two "COVID traps" were positive for SARS-CoV-2, both were near a patient requiring the use of respiratory assistance. The authors conclude it was unequivocally the result of virus transmission in air.
Santarpia (2020) (43) Biological monitoring study USA Mar 2020	Air samples from negative pressure isolation spaces and wards housing COVID-19 cases were collected using a Sartorius Airport MD8 air sampler and tested for SARS-CoV-2 viral RNA by RT-PCR. A subset of positive samples were examined for viral propagation in Vero E6 cells. Several indicators were utilized to determine viral replication including cytopathic effect (CPE), immunofluorescent staining, time	63.2% of in-room air samples were positive by RT-PCR (mean concentration 2.42 copies/L of air). Two samples placed at different proximity to a patient, including a sample from <2 meters away the patient, were positive. Viral concentration was higher in the air sample collected closer to the patient (4.07 vs. 2.48 copies/L of air). 58.3% of air samples collected from hallways were positive (mean

	course PCR of cell culture supernatant, and electron microscopy.	concentration of 2.51 copies/L of air). In a single positive sample from a hallway, there was some presence of viral replication.
Santarpia (2020) (30) *Preprint* Biological monitoring study USA Apr 2020 Note: Additional results on viral RNA viability in aerosols are summarized in Table 3.	Patient generated aerosols in hospital settings were collected using a NIOSH BC251 aerosol sampler at the foot of COVID-19 patient beds. Aerosol sizes and concentration was concurrently measured during sample collection using an Aerodynamic Particle Sizer Spectrometer. Aerosols were distinguished by the proportion of different sizes (>4.1 µm, 1-4 µm, and <1 µm) among samples.	RNA was detected in all six patient rooms, and included all aerosol particle size fractions (defined as >4.1 µm, 1-4 µm, and <1 µm). Replicating virus in cell culture was observed in most <1 µm aerosol samples, two of the 1-4 µm size aerosol samples and two of the >4.1µm samples. Western blot and TEM analysis of these samples also showed evidence of viral proteins and intact virions.
Zhou (2020) (42) *preprint* Biological monitoring study UK Apr 2020	Three to five air samples were collected from multiple hospital environments using a Coriolis air sampler, presence of SARS-CoV-2 RNA was quantified by RT-PCR and then Vero E6 and Caco2 cells cultures were used to culture virus.	38.7% (n=14/31) of the collected air samples were positive for viral RNA, but SARS-CoV-2 virus could not be cultured due to low recovered viral loads. The odds of contamination in public areas was lower than areas immediately occupied by a COVID-19 patient (OR 0.5 95% CI 0.2-0.9).
Zhang (2020) (41) *Preprint* Biological monitoring study China Mar-Apr 2020	The study sampled outdoor environment aerosols (n=16) at three hospitals receiving COVID-19 patients. Aerosol samples were collected using bioaerosol samplers. Viral RNA was quantified by RT-PCR. Note: The infectiousness of recovered virus was not reported to be measured.	SARS-CoV-2 virus was identified within sampled aerosols at 285-1,130 copies/m^3 concentrations, similar to contamination levels observed in ICU units. Viral RNA was identified up to 5 meters away from outpatient buildings, as well as in hospital waste water treatment areas.

Reporting NO SARS-CoV-2 in samples		
Alsved (2020) (49) Biological monitoring study Sweden* Spring 2020* Note: Additional results on aerosols emission are summarized in Table 7.	SARS-CoV-2 RNA measured from COVID-19 cases (n=2) within 2 days of symptom onset. Air samples were collected 0.8 meters away from the case, as the individual was talking or singing. The measurements were carried out in an experimental airtight chamber with human volunteers.	Air samples collected within 0.8 meters of COVID-19 cases were negative for viral RNA. Viral loads in subject airways at the time of the experiment could not be obtained. Authors state qPCR Ct values of 22–25 to have been reported in clinical reports for the subjects within 24hrs of the experiment.
Cheng (2020) (50) Biological monitoring study China Jan-Apr 2020	Air samples were collected within 10 cm of asymptomatic and symptomatic COVID-19 patients (n=6) with and without surgical masks in an airborne infection isolation room (AIIR) were tested for SARS-CoV-2 contamination. Viral loads in respiratory patient fluid samples were also tested by having patients sneeze and spit into gelatin filters within air samplers. Viral loads were measured using assays (not specified) and RT-PCR.	No virus was detected in air samples from rooms with both surgical masked and non-masked patients. Except for one patient who had a respiratory fluid viral load of 2.54×10^4 copies/ml, all other patients' samples from sneezing were negative for virus RNA. Authors suggest aerosol transmission is not the predominate mode of infection transmission in the sampled settings. Appropriate PPE use, environmental disinfection, and single occupancy within AIIR are provided as reasons for observed results.
Kim (2020) (38) Biological monitoring study South Korea Mar-Apr 2020	Air samples (n=52) were collected 2 meters away from COVID-19 patients (n=8), before admission, and on hospital days 3, 5, and 7 using a MD8 Airport Portable Air Sampler. Some patients were housed in negative pressure rooms (e.g., AIIR).	All collected air samples were negative for viral RNA.

	RNA was measured by RT-PCR.	
Ong (2020) (51) Biological monitoring study Singapore Jan-Feb 2020	Air samples were collected from COVID-19 patients (n=3) in a negative pressure airborne infection isolation rooms (AIIR) at a dedicated SARS-CoV-2 outbreak center between day 4 and day 11 of their illness using SKC Universal pumps a Sartorius MD8 microbiological sampler. RNA was measured using RT-PCR.	No air samples were positive for SARS-CoV-2 virus.

