TOWN OF HARWICH

BOARD OF HEALTH
732 Main Street Harwich, MA 02645
508-430-7509 – Fax 508-430-7531
E-mail: health@town.harwich.ma.us

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TOWN OF HARWICH BOARD OF HEALTH
FRIDAY, MAY 21, 2021- 10:00 A.M.
HARWICH TOWN HALL – REMOTE MEETING
WORK SESSION MEETING

As required by law, the Town may audio or video record this meeting. Any person intending to either audio or video record this open session is required to inform the Chair

Pursuant to Governor Baker's March 12, 2020 Order Suspending Certain Provisions of the Open Meeting Law, G.L. c. 30A, §20, and the Governor's March 15, 2020 Order imposing strict limitations on the number of people that may gather in one place, this meeting of the Harwich Board of Health is being conducted via remote participation. No in-person attendance of members of the public will be permitted, but every effort will be made to ensure that the public can adequately access the proceedings as provided for in the Order.

Please join my meeting from your computer, tablet or smartphone.
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I **CALL TO ORDER**

II **REVIEW THE EXISTING MANDATORY MASK ZONE ORDER-** to consider modifying, lifting or keeping in place the existing Declaration of Public Health Emergency Order- mandatory mask zone order adopted by the Board of Health on July 21, 2020, which states that any member of the public utilizing Route 28 between Lower County Road and Bank Street between 9am and 10pm, must wear a face covering at all times over their nose and mouth and must exercise social distancing, whenever possible- *Vote to accept/deny/take this under consideration*

III **OTHER**- *Vote to accept/deny/take this under consideration*

IV **ADJOURN-** *Vote to accept/deny/take under consideration*

Authorized posting officer: Posted by:

Jennifer Clarke
Signature Date Town Clerk Date 5-14-21

Per the Attorney General's Office: The committee may hold an open session for topics not reasonably anticipated by the Chair 48 hours in advance of the meeting following "New Business." If you are deaf or hard of hearing or a person with a disability who requires an accommodation, contact the Selectmen's Office at 508-430-7513

Town of Harwich
Board of Health
732 Main Street Harwich, MA 02645
508-430-7509 – Fax 508-430-7531
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DECLARATION OF PUBLIC HEALTH EMERGENCY ORDER

Whereas, the Board of Health is concerned that as summer approaches and visitors return to Harwich the combination of large crowds and narrow roads and sidewalks will make it difficult to maintain social distancing as required by Governor Baker's Face Covering Order, dated May 1, 2020.

Now, therefore, the Board of Health adopts the following Emergency Order:

> **Any member of the public utilizing Route 28, between Lower County Road and Bank Street between 9 am and 10 pm, must wear a face covering at all times over their nose and mouth and must exercise social distancing, whenever possible, in accordance Governors Bakers Order, dated May 1, 2020, effective May 6th, *Order Requiring Face Covering in Public Places Where Social Distancing is Not Possible.***

Face coverings required by this Order may be removed for the consumption of food and or drink only when the consumer is practicing appropriate social distancing from persons not of their immediate family unit.

Violations of this Order may result in the following enforcement action/fines:

1) In the case of a first violation, a written warning shall be issued;
2) In the case of a second subsequent violation a fine of one hundred dollars ($100.00) shall be assessed.
3) In the case of a third or subsequent violation a fine of three hundred dollars ($300.00) shall be assessed.

Each day, or portion thereof, of non-compliance with any provision of this Order shall be deemed a separate violation hereunder.

Non-Criminal Disposition: Violations of any provision of this Order may be enforced by noncriminal disposition, as provided in Massachusetts General Laws, Chapter 40, Section 21D, or by any other lawful means.

Enforcement of this regulation shall be implemented by the Harwich Board of Health or its designated agents, (including Town of Harwich Police Officers).

This Emergency Order shall be effective beginning Thursday, July 23, 2020 at 12:01AM and remain in effect until notice is given, pursuant to the Board of Health's judgement that the Order is no longer necessary.

ORDERED on this Day July 21, 2020

HARWICH BOARD OF HEALTH:

Pamela Howell, Chairman
Sharon Pfleger, Vice Chairman
Ronald Dowgiallo, Member
Matt Antoine, Member

Harwich Health

From: KEN & SUE MILLER <smillerk@comcast.net>
Sent: Monday, May 17, 2021 7:50 AM
To: Harwich Health
Subject: Harwich Port Mask Order

To the board,

My wife and I were completely dismayed but the comments made in the recent Chronicle article regarding the mask mandate in Harwich Port. The need to continue outdoor mask use because , to paraphrase " we don't know if people coming into town have been vaccinated" and "some people do not want to be vaccinated". So what you are saying is the majority of people should continue to wear masks to protect the very small minority who for whatever reason at this point are not vaccinated. Those individuals can still choose to wear masks to protect themselves correct? Vaccines are readily available to those who want them and we think your continued stance on the mask mandate is misguided.

Ken and Sue Miller
12 Ocean Ave

Harwich Health

From: mike@capecodare.com
Sent: Thursday, May 13, 2021 3:12 PM
To: Larry Ballantine; Harwich Health
Cc: Cyndi Williams
Subject: Harwich Port masks

Dear Board of Health,

I recently read a very interesting NY Times story on outdoor transmission of the virus. I have attached the article in a link below.

According to the article, the CDC is not using good data for their position on outside transmission of the virus. Rather it is based on an overly cautious CDC. The CDC used numbers from many Singapore construction sites to come up with their admittedly inflated 10% number. The actual number of transmissions occurring out of doors appears to be closer to .01%.

Wearing masks outside in the hot muggy summer months could potentially cause respiratory challenges for the elderly and those with asthma etc. while offering no benefit. With virtually no cases of transmission occurring outside requiring masks doesn't seem necessary.

Fortunately the number of cases in Harwich, Barnstable County and the State continue to plummet and hospitalizations are at an all time low. Surely people that feel more comfortable with a mask will continue to wear one.

Here is the link to the article: https://www.nytimes.com/2021/05/11/briefing/outdoor-covid-transmission-cdc-number.html

Thank you for your time and consideration.

Yours truly,

Mike

R. Michael Ulrich, Broker/President
C: 508-737-3574 O: 508-432-8600
Office License 7116 Broker License 9024670
571 Route 28 Harwich Port MA 02646

Cape Cod Associates
REAL ESTATE

Harwich Health

From: Marvin Slayton <mcslayton@comcast.net>
Sent: Wednesday, May 12, 2021 3:19 PM
To: Harwich Health
Subject: Mask wearing mandate in Harwich Port

"These recommendations would be more grounded in science if anywhere close to 10 percent of Covid transmission were occurring outdoors. But it is not," David Leonhardt wrote in the Times' morning newsletter. "There is not a single documented Covid infection anywhere in the world from casual outdoor interactions, such as walking past someone on a street or eating at a nearby table."

It looks like you're not following the science. Too bad. You're making it very difficult for our community's businesses.

Marvin Slayton
18 Harwich Pines, Harwich, MA 02645

Harwich Health

From: John Rinkacs <rinkacs@comcast.net>
Sent: Tuesday, May 11, 2021 1:46 PM
To: Harwich Health
Subject: Clarification on Mask rules

Good afternoon,

I just noticed that the BOH has continued the outdoor mask mandate. The continuation does not mention vaccination status. Could you please clarify- are you mandating masks be worn even if you are vaccinated? And you still intend to fine individuals despite the Governor rescinding outdoor fines? Will these rules be throughout the entire summer or will you revisit the mandate as numbers continue to drop ?

Thanks,
John Rinkacs

Sent from my iPhone

BOSTON — Today, the Baker-Polito Administration announced that the Commonwealth is on track to meet the goal of vaccinating 4.1 million residents by the first week of June and all remaining COVID-19 restrictions will be lifted effective May 29.

The Commonwealth's face covering order will also be rescinded on May 29. The Department of Public Health will issue a new face covering advisory consistent with the Centers for Disease Control and Prevention's updated guidance. Face coverings will still be mandatory for all individuals on public and private transportation systems (including rideshares, livery, taxi, ferries, MBTA, Commuter Rail and transportation stations), in healthcare facilities and in other settings hosting vulnerable populations, such as congregate care settings.

Governor Charlie Baker will end the State of Emergency June 15.

The Administration also announced updates that will be effective May 18 to revise face covering requirements for youth and amateur sports and other guidance relating to childcare programs and K-12 schools. The Administration will release updated guidance for summer camps effective May 29.

The Administration is able to take these steps to reopen the Commonwealth's economy because Massachusetts is on track to meet the goal set in December to fully vaccinate over 4 million individuals by the first week of June. The Commonwealth leads the nation in vaccinating residents, with 75% of adults receiving at least one dose. To date, over 4 million residents have received a first dose, with 3.2 million fully vaccinated.

New cases have dropped by 89% since January 8. COVID hospitalizations are down 88% since January 1 and the positive test rate is down by 88% from peaking at 8.7% on January 1 to 1% today.

Effective May 29

Effective May 29, all industries will be permitted to open. With the exception of remaining face-covering requirements for public and private transportation systems and facilities housing vulnerable populations, all industry restrictions will be lifted, and capacity will increase to 100% for all industries. The gathering limit will be rescinded.

All industries will be encouraged to follow CDC guidance for cleaning and hygiene protocols.

On May 18, 2020, the Administration published the reopening phases, which called for ending restrictions when vaccines became widely available. Today, there are over 975 locations for Massachusetts residents to access vaccines without delay.

Face Covering Guidance

In line with updated CDC face covering guidance, the Administration will rescind the current face covering order and issue a new face covering advisory effective May 29.

Non-vaccinated individuals are advised to continue wearing face masks and to continue distancing in most settings. The advisory will also recommend fully vaccinated individuals no longer need to wear a face covering or social distance indoors or outdoors except for in certain situations.

Face coverings will still be required for all individuals on public and private transportation (including rideshares, livery, taxi, ferries, MBTA, Commuter Rail and transportation stations), healthcare facilities and providers, congregate care settings and health and rehabilitative day services.

Face coverings will also remain required indoors for staff and students of K-12 schools and early education providers.

Link to mask guidance

Youth and Amateur Sports Face Covering Guidance

Effective May 18, the youth and amateur sports guidance will be updated to no longer require face coverings for youth athletes 18 and under while playing outdoor sports. Effective May 29, all youth and amateur sports restrictions will be lifted.

Link to youth sports guidance

K-12, Early Education and Summer Camp Guidance

Effective May 18, guidance from the Department of Elementary and Secondary Education and the Department of Early Education and Care will be updated to no longer require masks for outdoor activities like recess and to allow for the sharing of objects in classrooms, in both K-12 and childcare settings. This guidance will remain in effect beyond May 29.

The Administration will release updated guidance for summer camps, effective May 29, which will include no longer requiring masks for outdoor activities.

Link to DESE guidance

Link to EEC guidance

State of Emergency Order

Governor Baker will end the State of Emergency June 15, and the Administration will work with legislative and municipal partners during this period in order to manage an orderly transition from emergency measures adopted by executive order and special legislation during the period of the State of Emergency.

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Town of Orleans

Board of Health

19 School Road - Orleans, MA 02653-3699

T: 508-240-3700
X2450

F: 508-240-3746

Order Requiring Face Coverings in Public Places Where Social Distancing is Not Possible

Board of Health Order 2020-01

The Town of Orleans Board of Health pursuant to MGL C.111 §§26-26C, 31, 104 and the Board's authority to prevent the spread of infectious disease deems that the following action is necessary to protect public health.

Whereas, COVID-19 is a highly contagious and potentially fatal respiratory disease, and the Centers for Disease Control and Prevention (CDC) has advised that the spread of the disease from person to person is caused by close or personal contact and through respiratory droplets produced when an infected person coughs or sneezes. And people can potentially spread the disease even before they experience symptoms; and

Whereas, the CDC recommends that individuals wear masks or other suitable facial covering to prevent individuals from infecting others.

Whereas, On May 1, 2020, Massachusetts Governor Baker issued COVID-19 Order No. 31, "Order Requiring Face Coverings in Public Places where Social Distancing is Not Possible." Governor Baker's order is effective Wednesday, May 6, 2020, and shall remain in effect until rescinded or until the emergency is terminated, whichever happens first.

The Board of Health hereby orders:

1) The Board of Health adopts as its own, Governor Baker's COVID-19 Order No. 31 in its entirety.

2) Whoever violates any provision of this order may be penalized by the non-criminal method of disposition as provided in Massachusetts General Laws, Chapter 40, Section 21D.

This order is effective as of 12:01 A.M. on Wednesday May 6, 2020, and shall remain in effect until Governor Baker's COVID-19 Order No. 31 is rescinded or until the emergency is terminated, whichever happens first.

To the extent necessary, this order shall be enforced by the Board of Health, the Health Department, the Police Department, and the Department of Public Works and Natural Resources. Any business or individual violating this order shall be punished as follows:

(a) A warning shall be issued in the case the first violation.
(b) A fine of One Hundred Dollars ($100) shall be issued in the case of a second violation.
(c) A fine of Three Hundred Dollars ($300) shall be issued in the case of a third violation.

Ordered this 4th day of May 2020.

Robert J. Canning

Robert J. Canning
Agent for the Board of Health

RULE AND ORDER REQUIRING THE USE OF MASKS AND OTHER PROTECTIVE MEASURES

Pursuant to the declaration of a State-wide public health emergency on March 10, 2020, Massachusetts General Laws, Chapter 111, Sections 31 and 122, 310 CMR 11.05, 105 CMR 300.200 and all other authorizing statutes and regulations, we, the members of the Truro Board of Health hereby order the following:

1. In addition to social distancing and in an effort to protect others, all members of the public entering any place allowed to be open to the public pursuant to Governor Baker's Covid-19 Executive Orders, including but not limited to grocery stores, gas stations, the Town's transfer station and the like must wear a cloth face covering that covers their nose and mouth, such as a fabric mask, scarf or bandana, over their nose and mouth. Wearing a mask is not a substitute for social distancing.
2. The cloth face coverings required are not surgical masks or N-95 respirators, which should be left for medical professionals and first responders. See the following links for information on cloth face coverings:
   a. **Graphic:** https://www.cdc.gov/coronavirus/2019-ncov/images/face-covering-checklist.jpg
   b. **How to make a mask**: https://www.cdc.gov/coronavirus/2019-ncov/prevent-gettingsick/cloth-face-cover.html
   c. **How to wear/wash cloth face coverings:** https://www.cdc.gov/coronavirus/2019- ncov/prevent-getting-sick/diy-cloth-face-coverings.html
3. The face covering requirements of this Order shall also apply to all members of the public picking up food from a restaurant or other establishment serving food to be consumed off-premises. This requirement shall apply whether the food is picked-up inside or outside. If customers are waiting in line, they shall be wearing masks and standing at least six feet apart. Establishments shall make markings on the floor to ensure that this requirement is met.
4. Notwithstanding any provision in this Order, pursuant to guidance issued by the CDC face coverings should not be placed on young children under 2-years-old, anyone who has trouble breathing, anyone who is unconscious, incapacitated or otherwise unable to remove the mask without assistance, or anyone who due to disability is unable to wear a mask.
5. All establishments open to the public shall post a sign on their main entrance doors advising consumers that they are required to wear a face covering upon entering.

6. All employees of all essential businesses open to the public shall wear a face covering over their mouth and nose when interacting with the public and within six feet of a co-worker. Employers shall provide face coverings to employees who do not use their own. Employers must prescribe protocols and guidelines for masks and personal protective gear, and hand sanitizer shall be provided by the employer for staff use.

7. Any resident or member of the general public entering or exiting a residential or commercial building complex of greater than one (1) unit must wear a face covering over their nose and mouth while in common areas and communal spaces and must exercise social distancing in these spaces in accordance with CDC guidelines. See these guidelines at: www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/social-distancing.html

8. Brick and mortar establishments included on Governor Baker's list of essential businesses will be allowed to operate in accordance with the orders and guidance of the Governor and Department of Public Health, including but not limited to effective social distancing and occupancy limit measures.

9. To the extent necessary, this Order shall be enforced by the Truro Health Agent, assistant Health Agent and Truro Police Officers.

10. Whoever violates any provision of this Order may be penalized by a noncriminal disposition process as provided in Massachusetts General Laws, Chapter 40, section 21D and the Town's non-criminal disposition by-law.

11. If non-criminal disposition is elected, then any person who violates any provision of this Regulation shall be subject to: for a first offense, a written warning; for a second offense, a penalty in the amount of one hundred dollars ($100), for a third offense, a penalty of two hundred dollars ($200); and for a fourth or subsequent offense, a penalty in the amount of three hundred dollars ($300.00). Each day or portion thereof shall constitute a separate offense. If more than one, each condition violated shall constitute a separate offense.

This Order shall be effective beginning May 1, 2020 and remain in effect until notice is given, pursuant to the Truro Board of Health's judgement that the Public Health Emergency no longer exists.

Tracey Rose

Tracey Rose, Chair
Truro Board of Health

Town	Mask Mandate?
Barnstable	Left a message for Health Director.
Bourne	Left a message for Health Director.
Brewster	No additional mandate.
Chatham	Rescinded mask mandate on 5/17/21.
Dennis	No additional mandate.
Eastham	No additional mandate.
Falmouth	Has "mask required" signs on Main Street and in Woods Hole. Their Board of Health will be meeting on Monday to re-evaluate. Staff stated that they hope to follow what the state guidelines are.
Mashpee	Left a message for Health Director.
Orleans	Has a face coverings order in place. They track with whatever the state guidance is. (see attached)
Provincetown	Follows the state's guidelines and advisories, except where noted in the Joint Order of the Select Board and Board of Health. On April 29, 2021, the Board of Health and Select Board met regarding their local order. As of Friday, April 30, 2021, Provincetown will follow the State's Face Coverings Order, which will be relaxed for some outdoor settings: Face coverings will only be required outside in public when it is not possible to socially distance, and at other times required by sector-specific guidance. Face coverings will still be required at all times in indoor public places. Face coverings will also continue to be required at all times at events, whether held indoors or outdoors and whether held in a public space or private home, except for when eating or drinking. As of Friday, May 28, 2021, Provincetown's local joint order will be fully rescinded and the Town will follow state guidelines for all industries, except outdoor dining shall remain in effect until 60 days after the end of the COVID State of Emergency.
Sandwich	Left a message for Health Director.
Truro	The Truro Board of Health issued an Order requiring that face masks be worn in public areas of Truro. Masks are required in addition to social distancing, to protect all members of the public at all places that can be open, and all housing or commercial complexes with more than 1 unit. Enforcement will be done by the Health Department and the Police Department. The Order is effective May 1. (see attached)
Wellfleet	Unable to reach any Health Department staff. (no one from Health Department available, Building Department answered their phones)
Yarmouth	Unable to reach any Health Department staff. (no answer on the phone and their email link does not work)

SARS-CoV-2 transmission dynamics should inform policy

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Summary: We argue that SARS-CoV-2 transmission dynamics should inform policy decisions about mitigation strategies for targeted interventions according to the needs of the society

by directing attention to the settings, activities and socioeconomic factors

associated with the highest risks of transmission.

Abstract:

It is generally agreed that striking a balance between resuming economic and social activities and keeping the effective reproductive number (R0) below 1 using non-pharmaceutical interventions is an important goal until and even after effective vaccines become available. Therefore, the need remains to understand how the virus is transmitted in order to identify high-risk environments and activities that disproportionately contribute to its spread so that effective preventative measures could be put in place. Contact tracing and household studies in particular provide robust evidence about the parameters of transmission. In this viewpoint, we discuss the available evidence from large-scale, well-conducted contact tracing studies from across the world and argue that SARS-CoV-2 transmission dynamics should inform policy decisions about mitigation strategies for targeted interventions according to the needs of the society by directing attention to the settings, activities and socioeconomic factors associated with the highest risks of transmission.

Key words: COVID-19, coronavirus, SARS-CoV-2, novel coronavirus, transmission

Introduction:

Since coronavirus disease 2019 (COVID-19) was first described in December 2019, we have witnessed widespread implementation of local and national restrictions in many areas of the world, and social, health and economic devastation due to direct and indirect impact of the pandemic. It is generally agreed that striking a balance between resuming economic and social activities and keeping the effective reproductive number (R0) below 1 using non-pharmaceutical interventions is an important goal until and even after effective vaccines become available. Achieving this balance requires an understanding of how the virus is spread. There is also a need to identify the structural factors that contribute to transmission, a particular concern considering the already stark health disparities driven by socioeconomic and racial/ethnic inequities in our societies.

An understanding of SARS-CoV-2 transmission dynamics can inform policy decisions by directing attention to the settings and activities that confer the highest risk of transmission and understanding of the intersection between poverty, household crowding, and COVID-19. This understanding will allow policymakers and public health practitioners to shape the best strategy, preventative measures and inform the public about transmission risk. Epidemiological investigations including contact tracing studies and outbreak investigations conducted so far across the world already provide crucial information about the probability of infection in close contacts and various environments. We argue that health authorities should use the large-scale, well-conducted contact tracing studies and observations from across the world to date in their risk assessment and mitigation strategies. This article summarizes current knowledge about transmission dynamics and discusses recommendations that could prevent infections by focusing on factors associated with risk of transmission.

Factors influencing transmission dynamics

Emerging data suggests that risk of transmission depends on several factors, including contact pattern, host-related infectivity/susceptibility pattern, environment and socioeconomic factors (Figure 1). We will discuss the emerging evidence relating to each of these aspects of transmission.

1- Contact pattern

Contact tracing studies provide early evidence that sustained close contact drives the majority of infections and clusters. For instance, living with the case, family/friend gatherings, dining, or travelling on public transport were found to have a higher risk for transmission than market shopping or brief (<10 mins) community encounters [1-3]. While people are more likely to recall and disclose close and household contacts, and it is easier for tracers to identify the source, household studies provide important information about the contact patterns and activities associated with higher attack rates. Close contacts with the highest risk of transmission are typically friends, household members, and extended family, with a secondary attack rate that ranges from 4 to 35% [1, 4-8]. In the same household, higher attack rates are observed among spouses compared to the rest of the household [8]. In a systematic review including five studies based on relationship demonstrated that household SAR to spouses (43,4%; 95% CI: 27,1%–59,6%) was significantly higher than to other relationships (18,3%, 95% CI: 10,4%–26,2%) [8]. Similar results were observed in the USS Theodora Roosevelt outbreak in which those sharing the same sleeping space had higher risk of being infected [9]. In addition, the attack rate has shown to be higher when the index case is isolated in the same room with the rest of the household or when the household members have daily close contact with the index case [10, 11]. Transmission is significantly reduced when the index case is isolated away from the family, or preventative measures such as social distancing, hand hygiene, disinfection and use of face masks at home are applied [10, 11]. In a study of an outbreak in the largest meat processing plant in Germany, while the universal point of potential contact among all cases was workplace, positive rates were statistically significant for a single shared apartment, shared bedroom and associated carpool

[12]. These findings suggest that sleeping in the same room or sharing the same sleeping space, increased contact frequency constitutes high risk of transmission.

Large clusters have been observed in family, friend, work-colleague gatherings including weddings and birthday parties [13, 14]. Other examples include gatherings in pubs, church services, and close business meetings [14-17]. These findings suggest that group activities pose a higher risk of transmission. In non-household contact tracing studies, dining together or engaging in group activities such as board games have been found to be high risk for transmission as well [18]. In the same household, frequent daily contact with the index case, and dining in close proximity has been associated with increased attack rates [10, 11].

Large, long-term care facilities such as nursing homes and homeless shelters have seen increased rates of infection, in part because of patterns of contact among staff and residents. In nursing home outbreak investigations from the Netherlands, Boston, and London, multiple viral genomes were identified, suggesting multiple introductions to the facility leading to infections among residents [19-21]. In an investigation of 17 nursing homes that implemented voluntary staff confinement with residents, including 794 staff members and 1250 residents in France, staff confining themselves to a single facility for a weeklong period was associated with decreased outbreaks in these facilities [22].

These findings emphasise that contact patterns, including the duration of contact, contact frequency, proximity to index case and types of activities influence transmission risk, highlighting the need for tailored prevention strategies for different settings.

2- Host factors

Contact tracing and outbreak investigations suggest that many SARS-CoV-2-infected people either do not contribute to onward transmission or have minimal potential to do so [6, 17], and a large number of secondary cases are often caused by a small number of infected patients. While this may also be due to contact pattern and the environmental factors, host factors strongly influence this variation; individual variation in infectiousness is an expected feature of superspreading events.

Timing of the contact with an index case is key in transmission dynamics as it relates to the infectiousness of the index case. In a living systematic review of studies published up to 6 June 2020, we found that viral load peaks early in the disease course, with the highest viral loads observed from symptom onset to day 5, indicating high level of infectiousness during this period [23] (Figure 2). Supporting these findings, transmission events are estimated to occur in a short window, likely a few days prior to and following symptom onset [4, 23]. For example, a contact tracing study that followed up 2761 contacts of 100 confirmed COVID-19 cases demonstrated that infection risk was higher if the exposure occurred within the first five days after the symptom onset, with no secondary cases documented after this point [4]. This understanding indicates that viral dose plays an important role in transmission dynamics. In contrast, higher viral loads in SARS-CoV-1 and MERS-CoV were identified in the second week after symptom onset, suggesting that patients had viral load peak after hospitalisation [23]. Therefore, early viral load peak also explains efficient community SARS-CoV-2 spread in contrast to SARS-CoV-1 and MERS-CoV during which community spread was put under control; however, nosocomial spread was an important feature of the outbreaks. In contrast during COVID-19, only a small number of hospital-based outbreaks have been reported so far, which may be due to downtrend viral load levels later in disease course [23, 24].

Symptoms and severity of illness appear to influence transmission dynamics as well. People with symptoms appear to have a higher secondary attack rate compared to pre-symptomatic and asymptomatic index cases (those who develop no symptoms throughout the illness) [18]. While asymptomatic patients can transmit the virus to others, the findings from nine studies in a systematic review, including studies published up to 3 July 2020, found secondary attack rates of zero to 2.8%, compared with secondary attack rates of 0.7% to 16.2% in symptomatic cases in the same studies, suggesting asymptomatiic index cases transmit to fewer secondary cases [18]. Another systematic review that included studies published up to 10 June 2020 similarly found a reduced risk of transmission for asymptomatic versus symptomatic cases (0.35, 95% CI 0.10, 1.27) and pre-symptomatic versus symptomatic cases (0.63, 95% CI 0.18, 2.26) [25]. There are also differences in attack rates based on symptom severity. In the Zhang et al. study the secondary attack rate was 3.5% for those with mild symptoms, 5.7% for those with moderate symptoms, and 4.5% for those with severe symptoms (based on CDC China guidelines) [26]. In a contact tracing study, contacts of severe cases were more likely to develop severe infections themselves [4].

Virus transmission is also affected by a number of other host factors, including host defense mechanisms, and age. Current synthesis of the literature demonstrates significantly lower susceptibility to infection for children aged under 10 years compared to adults given the same exposure, and elevated susceptibility to infection in adults aged over 60 years compared to younger or middle-aged adults [27].

3- Environment

Transmission risk is not one-dimensional and contact patterns also depend on the setting of the encounter. Findings from contact tracing studies in Japan suggest an 18.7-fold higher risk of transmission indoors compared with outdoor environments [28]. These findings are in keeping with our understanding about transmission patterns of respiratory viral infections. While outdoor settings usually have lower risk, prolonged contact in an enclosed setting can lead to increased risk of transmission. Especially when combined with environmental factors such as poor ventilation and crowding this may lead to further increase in attack rates. Epidemiological studies so far support this knowledge. SARS-CoV-2 is much more efficiently spread in enclosed and crowded environments. Largest outbreaks from across the world are reported in long term care facilities such as nursing homes, homeless shelters, prisons, and also workplaces including meat-packing plants and factories, where many people spend several hours working together, dining and sharing communal spaces [12, 14]. In six London care homes experiencing SARS Cov-2 outbreaks identified a high proportion of residents (39.8%) and staff (20.9%) tested positive for SARS-CoV-2 [20]. Among 408 individuals residing at a large homeless shelter in Boston, 36% of those tested were found to be positive [16]. Although it is much harder to obtain data from incarcerated populations, the largest clusters of cases observed in the USA have all been associated with prisons or jails, suggesting a high attack rate in these institutional settings [29]. Social distancing is the opposite of incarceration, and overcrowding, poor sanitation and ventilation, and inadequate healthcare contribute to the disproportionate rates of infections seen in prisons and jails, which demonstrates the larger pattern of the health disparities in our societies.