*Estimated based on author affiliations and publication date.

SARS-COV-2 VIRAL LOADS IN RESPIRATORY PARTICLES

A systematic review meta-analysis informed a model to estimate the relationship between viable SARS-CoV-2 virus, case viral loads, and virus laden droplet and aerosol emission (36). The study reported the evidence places peak viral load from one day before to five days post symptom onset (36). The model estimated the likelihood of viable virus in respiratory aerosols expelled by an individual at peak viral load was ≤61.1% (95% CI: 51.8-70.4%), this was substantially lower for an individual with a mean viral load ≤ 0.69% (95% CI: 0.43-0.95%).

Table 6: SARS-CoV-2 viral load in respiratory particles (n=1)

STUDY	METHOD	KEY OUTCOMES
Chen (2020) (36) Systematic Review informed *in silico* analysis Canada* Aug 2020	A systematic review and meta-analysis were conducted (Aug 2020) to developed a dataset and summarize data on SARS-CoV-2 respiratory viral load (rVL). A model was developed to estimate the likelihood of respiratory droplets and aerosols containing viable virus assuming different viral load estimates, and different activities.	The meta-analysis showed there was a large degree of heterogeneity in viral loads across individuals, studies, and stage of infection. This suggests intrinsic virological factors mediate the over dispersion seen in the pandemic. Many cases present minimal transmission risk, whereas highly infectious individuals were estimated to shed 9.84 (95% CI 9.17-10.56,) $\log_{10}$ SARS-CoV-2 virions /ml via droplets and aerosols while breathing, talking and singing. The model estimates coughing increased the contagiousness of symptomatic cases. The likelihood of viable virus in respiratory aerosols at peak viral

		load was estimated to be ≤61.1% (95% CI: 51.8-70.4%) for the most infectious cases, and ≤ 0.69% (95% CI: 0.43-0.95%) for cases with mean viral load.

*Estimated based on author affiliations and publication date.

FLUID DYNAMICS SIMULATIONS AND ANALYSES

Several simulations and analyses estimating fluid dynamic properties of respiratory and oral fluid particles that are expelled during various activities (e.g., breathing, coughing, singing, and speaking) and under a range of conditions were identified. The identified studies were restricted to evidence published in the context of SARS-CoV-2. Overall, the findings summarized across studies tend to vary based on experimental technique and simulated conditions, but most confirm respiratory particles can travel further than two meters and become suspended in air for extended periods of time (Table 7). As such, this evidence indirectly supports the plausibility of SARS-CoV-2 transmission by aerosols.

Nine publications and a short communication reporting on fluid particle dispersion and suspension from laboratory simulation studies were identified. Techniques such as laser light scattering, particle detectors, tracer gas/fog and agar plates are used to measure particle dispersion. One study provides visual evidence that fine particles generated by normal speech can remain suspended in air for longer than eight minutes in a stagnant environment (52). Another describes how turbulent gas clouds generated during a simulated sneeze can travel up to 7-8 meters (3). Experimental simulations of heavy cough jets show generated particles can travel as far as 3.3 meters in 50 seconds (53).

Eleven studies presenting *in silico* evidence on droplet dispersion and suspension, derived from a variety of computer based simulations, models, and risk assessments, were identified. One mathematical analysis estimates respiratory aerosols generated by 30 seconds of speech can linger in environmental air for greater than one hour, while another estimates speech and cough generated droplets to linger in air for up to 20 minutes (54, 55). Another computer analysis concludes, although a distance of 1.5 meters may be a protective distance when standing still, distances greater than 1.5 meters are necessary to avoid respiratory particle exposures when individuals are running or moving fast (56).

According to the summarized fluid dynamics evidence, droplet size, air flow/turbulence, room ventilation, humidity, temperature, and activity can all impact the travel path and decay of respiratory particles (Table 7). Generally, smaller particles remain suspended in air for longer periods of time and disperse to greater distances than larger particles. Indoor air currents can increase the dispersion of respiratory particles to beyond two meters, while suboptimal ventilation and air circulation in some indoor settings can lead to the accumulation of infectious particles in the air, which increases infection exposure risk. Ambient temperature and humidity also influence particle size and flow, with some researchers suggesting high relative humidity increases droplet size and droplet transmission while low relative humidity (40%) and high temperatures enhance the formation of smaller particles such as aerosols and droplet nuclei (57, 58). Physical activity can also influence particle fluid dynamics, as dispersion and the amount of SARS-

CoV-2 laden particles appears increased by coughing, sneezing, and singing. Heavy breathing is also found to increase expelled particle volumes and concentrations.

Table 7: Fluid dynamics studies estimating particle dispersion and suspension (n=21)

STUDY	METHOD	KEY OUTCOMES
Laboratory simulations		
Alsved (2020) (49) Simulation study Sweden* Aug 2020* Note: Additional results on viral RNA in air samples are summarized in Table 5.	Investigated aerosol (defined as 0.5–10 µm diameter) and droplet emissions (with no upper size limit) during singing compared to talking and breathing. The measurements were carried out in an experimental airtight chamber with human volunteers.	There were significant differences in particle emissions between different activities. Singing generated more aerosol particles than normal talking; loud singing produced more particles than normal singing. A face mask is found to reduce the amount of emitted aerosols. Median (range) of aerosol particles per second emission rates were: - 135 (85-691) for breathing - 270 (120–1380) for talking - 570 (180–1760) for loud talking - 690 (320–2870) for singing - 980 (390–2870) for loud singing, and -1480 (500-2820) for loud singing with exaggerated diction - 410 (200–1150) with a face mask.
Edwards (2020) (23) *Preprint* Simulation experiment USA Oct 2020* Note: Additional results on laboratory animal experiments consistent with aerosol transmission	To assess respiratory droplet generation and exhalation in healthy humans (n=74), exhaled particles were measured by a particle detector designed to count airborne particles in the size range of 0.3 to 5µm.	The study found the number of exhaled aerosol particles increased with age, BMI and COVID-19 infection. Findings indicate that 80% of exhaled aerosols were emitted by 20% of the human sample.