4- Socioeconomic factors and racial/ethnic disparities

Global figures suggest that there is a strong association between socioeconomic deprivation, race/ethnicity and a higher risk of infection and death from COVID-19 [30, 31]. People facing the greatest socioeconomic deprivation experience a higher risk of household and occupational exposure to SARS-CoV-2, and existing poor health leads to more severe outcomes if infected [32]. People with lower-paid and public-facing occupations are often classified as essential workers who must work outside the home and may travel to work on public transport. Indeed, in New York City, higher cumulative infection rates were observed in neighbourhoods that continued to engage in mobility behaviours consistent with commuting for work [33]. These occupations often involve greater social mixing and greater exposure risk due to prolonged working hours, resulting in reduced ability to practice social distancing among low-income families [34]. In addition, households in socioeconomically deprived areas are more likely to be overcrowded, increasing the risk of transmission within the household. Black, Hispanic, and other marginalised, racial/ethnic and migrant groups have also been shown to be at greater risk of infection, severe disease, and death from COVID-19 [31, 35-37]. These increased risks are also likely due to socioeconomic conditions that increase risk of transmission, inequitable access to adequate healthcare, and higher rates of comorbidities due to adverse living and working conditions and structural racism. It is not surprising that the largest outbreaks are observed in meat-packing plants, and most commonly exposed occupations include nurses, taxi and bus drivers and factory workers [31]. These disparities also shape the strong geographic heterogeneities observed in the burden of cases and deaths, for example across the USA and the UK [31, 38]. These findings support the hypothesis that the COVID19 pandemic is strongly shaped by structural inequities that drive household and occupational risks, emphasising the need to tailor effective control and recovery measures for these disadvantaged communities proportionate to their greater needs and vulnerabilities.

5- Large clusters and superspreading events

Clusters have become a prominent characteristic of SARS-CoV-2, which distinguishes it from seasonal influenza [14, 17]. This emphasises that large clusters and superspreading events may be the driver of the majority of infections, just as they were for SARS in 2002-2003 [39, 40]. For instance, during the 2003 SARS outbreak, over 70% of infections were linked to superspreading events in Hong Kong and Singapore [39]. Hallmarks for superspreading events include a combination of factors, typically a highly infectious individual(s) gathered with other individuals in enclosed and crowded environments [14, 17]. There have been several superspreading events reported so far. For example, an outbreak investigation from China identified that 24 out of 67 passengers were infected during a 50-minute return bus journey, which was linked to an index case who was symptomatic the day before the trip. In contrast, during the event, only six people were infected, all of whom were in close contact with the same index case [41]. In Washington state, a mildly symptomatic index case attended a choir practice (the practice was 2.5 hours), and out of 61 persons, 32 confirmed and 20 probable secondary COVID-19 cases occurred with an attack rate of 53.3% to 86.7%) [42]. While these superspreading events occur, the frequency of these events and whether they are caused by a single index case are unclear. The modelling suggests that several independent introductions might be needed before a COVID-19 outbreak eventually takes off, meaning often these large outbreaks occur when multiple infected persons are introduced to the environment as shown in the nursing home investigation [43]. Other large outbreaks are reported in night clubs, karaoke bars, pubs [14, 17], which may be related to crowding, leading to multiple introductions into the same setting as seen in nursing home investigations. These findings and observations suggest that contact tracing investigations need to be combined with phylogenetic analysis to understand the settings and activities most likely to yield a superspreading event to inform preventative measures.

Recommendations

Increased risk of transmission in deprived areas and among people in low-paid jobs suggest that poverty and household crowding need to be addressed with interventions that go beyond guidance on social distancing, hand hygiene, and mask use. Previous research suggests that although social distancing during the 2009 H1N1 swine flu pandemic was effective in reducing infections, this effect was most pronounced in households with greater socioeconomic advantage. Similar findings are emerging for COVID-19, with the ability to practice social distancing strongly differentiated by county and household income [34]. The disproportionate impact of COVID-19 on households living in poverty, and the racial and ethnic disparities observed in many countries, emphasize the need to urgently address these inequities that directly impact health outcomes. This includes social and income protection and support to ensure low paid, non-salaried and zero-hours contract workers can afford to follow isolation and quarantine recommendations, provision of protective equipment for workplaces and community settings, appropriate return-to-work guidelines, and testing and opportunities for isolation outside of the home to protect those still at work.

Second, knowing which contacts and settings confer the highest risk for transmission can help direct contact tracing and testing efforts to increase the efficiency of mitigation strategies. Early viral load peak in the disease course indicates that preventing onward transmission requires immediate self-isolation with symptom onset, prompt testing and results with a 24-48 hours turnaround time, and robust contact tracing. In many countries, people with symptoms access testing late in the disease course, by which time they may have had multiple contacts while in the most infectious period. While self-isolation with symptoms is crucial, 75% of those with symptoms and their contacts in the UK reported not fully self-isolating [44]. While presymptomatic transmission likely contributes to a fraction of onward transmission, over half of transmission is caused by those with symptoms, especially in the first few days after symptom onset. These findings suggest that messages should prioritise isolation practice, and policies should include supported isolation and quarantine.

Third, policy makers and health experts can help the public differentiate between lower-risk and higher-risk activities and environments and public health messages could convey a spectrum of risk to the public to support engagement in alternatives for safer interaction, such as in outdoor settings. Without clear public health communication about risk, individuals may fixate on unlikely sources of transmission —outdoor activities — while undervaluing higher-risk settings, such as family and friend gatherings, and indoor settings. Enhancing community awareness about risk can also encourage symptomatic persons and contacts of ill persons to isolate or self-quarantine to prevent ongoing transmission.

Finally, because crowded, indoor spaces and gatherings likely will continue to be the driver of transmission, public health strategies will be needed to mitigate transmission in these settings, such as nursing homes, prisons and jails, shelters, meat-packing plants such as personal protective equipment and routine testing to identify infected individuals early in the disease course. As part of the pandemic response we may need to consider fundamentally redesigning these settings, including improved ventilation, just as improved sanitation was a response to cholera. Such strategies should be adopted in settings where large outbreaks and superspreading events have been identified by contact tracing studies.

While modelling studies and computer simulations could contribute to our understanding of transmission dynamics and aero-dynamics of droplets, contact-tracing studies provide real-life transmission dynamics, individual and structural factors associated with SARS-CoV-2 transmission, which are essential to shape our public health plans, mitigate superspreading events, and control the current pandemic. Further understanding of transmission dynamics is also critical to developing policy recommendations for reopening businesses, primary and secondary schools, and universities.

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Conflict of interest:

MC, CB, TS have nothing to declare. JM has consulted for Kaiser Permanente Northern California on a research grant from Gilead Sciences and

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Figure legends

Figure 1: Factors influencing transmission dynamics

Transmission depends on several factors, including contact pattern (duration of contact, gathering, proximity, activity), environment (outdoor, indoor, ventilation), host-related infectivity/susceptibility pattern (i.e. viral load in relation to disease course, severity of illness, age) and socioeconomic factors (i.e. crowded housing, job insecurity, poverty). Virus infectivity and differences between other viruses, and host immune factors are not discussed in this review. (This figure is created by the authors based on available literature about SARS-CoV-2 transmission dynamics)

Figure 2: SARS-CoV-2 viral load dynamics and period of infectiousness

Incubation period (time from exposure to symptom onset) 6 days (2-21 days), peak viral load levels documented from day 0 (symptom onset) to day5, infectious period starts before symptom onset up to 10 days (this may be extended in patients with severe illness), RNA shedding continues for a prolonged period of time but culturable virus has been identified up to day 9 of illness. (This figure is created by the authors on Biorender based on available literature about SARS-CoV-2 viral load dynamics)

Figure 1

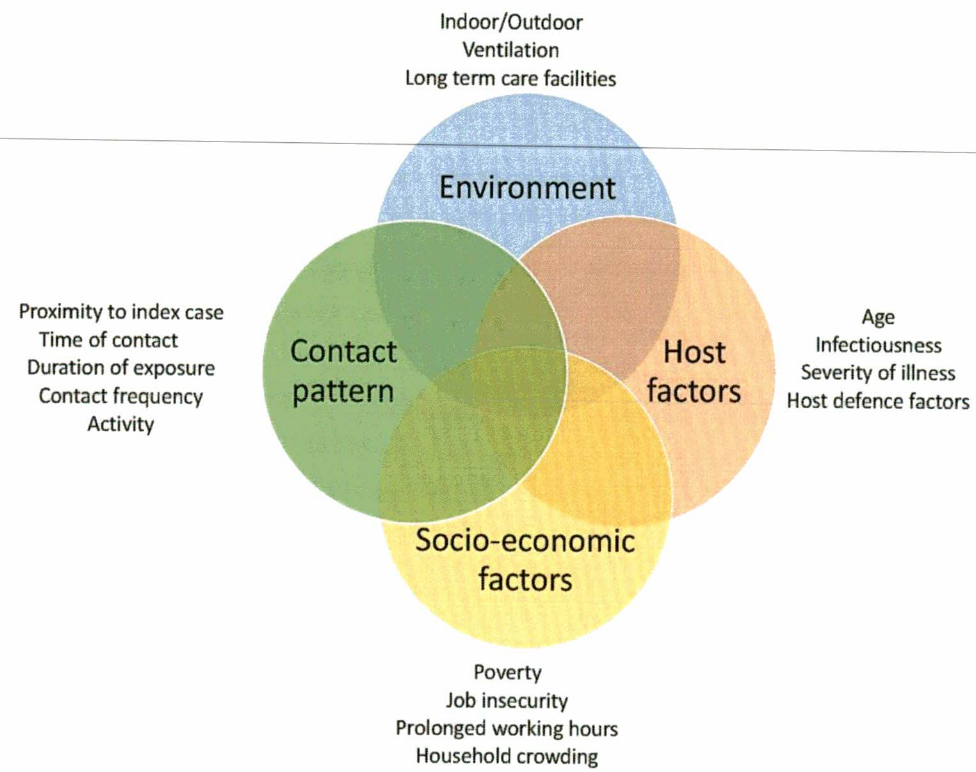
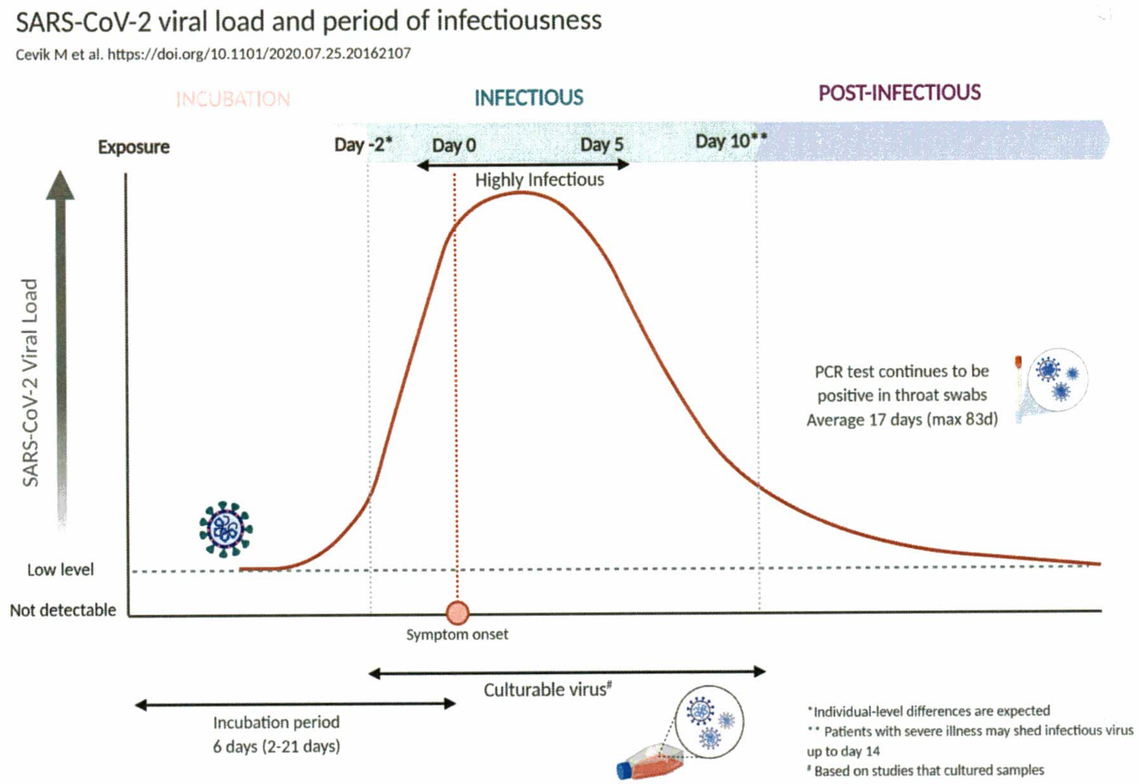

Indoor/Outdoor
Ventilation
Long term care facilities
Environment
Proximity to index case
Time of contact
Duration of exposure
Contact frequency
Activity
Contact pattern
Host factors
Age
Infectiousness
Severity of illness
Host defence factors
Socio-economic factors
Poverty
Job insecurity
Prolonged working hours
Household crowding

Figure 2


SARS-CoV-2 viral load and period of infectiousness
Cevik M et al. https://doi.org/10.1101/2020.07.25.20162107
INCUBATION
INFECTIOUS
POST-INFECTIOUS
Exposure
Day -2*
Day 0
Day 5
Day 10**
Highly Infectious
SARS-CoV-2 Viral Load
Low level
Not detectable
Symptom onset
PCR test continues to be
positive in throat swabs
Average 17 days (max 83d)
Culturable virus#
Incubation period
6 days (2-21 days)
*Individual-level differences are expected
** Patients with severe illness may shed infectious virus up to day 14
# Based on studies that cultured samples

Outdoor Transmission of SARS-CoV-2 and Other Respiratory Viruses, a Systematic Review

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Summary:

This systematic review found that while outdoor environments do seem at lower risk for transmission of SARS-CoV-2 and other respiratory viruses than indoor environments, there are data showing that infection transmission is possible outdoors, thus warranting further rigorous investigation.

Abstract

Background

While risk of outdoor transmission of respiratory viral infections is hypothesized to be low, there is limited data of SARS-CoV-2 transmission in outdoor compared to indoor settings.

Methods

We conducted a systematic review of peer-reviewed papers indexed in PubMed, EMBASE and Web of Science and pre-prints in Europe PMC through August 12th, 2020 that described cases of human transmission of SARS-CoV-2. Reports of other respiratory virus transmission were included for reference.

Results

Five identified studies found that a low proportion of reported global SARS-CoV-2 infections have occurred outdoors (<10%) and the odds of indoor transmission was very high compared to outdoors (18.7 times; 95% CI 6.0, 57.9). Five studies described influenza transmission outdoors and two described adenovirus transmission outdoors. There was high heterogeneity in study quality and individual definitions of outdoor settings which limited our ability to draw conclusions about outdoor transmission risks. In general, factors such as duration and frequency of personal contact, lack of personal protective equipment and occasional indoor gathering during a largely outdoor experience were associated with outdoor reports of infection.

Conclusion

Existing evidence supports the wide-held belief that the the risk of SARS-CoV-2 transmission is lower outdoors but there are significant gaps in our understanding of specific pathways.

Keywords: coronaviruses, SARS-CoV-2, COVID-19, transmission, outdoor

Background

Recommendations about methods to curb transmission of the severe acute respiratory syndrome coronavirus type 2 (SARS-CoV-2) beyond wearing masks and maintaining social distance have varied, especially regarding outdoor transmission.[1] This variability reflects a general lack of information on how SARS-CoV-2 is transmitted outdoors.

Outdoor spaces generally allow for more physical distancing, which mitigates the risk of virus transmission through larger respiratory droplets [2]. Outdoor spaces allow for airflow, ventilation, and lack of recycled air, which all minimize the theoretical risk of aerosol transmission through smaller respiratory droplets. While aerosol spread in community settings is controversial, emerging data suggest that indoor recycled air can spread SARS-CoV-2 — with examples of spreading events in a restaurant in Guangzhou [3], at an indoor choir practice in Skagit, Washington, USA [4], at a South Korean call center [5], at meat-packing plants in the USA [6] and in a nursing home in the Netherlands [7]. In areas with low ventilation, aerosolized droplets have the capacity to linger for longer before being inhaled or falling to a surface, which could result in fomite transmission [8]. In enclosed environments, low humidity, air conditioning, and low UV light may all contribute to longer survival of viral particles [9]. Outdoor environments also generally have fewer high touch surfaces that may harbor the virus. UV light, present outdoors from sunlight, results in a ten-fold decrease in virus survival on surfaces [10]. Finally, indoor environments may increase host susceptibility; the low indoor humidity has been associated with slower host ciliary clearance and complications such as pneumonia, and lack of sunlight has been associated with lower vitamin D levels [11]. For these reasons, the risk of virus transmission in outdoor locations has been hypothesized to be lower than in indoor spaces.

We sought to quantify the risk of SAR-CoV-2 transmission in outdoor settings. We conducted a systematic review of the literature on transmission of SARS-CoV-2 to better understand the risks of outdoor transmission. Where data was available, we estimated the risk of outdoor compared to indoor transmission. Anticipating a paucity of data on SARS-CoV-2, we chose a broad search strategy that included other human beta coronaviruses and respiratory viruses.

Methods

Search strategy and selection criteria

Data for this review were identified by searches of PubMed, EMBASE, Web of Science, as well as preprints available in Europe PMC [12]. Details of our search strategies and eligibility criteria can be found in our protocol published on August 3rd, 2020 on PROSPERO (ID: 183826). The search was conducted on June 17th, 2020, and because of the rapidly expanding data on SARS-CoV-2, the search was repeated to include most recent literature on August 12th, 2020.

Exposures and outcomes

The exposure of interest - outdoor gatherings - was defined as persons congregating outdoors for work, social or recreational activities (Supplementary Material 1 for our full search strategy). The outcome of interest included cases of transmission of SARS-CoV-2 or other respiratory viruses identified by a case report, illness, or mortality. We also included secondary outcomes of clusters or outbreaks of cases. Our search included any viral infection that can be spread by respiratory droplets and, in addition to SARS-CoV-2, included the other two recognized human beta-human coronaviruses viruses (SARS-CoV-1 and Middle East Respiratory Syndrome), human influenza viruses, adenoviruses, rhinoviruses, human metapneumoviruses, and respiratory syncytial virus.

We included studies (experimental or observational with empirical data collection) that described human-to-human transmission of respiratory viruses between humans in an outdoor setting, any review of these studies, and any study (experimental or observational) that compared respiratory viral transmission among humans in an outdoor versus indoor settings.

We excluded reviews of previously published data, studies of exclusively indoor outbreaks, outdoor outbreaks within animal populations or between animals and humans, and outbreaks where the site of transmission was not listed or was unclear. We also excluded studies limited to built environments (homes, apartment buildings, military barracks), hospitals, or forms of transportation (airplanes, trains, buses, cars, ships).

Data Selection and Extraction

After removing duplicate records, one author (TCB) reviewed all downloaded citations based on their titles and pre-specified inclusion criteria. A second co-author (MM) reviewed a 5% random sample of the excluded titles (rejected from initial search results) for quality control. Two authors (TCB and NR) then independently screened the titles, abstracts and descriptor terms and compared and discussed discrepancies until consensus was reached; a third author (MM) served as an arbiter when needed. Two authors (TCB and NR) then independently inspected the full texts of the remaining studies for relevance based on exposure, design and outcome measures to select the included papers, and discussed discrepancies until consensus was reached with a third author (MM) serving as arbiter. We used Endnote X9.3.2 (Clarivate

Analytics, Philadelphia, Pennsylvania, USA) and Rayyan (Qatar Computing Research Institute, Doha, Qatar) web-based software to manage search results [13].

Two authors (TCB and NR) extracted the following data from each paper into a pre-piloted data extraction form in Excel spread sheets : complete citation, study location, study design, details of participants (risk group or groups, sample size), exposure details (type of gathering, characteristics of gathering place, number of people, duration, proportion of time spent outdoors, amount if any of indoor transmission, how the non-exposure state (indoors) was defined, outcomes (numerators and denominators associated with each outcome, definitions and descriptions of outcomes provided in papers, details of how outcomes were assessed, individual cases of infection and/or large spreading events, mortality), methodological details (sample characteristics, how the information was gathered, how the outbreak was investigated), and details related to bias assessment.

Results

The combined searches yielded 10,912 unique citations, of which 12 studies met our inclusion criteria. Nine studies were identified from the June 17th search, two from the August 12th, and one from a targeted search. Out of the 12 that met our inclusion criteria, five were pertaining to SARS-CoV-2 **(Table 1 and 2)**, five reported on influenza or influenza-like viruses **(Table 3)**, and two reported on adenovirus transmission. Of note, 33 studies were excluded because they did not specify the location of transmission (Supplementary Material 2). The PRISMA diagram is shown in **Figure 1**.

Five studies related to SARS-CoV-2 transmission found that less than 10 percent of reported transmission occurred in outdoor settings, less than 5% of cases were related to outdoor occupations, and the odds of transmission or super spreading are much lower outdoors **(Table 1)** [14–17].

Of 318 identified outbreaks involving three or more cases in China reported to local Municipal Health Commissions from January 4 to February 11, 2020, Qian et al. found that all occurred in indoor environments [14]. They reported a single transmission that occurred outdoors (one case of outdoor transmission out of 7,324 total reported cases). This report, however, might be affected by strict interventions prohibiting mass gatherings outdoors, which may have contributed to the low number of cases contracted outdoors. Additionally, relying on local health department reports may have led to underestimates of the total number of transmissions, especially those which were asymptomatic [14].

Nishiura et al. [15] analyzed the transmission pattern of COVID-19 reported through February 28, 2020 (11 clusters and sporadic cases) in Japan. They concluded that the odds of a primary case transmitting COVID-19 in a closed environment were 18.7 times greater compared to outdoor setting (defined as an open-air environment) (95% confidence interval [CI]: 6.0, 57.9). The odds of a single case spreading to 3 or more individuals, which they defined as a super spreader event, in closed environments compared to open air were as 32.6 (95% CI: 3.7, 289.5). This report, however, included no description of the context or location of the outdoor transmission nor were any raw data provided. It is unclear whether this report is relying on proportions, which again, may be subject to the fact that fewer people would have been outdoors during winter months in Japan .

Leclerc et al. [16] reviewed 201 transmission clusters of COVID-19 world-wide that had been reported up to March 30, 2020. The vast majority of these transmissions were associated with "indoor" or "indoor/outdoor" settings (197/201 clusters or 21/22 locations). The one "outdoor" setting was at multiple construction sites in Singapore, where four outbreaks occurred.

Lan et al. [17] investigated 103 possible work-related cases of COVID-19 among a total of 690 local cases in six Asian countries or regions, including Hong Kong, Japan, Singapore, Taiwan, Thailand, and Vietnam. In this paper, construction workers in Singapore constituted only 5% of the total work-related transmissions. While this paper did not explicitly state whether the location of work-related transmission was outdoor or indoors, it was included based on Leclerc's classification of the same construction workers as an "outdoor" setting. This does not rule out that that transmission may have occurred in indoor locations at construction sites.

Szablewski et al. [18] report SARS-CoV-2 transmission at an overnight camp in Georgia, USA, where attack rates increased with increasing length of time at the camp, and with co-housing. Staff members, who stayed the longest at camp, had the highest attack rate (56%). The outbreak was clustered by cabin assignments, which suggests a high likelihood of transmission in indoor spaces during overnight cabin stays rather than during outdoor activities during the day. The authors state that non-pharmaceutical interventions such as cohorting and adults wearing masks during the day, were not protective, although no further information is given about this claim.

While there is high heterogeneity in the studies describing outdoor transmission of SARS-CoV-2, the studies we found highlight the conditions of outdoor exposure and transmission. The location and context of SARS-CoV-2 transmissions reported in this review are summarized in **Table 4**. Among these are examples of transmissions at a gathering in a park, but over multiple days with the same people, and at a camp, which lasted for several days and had indoor housing components.

Five other studies included in **Table 3** describe outdoor transmission of influenza or influenza-like viruses. Summers et al. [19] conducted a historical analysis of a large outbreak of the 1918 influenza virus on a military troop ship in July 1918. The outbreak involved over 1000 of the 1,217 crew members and caused 68 deaths. Analysis of factors that might have contributed to mortality revealed a significant association between individuals who slept indoors, in cabins with bunks (mortality of 146.1/1,000 population), versus individuals who slept in hammocks in open-air areas (mortality of 34.1/1,000 population). This study is of particular interest because the duration of exposure and distance between individuals was held constant. This was one of the few studies which investigated potential confounders such as age and social class – mortality changed with age, but not with social class or rurality. Age did not change the discrepancy in deaths seen outdoors compared to indoors.

Pestre et al. [20] conducted a retrospective analysis of a 2009 H1N1 influenza outbreak at a summer camp in France. Investigations revealed that all febrile individuals had travelled together in the same train wagon to reach camp, suggesting that the enclosed space facilitated transmission. The three individuals out of 32 that had not travelled in the same train wagon as all the other participants never developed symptoms, even though they were still present at camp for two days with all other infected individuals - presumably mostly in outdoor spaces.

Finally, three manuscripts about respiratory illnesses at mass open-air gatherings emphasized that while influenza outbreaks were uncommon, the duration of the event (multi-day over single day) and communal housing were risk factors for outbreaks (**Table 3**). [21–23] Rainey et al. concluded that all reported outbreaks in summer camps had social contact and communal housing, none were reported without a shared housing component.[21] Of note, no single-day mass gathering related outbreaks were detected in the 72 outbreaks they detail. Figueroa et al. also did not identify any single day event-related outbreaks.[22] Botelho et al. found four outbreaks of Influenza A (H1N1) and one of Influenza A and B; all events with an outbreak were multi-day sport events while single-day events had none.[23]

Two articles discussed adenovirus outbreaks associated with lakes [24] and outdoor swimming pools [25]. In both studies respiratory viral infection occurred in swimmers and in others who did not swim, such as fellow camp attendees and family members, suggesting human-to-human transmission prevalently occurring outdoors.

Discussion

While the studies included in this review were highly heterogeneous, ranging in methodology, definition of "outdoor" transmission, and virus studied, several common factors were identified. The studies with direct comparison of SARS-CoV-2 location of transmission reported dramatically lower proportions occurring outdoors. The exact determinants of outdoor transmission that can be gleaned from this review are limited, the cases of outdoor transmission of SARS-CoV-2 we identified were affected by the duration of exposure, frequency of exposure, density of gathering, whether maks were used, and were confounded by the possibility of indoor transmission.

Historical evidence gleaned from influenza outbreaks further support the lower risk of transmission outdoors. Summers et al. showed that influenza mortality on a ship was significantly lower outdoors (sleeping in hammocks) compared to indoors (sleeping in cabins). While mortality does not provide direct information about transmission, it serves as a useful proxy. Outcomes from several investigations of influenza outbreaks during mass outdoor gatherings suggest that outdoor, single day events without communal sleeping arrangements have lower risks of influenza transmission than multi-day events with indoor components [21–23].