are summarized in Table 2.		
Mürbe (2020) (59) *Preprint* Simulation experiment Germany Sep 2020*	To assess aerosol emissions in children (n=8), aged 13-15, sat in a cleanroom and spoke, sang and shouted into a glass pipes containing a laser particle counter. All children were members of a semiprofessional children's choir.	The children emitted fewer aerosols than adults, with rates ranging from (particles/second) -16 to 267 for speaking, -141 to 1240 for singing, and -683 to 4332 for shouting. 99% of measured particles were smaller than 5 µm, further 70% were less than 1 µm.
Stadnytskyi (2020) (52) Simulation experiment USA Jun 2020*	Laser light scattering experiments are used to visualize droplet dispersion and decay.	The researchers estimated 1 min of loud speaking could generate a minimum of 1,000 droplet nuclei and that droplets generated during normal speech took 8-14 minutes to decay in closed stagnant environments (similar to indoor environments with poor ventilation).
Anfinrud (2020) (60) *Preprint* Simulation experiment USA Apr 2020*	A planar beam of laser light passed through a dust-free enclosure was to detect saliva droplets emitted while speaking.	Hundreds of respiratory and saliva droplets were emitted during normal speech and coughing. The author suggested speaking could be a mode of transmission of SARS-CoV-2. The investigation provides visual evidence infection transmission from droplets and aerosols is possible.
Bahl (2020) (61) Simulation experiment Australia* Aug 2020*	An LED light was used along with a high-speed camera 23 cm away from the singers' mouth to capture the light scattered by the droplets expelled when they sang, spoke and coughed.	Approximately 75% of expelled droplets were seen to be moving at velocities < 0.5 m/s. The maximum, velocity was 6 m/s. They followed the ambient airflow pattern; and did not settle rapidly. The author concluded that aerosols can linger in the air.
Viola (2020) (62)	In human subjects and simulation manikins, the relative effectiveness of	Heavy breathing had a nine-fold increase in velocity and a three-fold

Preprint Simulation experiment UK May 2020*	seven different types of personal protective equipment (PPE) (surgical mask, hand-made mask, FFP1, FFP2, a respirator, a lightweight face shield, and a heavy duty commercial face shield), for mitigating aerosol dispersal during regular and heavy breathing (as when exercising) and coughing were assessed, using a Background Oriented Schlieren technique to visualize airflow.	increase in volume flux and comes out a straight jet. Coughing had an aerosol flow that was about twice as fast as heavy breathing, it moved straight or slightly downward. All face covers without an outlet valve reduced the front flow through jet by >90%. Surgical and hand-made masks and face shields, generated several leakage jets, including intense backward and downwards jets. For the FFP1 and FFP2 masks without an exhalation valve, the front through flow did not extend beyond 0.5 and 0.25 meters, respectively. Without a mask, air flow goes gently upward as the closest layer of air to the body is warmer and lighter than the surrounding air and thus it moves upwards as a thermal plume. Thermal plumes were visible approximately 1.1 meter away from the source mouth during manikin generated coughing. Tested face covers effectively reduced frontal jets from simulated activities, but variable inhibition of secondary jets.
Verma (2020) (53) Simulation experiment USA* Jun 2020*	In an experimental set up dispersion distances of particles generated from simulated manikin sneezing and coughing (<10 μm) are visualized against a laser generated sheet.	The cough generated "fog" or "smoke" jets (comparable to droplets and aerosols generated by a cough) with an average jet distance of 2.4 meters. The emulated heavy cough jets traveled a maximum of 3.6 meters in 50 seconds.

		A range of face coverings, including a homemade mask, effectively halted forward dispersion of particles to less than 8 inches.
Rodriguez-palacios (2020) (63) Simulation experiment USA* May 2020*	In an experiment using a bacterial suspension and agar plates to culture bacterial contamination at set distances from the source, a sneeze was mimicked and the droplet dispersion was measured with and without masks: Textiles used: combed cotton, 300 thread cotton, polyester, microfiber.	With no barrier large droplets typically landed within 1.8 meters and most micro-droplets landed within 1.2m, however air turbulence carried droplets further. Compared to no barrier: • single layer textiles reduced dispersion to <30 cm and environmental contamination by 97.3%. • 2 layers of textiles reduced dispersion to <10 cm and environmental contamination by 99.7%
Bourouiba (2020) (3) Commentary Mar 2020		A short communication where the authors present findings from their past work (published in 2014) that show turbulent gas clouds generated during a sneeze can travel up to 7-8 meters from the generated source.
Computer/mathematical simulations and models		
Blocken 2020 (56) *preprint* *In silico* study The Netherlands* Apr-Jun 2020	A Computer Fluid Dynamics study that investigates the aerodynamic effects introduced by walking fast, running and cycling on droplet travel distance when two people are 1.5 meters or more apart.	Although particle exposure is negligible when two people are standing 1.5 meter apart, if the individuals are running or walking fast even at 1.5 meters apart there is some risk of infectious particle exposure to the trailing person if they are in the slipstream directly behind the leading person. Droplet exposure risk is less in staggered or side by side arrangement.
Bond (2020) (64)	A quantitative risk assessment to predict the Effective Re-Breathed	Outdoors, ERBV is dependent on proximity and wind dispersion and risk