These findings, as well as reports of influenza outbereaks and adenovirus outbreaks in outdoor bodies of water, suggest that while outdoor transmission is less common than indoor, it is not impossible. Case reports identified after our review was completed provide further evidence that high density outdoor gatherings, particularly with low mask use, may lead to higher transmission rates. Miron et. al noted that incidence of COVID-19 cases was significantly higher in 14 out of 20 counties that had a large outdoor gathering 15 days prior.[26] Dave et al. estimates that in the three weeks following the start of the Sturgis motorcycle rally started on August 7th 2020, South Dakota, USA, an multi-day event with 500,000 participants, cases grew more in counties with weak mitigation policies than those with strong mitigation policies (such as closure of restaurants and bars, or mask-wearing mandates) as participants returned to their homes [27]. In contrast, although COVID-19 rates increased in the three weeks following the mass protests in the United States [28], the uptick in cases due to these events was less than expected because social distancing and masking measures were more widespread [29]. The importance of protective measures is further exemplified by the outdoor outbreak that occurred at the White House Rose Garden event on September 26th 2020, where few of the 200 attendees were wearing masks or maintaining social distancing measures.[30]

Of note, our search did not find any studies on the transmission of COVID-19 in settings of outdoor agricultural work. In California prevalence of COVID-19 for agricultural workers is two to three times higher than the rate for workers in all other industries [31]. The experience of agricultural workers suggests that crowded working or sleeping conditions may be a substantive risk factor for transmission, but the contribution of work in outdoor spaces to transmission risk has not been assessed. We found that outdoor, single day events without communal sleeping arrangements have lower risks of transmission compared to multi-day, mass outdoor gatherings in the spread of influenza [21–23].

In order to better characterize the risks of outdoor SARS-CoV-2 exposure, future studies should fill the research gaps we have identified in this review. First, many research studies we identified did not report the location of transmission at all. This may be because understanding relationships between cases is more important than the location of interaction, or may be related to practical challenges in contact tracing outdoors. Second, it is difficult to isolate an outdoor exposure to a virus. While outdoor gatherings could be largely safe, if they are accompanied by time in indoor locations such as cabins or trains, it might be challenging to identify exact location of transmission. Szablewski et al., which was included in our review, while the summer camp may have been largely outdoors, it does not preclude from exposure in the dining halls or cabins. As for construction sites, once a building is framed and enclosed, it may be considered indoor work, which may in fact be the majority of the work. Third, in many reports published early in the SARS-CoV-2 pandemic, the measured outcome was "illness or death" due to viral infection, not SARS-CoV-2 infection itself, which was rarely assessed. If asymptomatic infections are more likely to occur outdoors, this could represent a systematic bias. Fourth, the definition of being “outdoors” is ambiguous, and the effect of exposure is likely modified by variable proximity to and contact with others. Fifth, in order to test the hypothesis that the risk of infection is lower outdoors, future research should collect data about time spent indoors versus outdoors. Given that 90% of time is spent indoors in high-and-middle income countries [32], then it would be expected that 90% of transmission to occur indoors, all else being equal. Lastly, there are few data that examine how respiratory droplets spread outdoors, such as how far they travel during running, biking, or during windy conditions. A study examined these variables but was calculated with no account of ventilation, sunlight, or humidity. [33]

Finally, most of the transmission events we identified in the literature did not report the socioeconic status of those impacted. Spreading events often occur in settings where marginalized and disempowered populations live or work such as lower-income, higher density urban settings, work settings such as meat packing plants, or even prisons [34]. While there are multiple reasons for the disproportionate impacts of COVID-19 in these populations, we postulate that lack of opportunity to move high-risk activities outdoors may be one of them. [35,36] While it was our intention to further explore this hypothesis by analyzing sub-group socio-economic and ethnicity data in the studies included in this review, the studies did not include these metrics.

Future studies could compare SARS-CoV-2 case rates at outdoor gatherings to known rates for indoor gatherings. There are several examples of studies that estimate the risk of indoor transmissison [37–39] which have ranged from 10.3% (95% confidence interval [CI] 5.3% – 19.0%) in a study of trains in China to 78% in a church in Arkansas [38]. Accurate estimation of the risk of outdoor transmission will require determining person-time at risk for infection, incidence rate ratios, and more nuanced information about the exposure environment; these data are still lacking.

Better understanding of how SARS-CoV-2 is transmitted outdoors is needed to inform sound policies that reconcile shelter-in-place orders with the many health benefits associated with time spent outdoors [40]. This is particularly relevant to outdoor parks and recreation agencies, which seek clear guidance on how being outdoors has a low risk of transmission. Other policy implications are to encourage moving essential activities outdoors, with appropriate masking and social distancing measures, given that transmission can still occur outdoors. The long term and potentially deleterious social and emotional effects of school closures can be potentially mitigated if, for example, it is known that outdoor schooling is a viable alternative. Finally, encouraging outdoor time may serve as a harm reduction model in allowing people to congregate, and therefore better tolerate long-term shelter in place mandates.

This systematic review has several limitations. The few and heterogenous studies on outdoor transmission of respiratory viruses had used various metrics, exposures and outcomes, making it challenging to compare findings quantitatively. The low proportion of outdoor COVID-19 cases may reflect the general decrease in outdoor activities since strict lockdowns were enacted in the countries surveyed. Relying on reports of symptomatic infections may under-represent asymptomatic cases that occur outdoors. If the viral inoculum affects the severity of respiratory viral infection, an outdoor exposure may reduce the viral inoculum to which the individual is exposed and therefore the subsequent clinical impact of the disease. If this theory were true for SARS-CoV-2, it may increase the proportion of infections that are asymptomatic.[41] The studies in this review did not contain much information about potential confounders such as the age of infected individuals, activities in which they participated, ethnicity, or social class. There was minimal information on mitigation efforts such as masks and social distancing and how that may have impacted/influenced viral transmission. This review did not explicitly include gray literature (such as case reports from health departments, lay newspaper sources) in its search strategy, as other comprehensive reviews of transmissions have done.[16] Including preprints may have decreased our risk of information bias.

Conclusion

While it has been acknowledged that spending time outside has general health benefits, our review posits that there are also benefits in reducing transmission of SARS-CoV-2 by reducing exposure time (substituting time indoors with time outdoors). These results suggest that moving activities to outdoor settings may reduce infections and ultimately save lives. However, it is important to note that infections are possible outdoors and the advantage may be overtaken by relaxed mitigation efforts.

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Table 1. Comparison of respiratory virus transmission outdoors compared to indoors ordered by virus studied.

Outcome	Virus Studied	Estimate of effect		Relative estimate of effect	Number of participants in the study
		Outdoor	Indoor		
Number of cases [14]	SARS-CoV-2	2/7,324 cases	7,322/7,324 cases	<1% of transmissions happened outdoors	7,324 cases, totaling 318 outbreaks.
Number of cases [17]	SARS-CoV-2	4/103 cases	99/103 cases	5% of work-related cases occurred outdoors	103 possible work-related cases among a total of 690 local transmissions.
Odds of transmission [15]	SARS-CoV-2	*(Raw data not available)*	*(Raw data not available)*	Odds of transmission in closed environments 18.7 (95% CI: 6.0, 57.9) times greater than in open air	110 cases: 27 primary cases and 83 secondary cases
Number of super-spreading events and odds of transmission* [15]	SARS-CoV-2	1/7 super-spreading events	6/7 super-spreading events	Odds ratio of super spreading in closed environments: 32.6 (95%CI: 3.7, 289.5)	110 cases: 27 primary cases and 83 secondary cases
Number of cases [16]	SARS-CoV-2	95/10,926 cases	10,831/10,926 cases	<1% of transmissions happened outdoors	10,926 cases, totaling 201 events of transmission
Number of cases [20]	H1N1 2009 Influenza	0/3 cases	24/29 cases	Out of 32 total people in a holiday camp, 29 traveled together in a train wagon	32 people at a holiday camp
Mortality [19]	H1N1 1918 Influenza	28/820 deaths sleeping in hammocks outside, 34.1 persons/1,000	39/267, deaths sleeping in cabins inside, 146.1 persons/1,000	Risk Ratio of 4.28, 95% CI 2.69-6.81	Total of 1,217 people on the ship.

* superspreading defined as events where the number of secondary cases generated by a single primary case is greater than the 95th percentile of the distribution (i.e. transmission to three or more persons)

Table 2. Studies reporting outdoor SARS-CoV-2 transmission.

Year	Author	Location and Date	Sample Description	Design	Outcomes measured	Outdoor exposure	Outdoor findings	Indoor findings	Bias
2020	Qian et al.	320 prefectural cities in China. Between 4 January and 11 February 2020	7,324 cases, 318 outbreaks	Retrospective analysis of all public health reports from local Municipal Health Commission website to determine location of transmission.	Location of transmissions, clusters and outbreaks. Cluster was defined as 3 or more infections that appear linked to the same infection venue. An outbreak was defined as a cluster in which a common index patient is suspected. Outbreaks were organized by relationship and also by location.	Open air	One outdoor transmission involving two cases in Shangqiu, Henan: a 27-year-old man had a conversation outdoors with an individual who had returned from Wuhan.	Of 318 identified outbreaks that involved 3 or more cases, they all occurred in indoor environments.	Relied on heterogenous case reports of the local health department, which might have missed cases because of differential allocation of resources or internal biases. Additionally, the data was collected partly after lock-down (started January 23rd in Wuhan), after which most people were indoors. There was no effort to access exact locations of infection. Not peer-reviewed at the time of review.
2020	Nishiura et al.	Seven prefectures in Japan. Start date of 28 February 2020	110 cases (27 primary cases, 83 secondary cases). Seven superspreading events identified.	Retrospective case investigation using contact tracing data.	Location and number of transmissions from primary to secondary cases. Super-spreading events defined as: number of	Open air	Odds of transmission in a closed environment was 18.7 times greater compared to an open-air environment (CI:	Out of seven superspreading events, six of these events (85.7%) took place in closed environments.	Small sample size and no raw data provided to support calculations of odds. Limitations were not discussed in the manuscript.

Table 2. Studies reporting outdoor SARS-CoV-2 transmission.

					secondary cases generated by a single primary case is greater than the 95th percentile of the distribution (i.e. transmission to three or more persons)		6.0, 57.9). The odds ratio of superspreading events in closed environments was as high as 32.6 (95% CI: 3.7, 289.5). One superspreading event occurred outdoors (not described).		Not peer-reviewed at the time of review.
2020	Leclerc et al.	Multiple world-wide locations, as of March 30th	201 events of transmission (clusters)	Review of all documented transmission clusters (world-wide) using literature review and open-source strategies	Settings of transmission clusters for 201 events	22 types of settings were determined. Outdoor locations were defined as "outdoor", while locations that were a mixture were defined as "indoor/outdoor". Indoor locations were defined as "indoor".	The transmissions in the only "outdoor" setting occurred in four outbreaks at outdoor construction sites in Singapore, totaling 95 cases. Updated results additionally revealed: - one transmission occurred while jogging in Codogno, Italy (non-peer re-viewed source) - Twenty cases in an outdoor park in Münster, Germany (non-peer reviewed source)	10/22 locations defined as indoor/outdoor, 11/ 22 defined as indoor. A total of 197 events occurred in these settings, totaling 10,831 cases.	Included reports from some non-peer reviewed sources (eg. local media outlets for the jogging and outdoor park transmission reports), which might have been individually influenced by recall bias and poor methodology. While the study conducted a systematic review, additional sources were collected using an open-source strategy which might have been affected by selection bias of respondents.
2020	Lan et al.	Six Asian	690 locally	Observational	Number of cases	Workplace largely	A total of 103	The five	The exact

Table 2. Studies reporting outdoor SARS-CoV-2 transmission.

		regions: including Hong Kong, Japan, Singapore, Taiwan, Thailand, and Vietnam Between January 23, 2020 and March 14, 2020.	transmitted cases	study, extracted confirmed COVID-19 cases from governmental investigation reports. Only locally transmitted (non-imported) cases were included. Transmission period was extended to 40 days from primary case.	per occupation across country/area and stratified into early (first 10 days) and late (11-40th day) transmission periods.	outdoors	possible work-related cases were determined to be outdoors among a total of 690 local transmissions. Of workers that might be prevalently outdoors, 5% of cases were construction workers. Tour guides (5% of cases) might also be considered to have occurred partly outdoors.	occupation groups with the most cases were healthcare workers (22%), drivers and transport workers (18%), services and sales workers (18%), cleaning and domestic workers (9%) and public safety workers (7%).	outdoor/indoor makeup of the location of transmission was not described. This is in part due to the fact that the transmission source was not always known, and detailed occupational histories were also not always known. Also, none of the reports arose from systematic testing of high-risk occupations, rather from individual case reports, which might have been affected by biased and heterogenous reporting mechanisms from different regions.
2020	Szablewski et al.	Overnight camp in Georgia, USA. June 17-27 2020.	During June 17–20 the overnight camp held orientation for 138 trainees and 120 staff members; staff members remained for the first camp session, scheduled during June 21–27, and were joined by 363	Retrospective Case Investigation (MMWR)	Positive test result for SARS-CoV-2 (symptomatic and asymptomatic)	Camp attendees were cohorted by cabin and engaged in a variety of indoor and outdoor activities, including daily vigorous singing and cheering.	On June 24 a staff member tested positive to SARS-CoV-2. Test results were later available for 344 attendees; among these, 260 (76%) were positive. The percentage of transmission that	Median cabin attack rate was 50% among 28 cabins that had one or more cases (on average, each cabin housed 15 people). Attack rate was highest in the larger cabin, suggesting the	Attack rates are likely an underestimate because cases might have been missed among persons not tested or whose test results were not reported. Some cases may have

Table 2. Studies reporting outdoor SARS-CoV-2 transmission.

			campers and three senior staff members on June 21. Children and adults attended.				developed solely outdoors was not investigated.	main location of transmission was in the cabins.	resulted from transmission occurring before or after camp attendance. Lastly, exact details of outdoor activities versus indoor were not described.

Table 3. Studies reporting other outdoor respiratory virus transmission ordered by infection identified.

Year	Author	Virus	Location and Date	Sample Description	Design	Outcomes measured	Outdoor exposure	Outdoor findings	Indoor findings	Bias
2017	Figueroa et al.	Respiratory disease outbreaks	United States, 2009-2014	18 mass gatherings in 8 states.	Data was collected on mass gathering related respiratory disease outcomes. 50 state health departments and 31 large local health departments were contacted via online assessment. 43 (53%) of 81 health jurisdictions responded.	Outbreak was defined as one or more cases of an infectious respiratory disease. Mass gathering (exposure) was defined as a planned or unplanned congregation of 1,000 or more persons in either an indoor or outdoor venue for a common purpose.	Mass gatherings were defined as indoors or indoor/outdoors.	All reported outbreaks occurred at multi-day mass gathering events. For Influenza A (H1N1) attack rates at two summer camps were of 1.4% and 4.8% respectively. Attack rate for a religious event was of 19.5%. At a sporting event in the spring, it was of 3.3% - but only included athletes. Attack rate of Inluenza A (H3) at another summer camp was of 0.02%.	At a professional conference in the winter, which was likely to be mostly indoors, attack rate was of 21.0%. Probable factors that affected attack rates were participant density and susceptibility, rather than gathering size alone. Use of non-pharmaceutical interventions (eg. handwashing, surface cleaning) might have been an additional factor.	Low response rate (around 50%) by state health departments, while there was no response from local health departments. There might be responded bias, given that departments which experienced mass gathering outbreaks might have been more willing to respond. Furthermore, the details of each mass gathering and their indoor/outdoor locations are not described.
2016	Rainey et al.	Respiratory disease outbreaks	United States, 2005-2014	21 published articles describing 72 mass gathering-related respiratory disease	Six medical, behavioral and social science literature databases were analyzed to extract relevant articles. NORS	Mass gatherings were defined as large events involving more than 1,000 persons in a specific	The authors did not specify outdoor vs indoor location of mass gathering.	Close social mixing and contact in communal housing/activities were associated with all other outbreaks identified. They	All reported outbreaks in summer camps had social contact and communal housing, none reported without	Search strategy might have not captured studies that did not use the word "outbreak", and might have missed any outbreak not captured by surveillance systems

Table 3. Studies reporting other outdoor respiratory virus transmission ordered by infection identified.

				outbreaks. 1,114 outbreaks reported to NORS (National Outbreaks Reporting System)	was also analyzed to estimate the frequency of mass gathering-related respiratory disease outbreaks.	location for a shared purpose. Definition of outbreak was deferred to the author's definition. Half of the reported outbreaks were related to a zoonotic source and were excluded. 38% of the outbreaks occurred at a variety of camps.		concluded that multiday mass gatherings with indoor residential overnight components can facilitate transmission.	a housing component.	(eg. smaller outbreaks, of diseases with longer incubation periods). Not much detail was shared on the indoor/outdoor locations and activities at the gatherings where outbreaks occurred.
2013	Botelho-Nevers et al.	Disease outbreaks (including respiratory disease)	"open air mass gatherings" worldwide, 1980-2012	9 published articles about respiratory infections at large, outdoor mass gatherings, festivals, or music festivals	Literature search using ProMed and MEDLINE database, with crossreferencing using search engines such as google and yahoo	Outbreaks in the setting of open-air gatherings.	Mass gatherings defined as "generally outdoors", but which may have onsite housing and food supply.	Four outbreaks of Influenza A (H1N1) and one of Influenza A and B were found. Overall, the estimated incidence of confirmed respiratory infections of influenza per 100,000 attendees ranged from 2 to 30. The discrepancy between sport events, which seem to have lower	No exclusively indoor events were included.	The infections related to large open air festivals may be under-reported, given difficulty in ascertaining exact location of transmission and sporadic surveillance systems. The search strategy of only using ProMed and MEDLINE might have limited the amounts of results that might otherwise be available on other reporting/surveillance agencies.

Table 3. Studies reporting other outdoor respiratory virus transmission ordered by infection identified.

								incidence, and large scale open air festivals in terms of infectious diseases may also be the consequence of the relatively short duration of sports events which frequently last shorter than one day.		
2011	Pestre et al.	2009 H1N1 Influenza	Summer camp in France, August 2009	32 persons participated in the holiday camp. 29 of them traveled in the same train wagon.	Retrospective Case Investigation	Infection of H1N1 influenza.	Individuals who did not travel in the same train wagon.	The outbreak involved 21 children and 3 adults who had all travelled together in the same wagon. The three individuals that did not take the same train wagon and were immediately thereafter in contact with the 24 infected individuals at camp did not experience influenza symptoms.	Out of 29 individuals who took the same train wagon, 21 children and 3 adults experienced symptoms.	Conditions of outdoor versus indoor activities at camp were not described. Given this, the comparison between indoor (train wagon) and outdoor (camp) exposure assumes that a majority of time at camp, as compared to the train wagon, was outdoors. Measurement of cases might have been affected by timing of testing and/or presence of asymptomatic cases. Limitations were not discussed.
2010	Summers et al.	1918 Influenza	His Majesty's New Zealand Transport military troop ship in Sierra	1,217 persons onboard	Retrospective Historical Outbreak Analysis	Mortality	Sleeping in hammocks as opposed to cabins with bunks	Out of 1,217 persons onboard, over 1,000 suspected cases of influenza, 68 deaths. Mortality rate for persons that slept in	Mortality rate for persons that slept in cabins with bunks was of 39/267 (146.1 persons/1,000 population). The difference	Historical evidence used in this paper is subject to transcription and/or recording errors, lack of case definitions, and approximate estimates of case numbers. While it is

Table 3. Studies reporting other outdoor respiratory virus transmission ordered by infection identified.

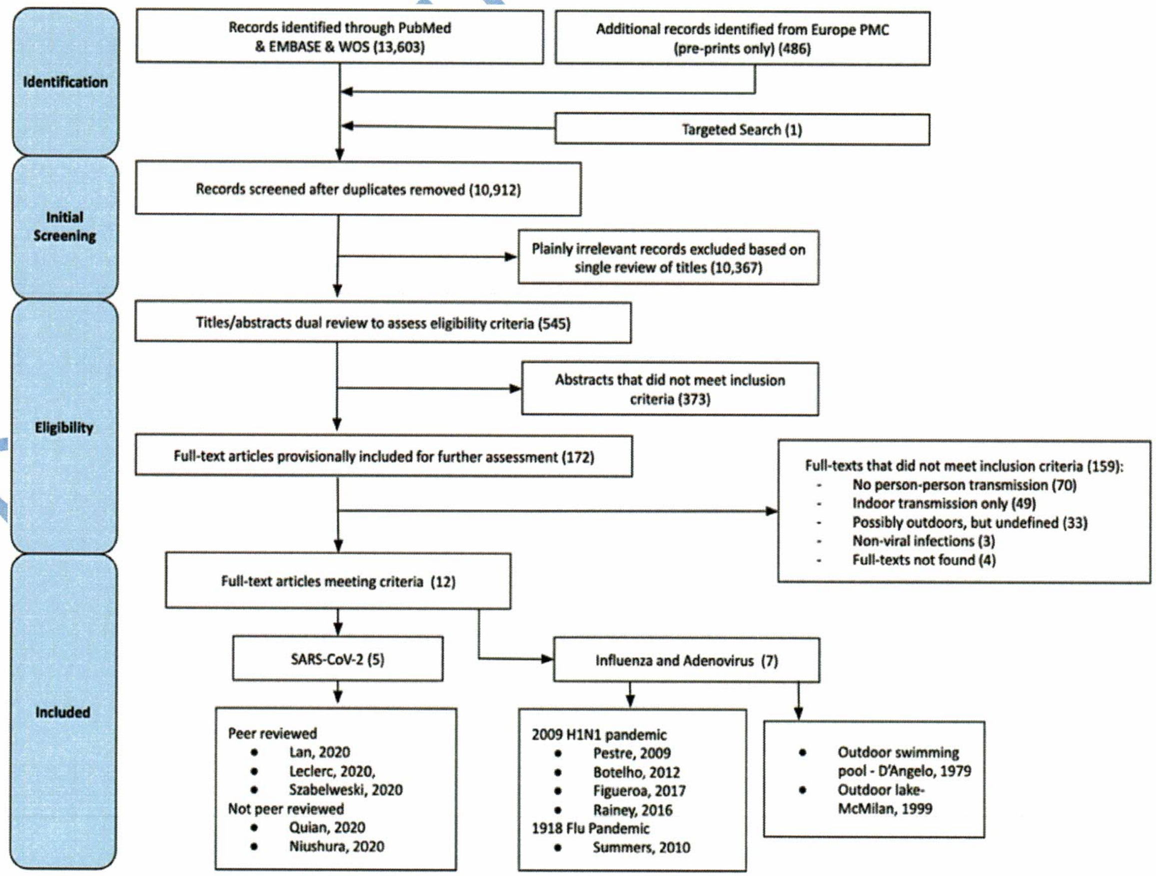
			Leone, July 1918					hammocks outdoors was of 28/820 or of 34.1 persons/1,000 population.	between hammocks was significant (crude RR 4.28, 95% CI 2.69–6.81). Density did not seem to be a contributing factor.	hinted that hammocks were in higher ventilated zones as compared to cabins, the exact location of hammocks was not described.

Table 4. Outdoor conditions where COVID-19 was transmitted

Setting	Description of transmission	Purely outdoors?	Use of Non-Pharmaceutical Interventions*
Overnight summer camp [18]	Outbreak of 260 cases during an overnight camp in Georgia. Everyone was tested negative for COVID less than or equal to 12 days prior to coming to camp. While exact outdoor activities were not described, the overnight component suggests that the attack rate increased with length of time spent at the camp. This was shown by staff members, who were present at camp the longest, having the highest attack rate (56%). Attack rate associated with being adult, length of stay, and being in a cabin together. Median attack rate in the cabins: 50%, overall attack rate 44%.	No	Yes. They state the NPI was not effective. The non-pharmaceutical interventions they tried was cohorting of attendees by cabin (less than or equal to 26 persons), staggering of cohorts for use of communal spaces, physical distancing outside of cabin cohorts, and enhanced cleaning and disinfection, especially of shared equipment and spaces. Cloth masks were required for staff members. Evidently, these interventions were not effective at preventing a majority of cases.
Conversation in outdoor setting [14]	One outdoor transmission involving two cases in Shangqiu, Henan: a 27-year-old man had a conversation outdoors with an individual who had returned from Wuhan. No secondary or tertiary cases from this transmission were reported	Yes	Unknown
Outdoor construction sites [16,17]	Four outbreaks at outdoor construction sites in Singapore, involving a total of 95 cases [16] Five cases of construction workers in Singapore [17]. Details of exact location of transmission were not described. Details of how "indoors" versus outdoors unknown. However, in Leclerc et al. building sites were described as "outdoor" settings.	Unknown	Unknown
Jogging outdoors [16]	One transmission while jogging in Codogno, Italy (reported by local news media, cited in Leclerc et al. open source database)	Yes	Unknown
Outdoor park [16]	Twenty cases in an outdoor park in Münster, Germany (reported by local news media, cited in Leclerc et al. open source database). The members of the extended family, who had been living in different houses in the Angelmodde district of Munster, were suspected to have met often on a playground in the Osthuesheide district. The activites of the family were not described, but it was described as a repeated exposure over days.	Yes	Unknown

* Such as masks, physical distance, cohorting.

Figure 1



Identification
Initial Screening
Eligibility
Included
Records identified through PubMed & EMBASE & WOS (13,603)
Additional records identified from Europe PMC (pre-prints only) (486)
Targeted Search (1)
Records screened after duplicates removed (10,912)
Plainly irrelevant records excluded based on single review of titles (10,367)
Titles/abstracts dual review to assess eligibility criteria (545)
Abstracts that did not meet inclusion criteria (373)
Full-text articles provisionally included for further assessment (172)
Full-texts that did not meet inclusion criteria (159):
- No person-person transmission (70)
- Indoor transmission only (49)
- Possibly outdoors, but undefined (33)
- Non-viral infections (3)
- Full-texts not found (4)
Full-text articles meeting criteria (12)
SARS-CoV-2 (5)
Influenza and Adenovirus (7)
Peer reviewed
Lan, 2020
Leclerc, 2020,
Szabelweski, 2020
Not peer reviewed
Quian, 2020
Niushura, 2020
2009 H1N1 pandemic
Pestre, 2009
Botelho, 2012
Figueroa, 2017
Rainey, 2016
1918 Flu Pandemic
Summers, 2010
Outdoor swimming pool - D'Angelo, 1979
Outdoor lake- McMilan, 1999

Check for updates

RESEARCH ARTICLE

REVISED **What settings have been linked to SARS-CoV-2 transmission clusters? [version 2; peer review: 2 approved]**

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Abstract

Background: Concern about the health impact of novel coronavirus SARS-CoV-2 has resulted in widespread enforced reductions in people's movement ("lockdowns"). However, there are increasing concerns about the severe economic and wider societal consequences of these measures. Some countries have begun to lift some of the rules on physical distancing in a stepwise manner, with differences in what these "exit strategies" entail and their timeframes. The aim of this work was to inform such exit strategies by exploring the types of indoor and outdoor settings where transmission of SARS-CoV-2 has been reported to occur and result in clusters of cases. Identifying potential settings that result in transmission clusters allows these to be kept under close surveillance and/or to remain closed as part of strategies that aim to avoid a resurgence in transmission following the lifting of lockdown measures.

Methods: We performed a systematic review of available literature and media reports to find settings reported in peer reviewed articles and media with these characteristics. These sources are curated and made available in an editable online database.

Results: We found many examples of SARS-CoV-2 clusters linked to a wide range of mostly indoor settings. Few reports came from schools, many from households, and an increasing number were reported in hospitals and elderly care settings across Europe.

Conclusions: We identified possible places that are linked to clusters of COVID-19 cases and could be closely monitored and/or remain closed in the first instance following the progressive removal of lockdown restrictions. However, in part due to the limits in surveillance capacities in many settings, the gathering of information such as cluster sizes and attack rates is limited in several ways: inherent recall bias, biased media reporting and missing data.

Keywords

SARS-CoV-2, COVID-19, coronavirus, cluster, transmission, settings, lockdown

Open Peer Review

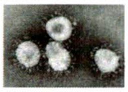
Reviewer Status ✔ ✔

	Invited Reviewers 1	2
version 2 (revision) 05 Jun 2020	✔ report	✔ report
version 1 01 May 2020	? report	

1 **Joël Mossong**, Laboratoire National de Santé, Dudelange, Luxembourg

2 **Samuel V. Scarpino**, Northeastern University, Boston, USA

Any reports and responses or comments on the article can be found at the end of the article.



This article is included in the Coronavirus (COVID-19) collection.