Preprint Risk Assessment USA* Sep 2020*	Volume (ERBV) under different indoor and outdoor conditions. ERBV is defined as the exhaled volume that contains the same number of particles as the air inhaled by a recipient for various exhaled particle diameters (1 µm, 10 µm, and 100 µm). Outdoors, ERBV is based on the application of steady-state Gaussian plume equation. Indoors, ERBV is based on the application of the well-mixed zone model.	is largely proportional to the interaction time. Dispersion distances of 2-3 meters are possible for particles based on wind speed. Indoors, ERBV rates are dependent on confinement, rather than proximity and depend on room size, ventilation, and accumulation of exhaled air overtime and found within 15 minutes indoors, person to person ERBV for small particles (1-10-µm) exceed ERBV levels at a 2-meter distance outdoors. The risk decreased with HVAC systems, air cleaners, and face masks.
Feng (2020) (57) *In silico* study USA* Sep 2020*	Air transmission of cough droplets with condensation and evaporation effects are modeled between two virtual humans under different environments and wind velocities.	Micro-droplets that follow airflow streamlines and can remain at head level at greater than 3.05 meter (10 feet) distances. High relative humidity (99.5%) also led to larger droplet sizes and greater deposition of cough droplets on surfaces while lower RH promoted evaporation into smaller particles. The study concludes, that due to environmental wind, convection effects and relative humidity on respiratory particles frequently recommended 1.83 meters (6 feet) of social distancing may not be sufficient to prevent inter-person aerosol transmission.
de Oliveira (2020) (55) *preprint* *In silico* study	Consider SARS CoV-2 virus decay rate, viral loads emitted by infected individuals, droplet composition, estimated SARS-CoV-1 infectious dose to derive theoretical estimates	Most large droplets (100 µm–1 mm) are found to progressively disappear as they reach the ground- within one minute of emission. Aerosols (< 5 µm) are found to linger the in the air for

UK* Jul 2020*	(based on Lagrangian approach) for suspended particle number and viable viral dose associated with a short cough and continuous, paced speech. The impact of upward and downward air streams and ventilation flow on infection risk are also considered.	greater than 1hr after emission from 30 seconds of speech. Infectious dose sufficient to cause infection is estimated to be possible from the total emitted liquid mass generated by a short cough and speech. The mass of particles emitted during 30 seconds of speech was found to be an order of magnitude greater than from a short cough. Upward air streams from ventilation could increase distance travelled by emitted droplets and increase infection risk (movement/suspension of viral particles) at face level. In contrast, downward streams (e.g., from under-floor negative pressure ventilation systems) can enhance droplet removal from face height and reduce infection risk. Based on their analysis the authors conclude standing 2 meters away from a coughing or speaking infected cases, without personal protective equipment to be unsafe.
Guerrero (2020) (65) *Preprint* *In silico* study Chile* Apr 2020*	Examined the spread of respiratory droplets in outdoor environments by applying a computational model of a sneezing person in an urban scenario under a medium intensity climatological wind.	Larger droplets (400 – 900µm) are spread between 2-5 meters during 2.3 seconds while smaller droplets (100 – 200µm) are transported between eight and eleven meters in 14.1 seconds when influenced by turbulent wind.
Li (2020) (66) *Preprint* *In silico* study Singapore*	Mathematical simulations applying the Eulerian-Lagrangian model to study droplet (2-100 µm) dispersion originating from a single cough/cougher alone, as well as to a	Large droplets generally separate from the droplet cloud generated by a cough and settle within a meter. Smaller droplets (2-10 µm) generally spread beyond a meter within 10

Aug 2020*	second person 1-2 meters away from the cougher, under realistic indoor conditions. Dispersion distances in the range of 0.5-2.0 meters and dispersion up to 10 seconds after the simulated cough are considered.	seconds of the cough with lateral dispersion fitting a 20°-30° wedge in front of the cougher that is inclined at an angle of 14° to 10° from the cougher's chest is shown to occur when small droplets do not evaporate. Evaporation of droplets into droplet nuclei will have a faster settling time than non-evaporated droplets. The highest viral transmission potential and risk of exposure to an individual 1 meter away is from droplets in the 32-40 µm range as they contain higher viral loads. Surgical masks filter out particles of this size.
McCarthy (2020) (67) *Preprint* *In silico* study USA* Aug 2020*	Use mathematical equations to quantify and compare SARS-CoV-2 infection risk (exposed viral loads) from short and long range aerosol transmission, due to prolonged time spent in an enclosed space. Perfect mixing was assumed.	The derived equation demonstrates infection risk is inversely proportional to the ventilation rate per person in an enclosed space.
Schijven (2020) (68) *Preprint* *In silico* study *Netherlands** Jul 2020*	An exposure assessment model was developed to estimate SARS-CoV-2 particles in expelled aerosol/droplets during breathing, speaking, coughing and sneezing by an infected person in an unventilated indoor environment, and the subsequent inhalation by others occupying the same space. Viral concentrations in mucus was estimated according to clinical data from nose and throat swabs of patients.	Estimated exposure probability depended on viral concentration in mucus, and the considered scenario. Exposure probabilities were generally below 1% when virus concentration in mucus below 105 per mL for all scenarios, but exposure risks rose steeply as mucus concentrations increased. The volume of expelled aerosol droplets was greatest for a sneeze, then a cough, then speaking for 20 minutes.

Pendar (2020) (69) *In silico* study Portugal* Aug 2020*	The Eulerian–Lagrangian method is applied to estimate saliva droplet dispersion generated by sneezing and coughing. Droplet transmission from an infected individual in multiple distances and configurations are explored.	Larger droplets are deposited at a horizontal distance of more than ≈2.8 meters, but away from mouth level when individuals are face to face. These droplets pass through the opposite person in the area below the chest area. Small droplets may drift beyond 6 feet (2 meters). Sneezing caused saliva droplets to be transported at a distance around 2.3 meters, but larger droplets (540 µm) dispersed at an even larger distance of more than 4 meters.
Vuorinen (2020) (54) *In silico* study Finland* Oct 2020*	Evidence on aerosol transport in air is combined with 3D computational fluid dynamic (CFD) simulation, Monte Carlo simulations and theoretical calculations, to generate estimates. Note: The exposure time to inhale 100 aerosols (assumed to be an adequate infectious dose) varies from 1 sec – 1 hour.	Simulations indicate droplets < 20 µm produced by speech and cough can become airborne and linger in air from 20 minutes to an hour. 3D computational fluid dynamic (CFD) simulations suggest aerosols (<20 µm) can be transported over 10 meters depending on relative humidity and airflow. The rapid drying of expelled mucus droplets would yield droplet nuclei and aerosols that can carry virus particles and could linger in the air for 20 sec to 3 minutes.
Zhao (2020) (58) *In silico* study USA* Sep 2020*	A comprehensive mathematical model to explore speech generated droplet evaporation, heat transfer and kinematics under different conditions (e.g., temperature, humidity and ventilation), is presented.	Low temperature and high humidity facilitate droplet transmission and dispersion, but suppress the formation of aerosols. High temperature and low humidity promote evaporation of droplets and reduce droplet travel distance, but increase risk from aerosol particles. The study concludes current social distancing recommendations may not be

		sufficient to diminish all airborne transmission risks.

*Estimated based on author affiliations and publication date.

Methods:

A daily scan of the literature (published and pre-published) is conducted by the Emerging Science Group, PHAC. The scan has compiled COVID-19 literature since the beginning of the outbreak and is updated daily. Searches to retrieve relevant COVID-19 literature are conducted in Pubmed, Scopus, BioRxiv, MedRxiv, ArXiv, SSRN, Research Square and cross-referenced with the literature on the WHO COVID literature list, and COVID-19 information centers run by Lancet, BMJ, Elsevier and Wiley. The daily summary and full scan results are maintained in a Refworks database and an excel list that can be searched. Targeted keyword searching is conducted within the COVID-19 database to identify relevant citations using search terms: aerosol, airborne, droplet.

Each potentially relevant citation was examined for relevance, the full text of potentially relevant research was examined to confirm relevance and a synopsis of the study was extracted into the review. This review contains research published up to November 6, 2020.

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References

1. WHO. Natural ventilation for infection control in health-care settings: World Health Organization; 2009.

2. WHO. Infection Prevention and Control of Epidemic and Pandemic Prone Acute Respiratory Infections in Health Care. 2014

3. Bourouiba L. Turbulent Gas Clouds and Respiratory Pathogen Emissions: Potential Implications for Reducing Transmission of COVID-19. JAMA. 2020;323(18):1837-8 doi:10.1001/jama.2020.4756.

4. Morawska L, Cao J. Airborne transmission of SARS-CoV-2: The world should face the reality. Environment International. 2020;139:105730 doi:https://doi.org/10.1016/j.envint.2020.105730.

5. Tellier R, Li Y, Cowling BJ, Tang JW. Recognition of aerosol transmission of infectious agents: a commentary. BMC Infectious Diseases. 2019;19(1):101 doi:10.1186/s12879-019-3707-y.

6. Tellier R. Review of aerosol transmission of influenza A virus. Emerging infectious diseases. 2006;12(11):1657

7. Jones RM, Brosseau LM. Aerosol transmission of infectious disease. 2005(1536-5948 (Electronic))

8. Shen Y, Li C, Dong H, Wang Z, Martinez L, Sun Z, et al. Community Outbreak Investigation of SARS-CoV-2 Transmission Among Bus Riders in Eastern China. JAMA Internal Medicine. 2020 doi:10.1001/jamainternmed.2020.5225.

9. Guenther T, Czech-Sioli M, Indenbirken D, Robitailles A, Tenhaken P, Exner M, et al. Investigation of a superspreading event preceding the largest meat processing plant-related SARS-Coronavirus 2 outbreak in Germany. Available at SSRN 3654517. 2020

10. Lu J, Jieni G, Kuibiao L, Conghui X, Wenzhe S, Zhisheng L, et al. COVID-19 Outbreak Associated with Air Conditioning in Restaurant, Guangzhou, China, 2020. Emerging Infectious Disease journal. 2020;26(7) doi:10.3201/eid2607.200764.

11. Li Y, Qian H, Hang J, Chen X, Hong L, Liang P, et al. Evidence for probable aerosol transmission of SARS-CoV-2 in a poorly ventilated restaurant. medRxiv. 2020:2020.04.16.20067728 doi:10.1101/2020.04.16.20067728.