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Author roles: Leclerc QJ: Data Curation, Formal Analysis, Investigation, Validation, Writing – Original Draft Preparation, Writing – Review & Editing; **Fuller NM**: Data Curation, Investigation, Validation, Writing – Original Draft Preparation, Writing – Review & Editing; **Knight LE**: Data Curation, Investigation, Validation, Writing – Review & Editing; **Funk S**: Conceptualization, Methodology, Supervision, Validation, Writing – Review & Editing; **Knight GM**: Conceptualization, Data Curation, Formal Analysis, Investigation, Methodology, Supervision, Validation, Writing – Original Draft Preparation, Writing – Review & Editing

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REVISED **Amendments from Version 1**

This article has been updated in response to reviewer comments, and to include 49 new transmission events which have been added to our online database. We now discuss a total of 201 transmission events (previously 152), classified into 22 setting types (previously 18).

Any further responses from the reviewers can be found at the end of the article

Introduction

The novel coronavirus SARS-CoV-2, responsible for coronavirus disease 2019 (COVID-19), was first identified in Wuhan, China at the end of 2019, and has since spread around the world (European Centre for Disease Prevention and Control, 2020). The capacity of the virus for human-to-human transmission, coupled with the lack of immunity in the population due to the novelty of SARS-CoV-2, has led to the implementation of severe reductions in people's movements in an effort to reduce disease impact. These strong measures are broadly described as "lockdowns". Due to the highly restrictive nature of lockdowns, and their impact on people's health, wellbeing and finances, it is likely that such interventions cannot be sustained for prolonged periods of time, and will have to be lifted, at least to some extent, before an effective vaccine becomes available.

To successfully remove these lockdown restrictions while avoiding a resurgence in SARS-CoV-2 transmission, we must better understand in which types of settings the virus is most likely to be transmitted. Determining particular places that are linked to clusters of cases could reveal settings that are responsible for amplifying the heterogeneity in transmission that has been reported: potentially 80% of transmission is being caused by only 10% of infected individuals (Endo *et al.*, 2020). Notably, the difference in transmission risk between households and larger communal settings is unclear, as is the difference between indoor and outdoor transmission.

Quantifying these differences in transmission can be further facilitated by the fact that, in many countries now under lockdown, intensive contact tracing of imported cases was performed in the early stages of the epidemic, resulting in the detection of clusters of cases. This data, on the first detected clusters in a country, can give knowledge of the types of settings facilitating transmission before intensive social and physical distancing took place.

The aim of our work is therefore to gather information on reported clusters of COVID-19 cases to determine types of settings in which SARS-CoV-2 transmission occurred. This could inform post-lockdown strategies by identifying places which should be kept under close surveillance and/or should still remain closed to avoid a resurgence in transmission.

Methods

Outline

We searched for scientific literature and media articles detailing clusters of SARS-CoV-2 transmission (details below) and extracted data into a Google Sheets file (accessible at https://bit.ly/3ar39ky; archived as *Underlying data* (Leclerc *et al.*, 2020)). We defined "settings" as sites where transmission was recorded resulting in a cluster of cases. We restricted our definition of "cluster" to the first-generation cases that acquired the infection due to transmission in a single specific setting at a specific time. For example, if a person was infected on a cruise ship, and later infected additional people after disembarking, we would not consider that the latter were part of that "cruise ship cluster", since they were not infected on the ship. We recorded the country and further details about the type of setting, the numbers of primary and secondary cases in the cluster, cluster sizes, and attack rates. We defined a case as a person reported to be infected with the SARS-CoV-2 virus, regardless of symptoms.

Search strategy

References were found in four ways. Firstly, we performed a systematic literature review for COVID-19 clusters in PubMed on the 30th March 2020 (search term below). A total of 67 papers were found. Two reviewers (GMK and QJL) performed data extraction into the online database. We chose to only search this database and use peer reviewed articles as a quality threshold. We included data from English abstracts (where possible), but otherwise excluded non-English publications.

PubMed search: ("COVID-19"[All Fields] OR "COVID-2019"[All Fields] OR "severe acute respiratory syndrome coronavirus 2"[Supplementary Concept] OR "severe acute respiratory syndrome coronavirus 2"[All Fields] OR "2019-nCoV"[All Fields] OR "SARS-CoV-2"[All Fields] OR "2019nCoV"[All Fields] OR (("Wuhan"[All Fields] AND ("coronavirus"[MeSH Terms] OR "coronavirus"[All Fields])) AND (2019/12[PDAT] OR 2020[PDAT]))) AND cluster [All Fields]

Secondly, we used the online Google search engine to find media articles detailing settings of SARS-CoV-2 transmission in general. We searched for combinations of either "COVID", "COVID-19", "COVID-2019","severe acute respiratory syndrome coronavirus 2", "2019-nCoV", "SARS-CoV-2", "2019nCoV" or "coronavirus", and the words "transmission cluster" (e.g. "COVID transmission cluster" or "SARS-CoV-2 transmission cluster"). We only included online articles in English. From the collated list of settings, we then performed a further search for transmission in each of these settings (week beginning 6th April 2020).

Thirdly, we investigated whether information on the settings in which the first 100 "transmission events" in countries with current COVID-19 outbreaks existed by searching for publicly available data sources. As substantial investigation of cases often occurs early in an outbreak, any clusters linked to the first ~100 cases in countries outside China could give information on the transmission of SARS-CoV-2 in the absence of any social distancing measures.

Finally, following the original publication of this article on 01/05/2020, we included a "Suggested updates" tab in our publicly available database (https://bit.ly/3ar39ky). This allows other individuals to suggest new clusters we should include in our analysis. We review these suggestions regularly, and add those with sufficient detail to our "Latest updated results" tab. In this revised version, we have updated our analysis to include suggestions we reviewed up to 26/05/2020.

Cluster characteristics and setting definition

With the above data, we then aimed to estimate both the final (proportion of people in that setting who became infected) and secondary (proportion of contacts of one case who became infected) attack rates in each setting. These were previously identified as key metrics, particularly within households, to estimate whether transmission is driven by a relatively small number of high-risk contacts (Liu *et al.*, 2020).

We defined a setting when several reports mentioned clusters linked to spaces with certain characteristics. For example, "Religious" includes churches and mosques, while "Public" here means public communal shared spaces such as markets or welfare centres. Where settings were a mixture of indoor and outdoor spaces, we used a mixed indoor/outdoor classification.

Results

We found evidence of SARS-CoV-2 transmission clusters for 201 events, which we classified into 22 types of settings (Table 1 and Table 2). All the studies with relevant data are compiled in an online database (accessible at https://bit.ly/3ar39ky; see also *Underlying data* (Leclerc *et al.*, 2020)). Many of the published reports with setting specific data came from China (47/201) and Singapore (51/201).

The vast majority of these clusters were associated with indoor or indoor/outdoor settings (21/22). Large clusters, such as those linked to churches and ships, were infrequently reported. Almost all clusters involved fewer than 100 cases (181/201), with the outliers being transmission in hospitals, elderly care, worker dormitories, food processing plants, prisons, schools, shopping and ship settings. Religious venues provided a further setting with large cluster sizes: there were separate clusters in South Korea, France, India and Malaysia (Ananthalakshmi & Sipalan, 2020; BBC, 2020; Salaün, 2020; Shin *et al.*, 2020). In addition to these settings with maximum cluster sizes of more than 100 cases per cluster, we identified five further settings with maximum cluster sizes between 50 and 100: sport (65 cases) (Korean Centre for Diease Control & Prevention, 2020), bar (80 cases) (Sim, 2020), wedding (98 cases) (Ministry of Health – New Zealand, 2020), work (97 cases) (Park *et al.*, 2020) and conference (89 cases) (Marcelo & O'brien, 2020).

We found a notably high number of transmission events reported in worker dormitories (21/201), although all of these were from Singapore. This type of setting had the second highest total cluster size out of all the recorded events we found, with 797 cases reported in the S11 dormitory cluster in Singapore (Data Against COVID19 SG, 2020).

We found only a small number of clusters linked to schools (8/201), and there the SARS-CoV-2 cases reported were most often in teachers or other staff. For example, for two school clusters in Singapore (Ministry of Health - Singapore, 2020), 16/26 and 7/8 cases were staff. Some children were also found to be infected in these clusters, as was the case in the Salanter Akiba Riverdale school in New York, USA (Ailworth & Berzon (2020)), although testing for infection was not always universal. In a retrospective close cohort study in a French high school however, 133 children and staff were seropositive for anti-SARS-CoV-2 antibodies, 92 of whom were pupils (Fontanet *et al.*, 2020).

We identified 9 clusters linked to food processing plants in 4 different countries (USA, Germany, Canada, Netherlands). These transmission events have led to large clusters, such as in a meat processing plant in South Dakota where a total of 518 employees were infected by SARS-CoV-2 (Cannon, 2020).

The setting with the greatest number of reported clusters of SARS-CoV-2 transmission was households (36/201). Again, most were from China (25/36) with all cluster sizes being less than 10. However, for 27 out of 36 studies, we were unable to calculate either the secondary or final attack rates due to a lack of information on total household size.

We aimed to estimate secondary and final attack rates in other settings but, as for households, we found that there was substantial missing data. In particular, the number of individuals in a setting was missing, and so we were unable to perform this analysis. Where attack rates could be estimated for individual clusters, these are reported in the online database.

Although information on the index and early cases in a setting was often reported, further information on the subsequently reported 10–100 cases in a country was difficult to extract. Moreover, the index cases were often quarantined and hence not linked to further transmission in most settings.

Discussion

In this review of SARS-CoV-2 transmission events, we found that clusters of cases were reported in many, predominantly indoor, settings. Note that we restrict cluster size to only include individuals infected within a specific setting, and exclude secondary infections which occurred outside the settings. Most clusters involved fewer than 100 cases, with the exceptions being in healthcare (hospitals and elderly care), large religious gatherings, food processing plants, schools, shopping, and large co-habiting settings (worker dormitories, prisons and ships). Other settings with examples of clusters between 50–100 cases in size were weddings, sport, bar, shopping and work. The majority of our reports are from China and Singapore.

Limitations

The settings collated here are biased due to the nature of our general search for SARS-CoV-2 transmission described above. Although based on a systematic review of published peer-reviewed literature, many of the reports included came from media articles where relevant epidemiological quantities were not always reported, resulting in many missing data. Many of the more detailed studies originated from the early outbreak in China, especially those providing household information. The settings

Table 1. Summary of gathered reported events as of 20th April 2020. Where only one study for this setting is reported, the minimum, maximum and median number of secondary cases in the cluster and/or total cluster size correspond to this single reported number (if given). Total cluster size accounts for all primary and secondary cases in the cluster. For references see the online database, accessible at https://bit.ly/3ar39ky.

Setting type	Number of reported events	Secondary cases			Total cluster size			Total number of cases across all clusters	Countries	Indoor / outdoor
		Min	Median	Max	Min	Median	Max			
Bar	12	2	9	16	3	13	80	319	Germany, Austria, Italy, Singapore, Japan, USA, Australia, New Zealand, Brazil	Indoor / outdoor
Building site	4	/	/	/	5	20.5	49	95	Singapore	Outdoor
Conference	5	/	/	/	3	10	89	148	Canada, Singapore, Japan, USA, New Zealand	Indoor / outdoor
Elderly care	17	/	/	/	5	19	167	638	UK, Canada, Scotland, France, Germany, Italy, USA, Japan, New Zealand, Luxembourg	Indoor
Food processing plant	9	2	2	2	3	84	518	1207	USA, Germany, Canada, Netherlands	Indoor
Funeral	1	3	3	3	4	4	4	4	USA	Indoor / outdoor
Hospital	9	1	3	14	2	10	118	224	China, Singapore, Italy, Taiwan, South Korea, Japan	Indoor
Hotel	2	/	/	/	3	5	7	10	Singapore	Indoor
Household	36	1	3	11	2	4	12	168	China, Italy, Vietnam, Taiwan, South Korea, Hong Kong, France	Indoor
Meal	17	1	3	10	2	5	47	134	Singapore, USA, Vietnam, China, South Korea, Japan	Indoor
Prison	4	351	351	351	66	226	353	871	USA, Ethiopia	Indoor
Public	4	/	/	/	10	10	27	57	China, Japan	Indoor / outdoor
Religious	15	1	18	52	2	23	130	570	USA, Singapore, South Korea, US, China, India, Netherlands, Germany	Indoor / outdoor
School	8	1	1	131	2	22	133	349	Singapore, France, USA, New Zealand, Australia, Sweden	Indoor / outdoor
Ship	5	619	619	619	78	662	1156	3597	Grand Princess, Diamond Princess, Ruby Princess, USS Theodore Roosevelt, Charles de Gaulle aircraft carrier	Indoor
Shipyard	1	/	/	/	22	22	22	22	Singapore	Indoor / outdoor
Shopping	9	5	10	19	7	20	163	361	China, Singapore, Peru, Mexico	Indoor / outdoor
Sport	6	1	1	1	2	7.5	65	95	South Korea, Singapore, Italy, Japan	Indoor / outdoor
Transport	1	1	1	1	3	3	3	3	China	Indoor
Wedding	3	/	/	/	13	43	98	154	Australia, New Zealand	Indoor / outdoor
Work	12	6	7	11	4	8.5	97	198	China, Singapore, South Korea, Germany	Indoor
Worker dormitories	21	/	/	/	3	24	797	1702	Singapore	Indoor

Table 2. Definitions used for each of our transmission setting types. The definitions describe in what environment transmission was deemed to occur.