12. Hamner L, Dubbel P, Capron I, Ross A, Jordan A, Jaxon L, et al. High SARS-CoV-2 attack rate following exposure at a choir practice—Skagit County, Washington, March 2020. MMWR Morbidity and mortality weekly report. 2020;69

13. Miller SL, Nazaroff WW, Jimenez JL, Boerstra A, Buonanno G, Dancer SJ, et al. Transmission of SARS-CoV-2 by inhalation of respiratory aerosol in the Skagit Valley Chorale superspreading event. Indoor Air. 2020;n/a(n/a) doi:https://doi.org/10.1111/ina.12751.

14. Buonanno G, Morawska L, Stabile L. Quantitative assessment of the risk of airborne transmission of SARS-CoV-2 infection: Prospective and retrospective applications. Environment International. 2020;145:106112 doi:https://doi.org/10.1016/j.envint.2020.106112.

15. Kriegel M, Buchholz U, Gastmeier P, Bischoff P, Abdelgawad I, Hartmann A. Predicted Infection Risk for Aerosol Transmission of SARS-CoV-2. medRxiv. 2020:2020.10.08.20209106 doi:10.1101/2020.10.08.20209106.

16. Azimi P, Keshavarz Z, Cedeno Laurent JG, Stephens BR, Allen JG. Mechanistic Transmission Modeling of COVID-19 on the Diamond Princess Cruise Ship Demonstrates the Importance of Aerosol Transmission. medRxiv. 2020:2020.07.13.20153049 doi:10.1101/2020.07.13.20153049.

17. Almilaji O, Thomas P. Air recirculation role in the infection with COVID-19, lessons learned from Diamond Princess cruise ship. medRxiv. 2020:2020.07.08.20148775 doi:10.1101/2020.07.08.20148775.

18. Xu P, Qian H, Miao T, Yen H-l, Tan H, Cowling BJ, et al. Transmission routes of Covid-19 virus in the Diamond Princess Cruise ship. medRxiv. 2020:2020.04.09.20059113 doi:10.1101/2020.04.09.20059113.

19. Jang S, Han SH, Rhee J-Y. Cluster of Coronavirus Disease Associated with Fitness Dance Classes, South Korea. Emerging infectious diseases. 2020;26(8):1917-20 doi:10.3201/eid2608.200633.

20. Brlek A, Vidovič Š, Vuzem S, Turk K, Simonović Z. Possible indirect transmission of COVID-19 at a squash court, Slovenia, March 2020: case report. Epidemiology and Infection. 2020;148:e120 doi:10.1017/S0950268820001326.

21. Cai J Fau - Sun W, Sun W Fau - Huang J, Huang J Fau - Gamber M, Gamber M Fau - Wu J, Wu J Fau - He G, He G. Indirect Virus Transmission in Cluster of COVID-19 Cases, Wenzhou, China, 2020. Emerging Infectious Diseases. 2020(1080-6059 (Electronic)) doi:10.3201/eid2606.200412.

22. Kang M, Wei J, Yuan J, Guo J, Zhang Y, Hang J, et al. Probable Evidence of Fecal Aerosol Transmission of SARS-CoV-2 in a High-Rise Building. Annals of Internal Medicine. 2020 doi:10.7326/M20-0928.

23. Edwards DA, Ausiello D, Langer R, Salzman J, Devlin T, Beddingfield BJ, et al. Exhaled aerosol increases with COVID-19 infection, and risk factors of disease symptom severity. medRxiv. 2020:2020.09.30.20199828 doi:10.1101/2020.09.30.20199828.

24. Kim YI, Kim S-G, Kim S-M, Kim E-H, Park S-J, Yu K-M, et al. Infection and Rapid Transmission of SARS-CoV-2 in Ferrets. Cell Host & Microbe. 2020;27(5):704-9.e2 doi:https://doi.org/10.1016/j.chom.2020.03.023.

25. Kutter JS, de Meulder D, Bestebroer TM, Lexmond P, Mulders A, Fouchier RAM, et al. SARS-CoV and SARS-CoV-2 are transmitted through the air between ferrets over more than one meter distance. bioRxiv. 2020:2020.10.19.345363 doi:10.1101/2020.10.19.345363.

26. Sia SF, Yan L-M, Chin AW, Fung K, Choy K-T, Wong AY, et al. Pathogenesis and transmission of SARS-CoV-2 in golden hamsters. Nature. 2020;583(7818):834-8

27. Fears AC, Klimstra WB, Duprex P, Hartman A, Weaver SC, Plante KC, et al. Comparative dynamic aerosol efficiencies of three emergent coronaviruses and the unusual persistence of SARS-CoV-2 in aerosol suspensions. medRxiv : the preprint server for health sciences. 2020:2020.04.13.20063784 doi:10.1101/2020.04.13.20063784.

28. van Doremalen N, Bushmaker T, Morris DH, Holbrook MG, Gamble A, Williamson BN, et al. Aerosol and Surface Stability of SARS-CoV-2 as Compared with SARS-CoV-1. New England Journal of Medicine. 2020;382(16):1564-7 doi:10.1056/NEJMc2004973.

29. Lednicky JA, Lauzardo M, Fan ZH, Jutla A, Tilly TB, Gangwar M, et al. Viable SARS-CoV-2 in the air of a hospital room with COVID-19 patients. International Journal of Infectious Diseases. 2020;100:476-82 doi:https://doi.org/10.1016/j.ijid.2020.09.025.

30. Santarpia JL, Herrera VL, Rivera DN, Ratnesar-Shumate S, Reid SP, Denton PW, et al. The Infectious Nature of Patient-Generated SARS-CoV-2 Aerosol. medRxiv. 2020:2020.07.13.20041632 doi:10.1101/2020.07.13.20041632.

31. Fears A, Klimstra W, Duprex P, Hartman A, Weaver S, Plante K, et al. Persistence of Severe Acute Respiratory Syndrome Coronavirus 2 in Aerosol Suspensions. Emerging Infectious Disease journal. 2020;26(9):2168 doi:10.3201/eid2609.201806.

32. Ma J, Qi X, Chen H, Li X, Zhan Z, Wang H, et al. Exhaled breath is a significant source of SARS-CoV-2 emission. medRxiv. 2020:2020.05.31.20115154 doi:10.1101/2020.05.31.20115154.

33. Feng B, Xu K, Gu S, Zheng S, Zou Q, Xu Y, et al. Multi-route transmission potential of SARS-CoV-2 in healthcare facilities. Journal of Hazardous Materials. 2021;402:123771 doi:https://doi.org/10.1016/j.jhazmat.2020.123771.

34. Horváth I, Hunt J, Barnes PJ. Exhaled breath condensate: methodological recommendations and unresolved questions. European Respiratory Journal. 2005;26(3):523-48

35. Winters BR, Pleil JD, Angrish MM, Stiegel MA, Risby TH, Madden MC. Standardization of the collection of exhaled breath condensate and exhaled breath aerosol using a feedback regulated sampling device. Journal of Breath Research. 2017;11(4):047107 doi:10.1088/1752-7163/aa8bbc.

36. Chen PZ, Bobrovitz N, Premji Z, Koopmans M, Fisman DN, Gu FX. Heterogeneity in transmissibility and shedding SARS-CoV-2 via droplets and aerosols. medRxiv. 2020:2020.10.13.20212233 doi:10.1101/2020.10.13.20212233.

37. Ding Z, Qian H, Xu B, Huang Y, Miao T, Yen H-L, et al. Toilets dominate environmental detection of SARS-CoV-2 virus in a hospital. medRxiv. 2020:2020.04.03.20052175 doi:10.1101/2020.04.03.20052175.

38. Kim UJ, Lee SY, Lee JY, Lee A, Kim SE, Choi O-J, et al. Air and Environmental Contamination Caused by COVID-19 Patients: a Multi-Center Study. J Korean Med Sci. 2020;35(37)

39. Ong SWX, Tan YK, Chia PY, Lee TH, Ng OT, Wong MSY, et al. Air, Surface Environmental, and Personal Protective Equipment Contamination by Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) From a Symptomatic Patient. JAMA. 2020 doi:10.1001/jama.2020.3227.

40. Liu Y, Ning Z, Chen Y, Guo M, Liu Y, Gali NK, et al. Aerodynamic analysis of SARS-CoV-2 in two Wuhan hospitals. Nature. 2020 doi:10.1038/s41586-020-2271-3.

41. Zhang D, Yang Y, Huang X, Jiang J, Li M, Zhang X, et al. SARS-CoV-2 spillover into hospital outdoor environments. medRxiv. 2020:2020.05.12.20097105 doi:10.1101/2020.05.12.20097105.

42. Zhou J, Otter JA, Price JR, Cimpeanu C, Garcia DM, Kinross J, et al. Investigating SARS-CoV-2 surface and air contamination in an acute healthcare setting during the peak of the COVID-19 pandemic in London. Clinical Infectious Diseases. 2020 doi:10.1093/cid/ciaa905.

43. Santarpia JL, Rivera DN, Herrera VL, Morwitzer MJ, Creager HM, Santarpia GW, et al. Aerosol and surface contamination of SARS-CoV-2 observed in quarantine and isolation care. Scientific Reports. 2020;10(1):12732 doi:10.1038/s41598-020-69286-3.

44. Chia PY, Coleman KK, Tan YK, Ong SWX, Gum M, Lau SK, et al. Detection of air and surface contamination by SARS-CoV-2 in hospital rooms of infected patients. Nature Communications. 2020;11(1):2800 doi:10.1038/s41467-020-16670-2.

45. Guo Z-D, Wang Z-Y, Zhang S-F, Li X, Li L, Li C, et al. Aerosol and Surface Distribution of Severe Acute Respiratory Syndrome Coronavirus 2 in Hospital Wards, Wuhan, China, 2020. Emerging Infectious Disease journal. 2020;26(7):1583 doi:10.3201/eid2607.200885.

46. Nissen K, Janina K, Dario A, Tove H, Jiaxin L, Åke L, et al. Long-distance airborne dispersal of SARS-CoV-2 in COVID-19 wards. Research Square. 2020 doi:10.21203/rs.3.rs-34643/v2.

47. Orenes-Piñero E, Baño F, Navas-Carrillo D, Moreno-Docón A, Marín JM, Misiego R, et al. Evidences of SARS-CoV-2 virus air transmission indoors using several untouched surfaces: A pilot study. Science of The Total Environment. 2021;751:142317 doi:https://doi.org/10.1016/j.scitotenv.2020.142317.

48. Liu Y, Ning Z, Chen Y, Guo M, Liu Y, Gali NK, et al. Aerodynamic analysis of SARS-CoV-2 in two Wuhan hospitals. Nature. 2020;582(7813):557-60 doi:10.1038/s41586-020-2271-3.

49. Alsved M, Matamis A, Bohlin R, Richter M, Bengtsson PE, Fraenkel CJ, et al. Exhaled respiratory particles during singing and talking. Aerosol Science and Technology. 2020;54(11):1245-8 doi:10.1080/02786826.2020.1812502.

50. Cheng VC-C, Wong S-C, Chan VW-M, So SY-C, Chen JH-K, Yip CC-Y, et al. Air and environmental sampling for SARS-CoV-2 around hospitalized patients with coronavirus disease 2019 (COVID-19). Infect Control Hosp Epidemiol. 2020:1-8 doi:10.1017/ice.2020.282.

51. Ong SWX, Tan YK, Chia PY, Lee TH, Ng OT, Wong MSY, et al. Air, Surface Environmental, and Personal Protective Equipment Contamination by Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) From a Symptomatic Patient. JAMA. 2020;323(16):1610-2 doi:10.1001/jama.2020.3227.

52. Stadnytskyi V, Bax CE, Bax A, Anfinrud P. The airborne lifetime of small speech droplets and their potential importance in SARS-CoV-2 transmission. Proceedings of the National Academy of Sciences. 2020;117(22):11875 doi:10.1073/pnas.2006874117.

53. Verma S, Dhanak M, Frankenfield J. Visualizing the effectiveness of face masks in obstructing respiratory jets. Phys Fluids (1994). 2020;32(6):061708- doi:10.1063/5.0016018.

54. Vuorinen V, Aarnio M, Alava M, Alopaeus V, Atanasova N, Auvinen M, et al. Modelling aerosol transport and virus exposure with numerical simulations in relation to SARS-CoV-2 transmission by inhalation indoors. Safety Science. 2020;130:104866 doi:https://doi.org/10.1016/j.ssci.2020.104866.

55. de Oliveira PM, Mesquita LCC, Gkantonas S, Giusti A, Mastorakos E. Evolution of spray and aerosol from respiratory releases: theoretical estimates for insight on viral transmission. medRxiv. 2020:2020.07.23.20160648 doi:10.1101/2020.07.23.20160648.

56. Blocken B, van Druenen T, van Hooff T, Verstappen PA, Marchal T, Marr LC. Can indoor sports centers be allowed to re-open during the COVID-19 pandemic based on a certificate of equivalence? Building and Environment. 2020;180:107022 doi:https://doi.org/10.1016/j.buildenv.2020.107022.

57. Feng Y, Marchal T, Sperry T, Yi H. Influence of wind and relative humidity on the social distancing effectiveness to prevent COVID-19 airborne transmission: A numerical study. Journal of Aerosol Science. 2020;147:105585 doi:https://doi.org/10.1016/j.jaerosci.2020.105585.

58. Zhao L, Qi Y, Luzzatto-Fegiz P, Cui Y, Zhu Y. COVID-19: Effects of Environmental Conditions on the Propagation of Respiratory Droplets. Nano Letters. 2020;20(10):7744-50 doi:10.1021/acs.nanolett.0c03331.

59. Murbe D, Kriegel M, Lange J, Schumann L, Hartmann A, Fleischer M. Aerosol emission of child voices during speaking, singing and shouting. medRxiv. 2020:2020.09.17.20196733 doi:10.1101/2020.09.17.20196733.

60. Anfinrud P, Bax CE, Stadnytskyi V, Bax A. Could SARS-CoV-2 be transmitted via speech droplets? medRxiv. 2020:2020.04.02.20051177 doi:10.1101/2020.04.02.20051177.

61. Bahl P, de Silva C, Bhattacharjee S, Stone H, Doolan C, Chughtai AA, et al. Droplets and Aerosols generated by singing and the risk of COVID-19 for choirs. Clinical Infectious Diseases. 2020 doi:10.1093/cid/ciaa1241.

62. Viola I, Peterson B, Pisetta G, Pavar G, Akhtar H, Menoloascina F, et al. Face Coverings, Aerosol Dispersion and Mitigation of Virus Transmission Risk. arXiv preprint arXiv:200510720. 2020

63. Rodriguez-Palacios A, Cominelli F, Basson AR, Pizarro TT, Ilic S. Textile Masks and Surface Covers—A Spray Simulation Method and a "Universal Droplet Reduction Model" Against Respiratory Pandemics. Frontiers in Medicine. 2020;7(260) doi:10.3389/fmed.2020.00260.

64. Bond TC, Bosco-Lauth A, Farmer DK, Francisco PW, Pierce JR, Fedak KM, et al. Quantifying proximity, confinement, and interventions in disease outbreaks: a decision support framework for air-transported pathogens. medRxiv. 2020:2020.09.09.20187625 doi:10.1101/2020.09.09.20187625.

65. Guerrero N, Brito J, Cornejo P. COVID-19. Transport of respiratory droplets in a microclimatologic urban scenario. medRxiv. 2020:2020.04.17.20064394 doi:10.1101/2020.04.17.20064394.

66. Li H, Leong FY, Xu G, Kang CW, Lim KH, Tan BH, et al. Airborne dispersion of droplets during coughing: a physical model of viral transmission. arXiv preprint arXiv:200801912. 2020

67. McCarthy JE, McCarthy MT, Dumas BA. Long range versus short range aerial transmission of SARS-CoV-2. arXiv preprint arXiv:200803558. 2020

68. Schijven JF, Vermeulen LC, Swart A, Meijer A, Duizer E, de Roda Husman AM. Exposure assessment for airborne transmission of SARS-CoV-2 via breathing, speaking, coughing and sneezing. medRxiv. 2020:2020.07.02.20144832 doi:10.1101/2020.07.02.20144832.

69. Pendar M-R, Páscoa JC. Numerical modeling of the distribution of virus carrying saliva droplets during sneeze and cough. Physics of Fluids. 2020;32(8):083305 doi:10.1063/5.0018432.