Transmission setting	Definition
Bar	Indoor space such as a bar, club, pub, small live music venues etc.
Building site	Outdoor space where construction work takes place.
Conference	Indoor professional event with many people interacting and meeting, shaking hands, eating together, team activities, etc.
Elderly Care	Care homes for the elderly; includes staff and residents. Transmission can occur between staff and residents but also from visitors.
Food processing plant	Any establishment that processes food for human consumption, such as a meat or vegetable packing plant.
Funeral	Indoor or outdoor burial ceremony; includes close contact with others such as hugging, shaking hands, eating together, singing, praying, etc.
Hospital	Any transmission that occurs within a hospital between patients and/or staff, in a COVID19 ward or not.
Hotel	Any transmission that occurs within the hotel e.g. hotel rooms, shared spaces, reception desk, etc.
Household	Transmission between individuals in a shared living space
Meal	When people eat together. Meals included took place in restaurants, hotels, cafes, home, etc. Transmission occurs over a meal by speaking, sharing foods, touching the same surfaces, etc.
Prison	Any transmission that occurs within a prison between prisoners and/or staff.
Public	Where transmission occurs on public property and does not fall into any of the other settings e.g. park, welfare centre, foodbank, etc.
Religious	Transmission occurs at a religious event such as at mass, services, prayer time, choir practice, etc.
School	Childcare or learning environments (schools, nurseries, kindergartens etc). Includes staff and children.
Ship	Any ship at sea. Includes crew and/or passengers onboard.
Shipyard	Large indoor or outdoor space where ships are made or repaired. Includes those working on the ship as well as customers
Shopping	A shop or shopping centre. Includes customers and those working in the shop.
Sport	Participation in a sporting activity indoor or outdoor e.g. gym or running.
Transport	Any means of public transportation, such as bus, plane, metro etc.
Wedding	Indoor or outdoor wedding celebration.
Work	In the workplace, typically an office.
Worker dormitories	A shared living space for workers.

we identified here therefore might not be representative of settings from a global perspective. Bias is present when relying on media coverage - a cluster is more likely to be reported if controversial or if there is an interesting social narrative. This is then compounded by the method search engines use to provide results where priority is given to high traffic stories. Overall, this can lead to some settings being overly represented in our database, which is why the numbers of clusters per settings should be compared cautiously.

Similarly, there is a bias in our reports which means that attendance in settings with many individuals is more likely to be linked to a cluster: recall bias (Spencer *et al.*, 2017). The accuracy of memories is influenced by subsequent events and experiences such that special, one-off events may be more likely to be remembered and potentially reported. If multiple single transmission events had occurred whilst walking in a park, for example, these would be less likely to be remembered, and more difficult to detect and hence record. Networks of close contacts also tend to be small, resulting in multiple opportunities for transmission, and hence potentially increase the importance of households or workplace for transmission instead of single outstanding settings of potential transmission. Hence, we cannot determine with any reliability the relative importance of the reported different types of settings beyond the record that clusters have been linked to such places.

Other events, such as large music concert (Dalling, 2020), political (Jones, 2020) and sporting (Hope, 2020; Roan, 2020; Wood & Carroll, 2020) gatherings, could potentially have been linked to clusters of COVID-19. But, in the absence of rigorous surveillance systems and widespread testing that would allow countries to link and report the transmissions of such events, such connections remain speculation. An example of this lack of surveillance would be the UK, where only 4/201 clusters have been recorded The outlier for this is Singapore which appears to investigate clusters systematically and provides a well-designed online dashboard with details of all clusters detected (Data Against COVID19 SG, 2020).

In many settings, only symptomatic cases of disease severe enough to require hospitalization are tested and ultimately reported. This misses those infections that result in mildly symptomatic or asymptomatic symptoms, although there is mounting evidence for a significant proportion of infections to remain asymptomatic (Gudbjartsson *et al.*, 2020; He *et al.*, 2020; Lavezzo *et al.*, 2020). For some of the clusters, primarily households, all contacts were tested for infection; but for most of the data collated here, the number of COVID-19 symptomatic cases was the only information provided. These reported cases are a subset of all infections and in the absence of more comprehensive data, such as could be collated through widespread cluster investigation and community testing, we cannot conclude anything about clusters of infections, nor that we have included all relevant settings in which transmission can occur. We were also unable to estimate attack rates from the available data, meaning that comparison between rates of transmission in settings is impossible to achieve.

Settings associated with large cluster sizes

One type of setting that was associated with large numbers of eventual cases was religious venues. The common features of these meetings are the large number of attendees, confined spaces and physical contact. For example, there were eventually more than 5000 COVID-19 cases linked to transmission at the Shincheonji Church of Jesus in South Korea (Shin *et al.*, 2020). In this particular religious venue, no preventative action was taken despite knowing members were infected with SARS-CoV-2. In other venues, transmission events took place without prior knowledge of any infections and before the WHO declared pandemic status. Other large clusters in this setting type were associated with annual religious events that took place over a few days or weeks (Ananthalakshmi & Sipalan, 2020; BBC, 2020; Salaün, 2020). Attendees returned to their home countries where they continued to transmit. This generated many secondary cases internationally as well as locally. However, it is clear from smaller "first-generation" clusters, which our analysis focuses on, that these settings provide ideal conditions for transmission: we found 7/16 identified religious clusters had 10 cases or less, whilst 9/16 had 23 or more (see online database https://bit.ly/3ar39ky and *Underlying data* (Leclerc *et al.*, 2020) for more information). The number of cases in each cluster is an approximation, and little is known about the number of index cases in these religious meetings to begin with, with the exception of the South Korea cluster. Religious events are well known sources of heightened transmission; there is a focus on vaccination recommendations for attendees to the annual Hajj pilgrimage for example, which is currently being postponed for 2020 (Aljazeera, 2020).

Worker dormitories have been recognised as key places linked to transmission in Singapore, with 893 out of 942 new cases recorded on April 18th being residents in such dormitories (Asia, 2020). We found 21 reported clusters, one of which had the second largest cluster size of all the events we report here; 797 cases which from the data we believe is a first-generation cluster. Worker dormitories are similar to households (Dalling, 2020) in the sense that they are places where people live together and come in frequent close contact; however, the number of residents in dormitories is higher than in most other households. This probably contributes to the higher cluster sizes seen in this setting. Additionally, hygiene facilities can be limited in worker dormitories (Paul *et al.*, 2020), which could also explain the higher transmission. These points also apply to prisons, another type of large co-habiting setting for which we have identified 4 clusters with a maximum cluster size of 353 cases. It would be beneficial to compare attack rates across households, worker dormitories and prisons, to better understand which factors influence the risk of transmission between people who share a living space. Unfortunately, we were unable to identify the total number of residents in these dormitories and prisons, which prevented us from deriving attack rates and making this comparison.

In addition to religious events and worker homes, we also identified clusters of more than 100 cases in elderly care homes, hospitals and ships. These are all known to be at risk of clusters of infectious disease (Blanco *et al.*, 2019; Kak, 2015; Lansbury *et al.*, 2017). Moreover, people in these settings are often older than the general population and hence at greater risk of severe forms of COVID-19 disease (U.S Centers for Disease Control and Prevention, 2020). The increased mortality and likely dependence on availability of personal protective equipment (PPE) mean that healthcare clusters are more politically sensitive and hence more likely to be reported.

A more unexpected setting type is perhaps food processing plants, in which we identified clusters of up to 518 cases (Cannon, 2020). These plants have been the source of clusters in multiple countries. It is possible that the cold atmosphere in this setting has facilitated the spread of the virus (Molteni, 2020). Other possible explanations include the close proximity of workers for prolonged periods shared welfare spaces, as well as the need to speak loudly to communicate over the noise of the machines, which could lead to an increased projection of viral particles. Another explanation is that we may not be seeing clusters from other manufacturing settings with similar working environments, as fewer have been in operation due to lockdown guidelines during the pandemic, whereas food production has continued.

We identified seven additional setting types with cluster sizes above 50 or 100 cases (school, sport, bar, shopping, wedding, work and conference), which shared characteristics with the settings described above (see online database for more information https://bit.ly/3ar39ky and *Underlying data* (Leclerc *et al.*, 2020)). Notably, sport, bars, shopping areas and conferences are predominantly indoor settings, where people are in close proximity. For conferences and work, like religious events, transmission within the cluster is facilitated by the duration of the events over several days, as well as the combination of interactions there (workshops, dinners etc…). This can also apply to weddings, where transmission is further increased due to the close-proximity interactions between people (kissing, hugging, dancing etc…). As for bars and shopping areas, these are places with important fluxes of people, which increases the diversity of contacts. Finally, schools, like religious groups, can sometimes represent tightly knit communities which facilitates disease transmission amongst individuals, as was the case with the Salanter Akiba Riverdale school in New York, with a cluster size of at least 60 cases (Ailworth & Berzon (2020)).

The first 100 transmission events & under reporting

The pursuit of the first 100 transmission events revealed little on settings of transmission. This reflects the wider issue we found of under reporting and is likely to reflect the fact that many public health surveillance systems were quickly overwhelmed and could not continue outbreak investigations. An example of this is the UK where only limited information on case follow-up and cluster investigation appears to be available. The impact of such under reporting is that we cannot say with certainty what contribution each setting had to overall transmission – we do not have the denominator information on time and contact in all settings. Nor do we have universal screening for detection of all infections, many of which will be asymptomatic. The importance of such universal testing for infection in interpreting whether transmission has occurred in a setting is highlighted by the difference between the low number of clusters linked to schools and the high level of infection reported in one French high school study (Fontanet *et al.*, 2020).

Further work could pursue data from early investigation of cases where available, to explore the relative importance of different settings to transmission. Importantly, this may counter a bias towards small cluster sizes: with a lack of follow-up only some of the cases actually linked to a setting may be reported and linked. Detailed outbreak investigations should also be explored to get information on the places where transmission is unlikely to have occurred, e.g. if a COVID-19 patient reports 30 contacts at place "A", "B" and "C", but only contacts in "C" subsequently become infected this reflects reduced risk in settings "A" and "B".

Implications for further work

We found that many clusters of cases were linked to indoor settings, but this may be because early spread in China was during their winter, with people naturally spending more time inside close spaces. Increasing evidence suggests that transmission of SARS-CoV-2 can occur via airborne droplets (Morawska & Cao, 2020); however, it is likely that outdoor transmission risk is lower (Nishiura *et al.*, 2020). Further work is needed to clarify this. We found only few clusters in school settings. However, there were many clusters associated with household transmission, and children could be the entry point for the virus into this setting. Although it should be noted in this context that the Report of the WHO-China Joint Mission on Coronavirus Disease 2019 (COVID-19) did not find a single instance where people recalled transmission from a child to an adult (WHO-China Joint Mission Members, 2020). More generally, the role of children in widespread transmission of the virus is unclear, and whether reopening schools could trigger increased introductions of the virus into households and further within-household spread will have to be carefully monitored.

Further investigation of settings that facilitate clusters of transmission could provide important information for containment strategies as countries lift some of the current restrictions. Previous work has suggested that there might be considerable heterogeneity in individual transmission, which would imply a disproportionate impact from preventing large transmission events from occurring (Endo *et al.*, 2020). Whilst widespread contact tracing is often considered part of future containment strategies, there is a need for this to be complemented with retrospective investigation of clusters in order to better understand the extent to which certain settings and behaviours are at particular risk of generating clusters of transmission. This could, in turn, inform contact tracing efforts and might be particularly relevant in the context of contact tracing using mobile phone apps, which has recently been suggested in support of more traditional contact tracing (Ferretti *et al.*, 2020). For example, past co-location in certain settings could be a trigger for notification of risk from an app instead of, or in addition to, individual contacts.

Online database of collected reports

The online database (accessible at https://bit.ly/3ar39ky) provides information on all collected reports, references and information on cluster sizes as well as notes about the study. This database will be kept as a static source linked to this report, but with an additional tab for newly reported settings. Readers can submit information in the "Suggested updates" tab and we will aim to update information if evidence for substantial new clusters are found linked to a setting that was not in this study.

Conclusions

In conclusion, we found evidence of SARS-CoV-2 transmission in many types of settings. Our results provide a basis to identify possible places that are linked to clusters of cases and could be closely monitored, for example by linking to app-based contact tracing, and/or remain closed in the first instance following the progressive removal of lockdown restrictions. However, reporting should be improved in the majority of settings, with implementation of systematic reporting on the number of potentially exposed individuals and the number of confirmed and suspected cases from these settings, to allow the estimation of attack rates.

Data availability

Underlying data

Figshare: COVID19 settings of transmission - collected reports database. https://doi.org/10.6084/m9.figshare.12173343.v3 (Leclerc *et al.*, 2020).

This project contains 'COVID-19 settings of transmission - database.xlsx', which contains the data extracted from the initial search, as well as an updated version of the dataset from 26/05/2020.

Up to date information on all collected reports is provided in an open-access online database (accessible at https://bit.ly/3ar39ky).

This database provides references and information on cluster sizes as well as notes about the studies.

Acknowledgments

We would like to thank Dr Joël Mossong for his review of our article. We would also like to thank all the anonymous individuals who suggested updates for transmission events in our online database.

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Open Peer Review

Current Peer Review Status: ✔ ✔

Version 2

Reviewer Report 30 June 2020

https://doi.org/10.21956/wellcomeopenres.17583.r39003

✔ **Samuel V. Scarpino**
Network Science Institute, Northeastern University, Boston, MA, USA

In this manuscript, the authors conduct a thorough literature review and identified SARS-CoV-2 transmission clusters. After assembling their data set, the authors discuss the possible similarities in settings associated with transmission. As stated, understanding how transmission risk varies across settings is critical for the safe relaxation of measures implemented to control the spread of COVID-19. This paper provides a valuable resource and synthesis of what is currently known. I should note that this article has already been evaluated and I believe the authors have adequately addressed the points raised by the previous reviewer. However, I do have a few additional comments/questions, which I hope the authors find constructive.

1. While Google Sheets is a convenient tool for entering and sharing small data sets, it is not "permanent" and also has the potential to be corrupted or heavily modified. There is also no easy way for authors to cite the "version" of the sheet used. The authors do provide a Figshare, but that appears to date back prior to the revised version. I would strongly suggest regularly archiving a version of the data set and assigning each update a version number. At a minimum, please provide a DOI for the revised data set.

2. I am concerned that one reason we don't see more evidence for transmission at schools is that schools were closed early in nearly all locations. To my knowledge, Sweden is not reporting data on whether there have been significant transmission in their schools (as the authors know not all of which are open). I believe the authors should provide a strong disclaimer, either in the abstract or early in the discussion that we really don't have much to go on w.r.t. schools. (Of course this is my opinion and likely subject to debate).

3. The authors state, "More generally, the role of children in widespread transmission of the virus is unclear, and whether reopening schools could trigger increased introductions of the virus into households and further within-household spread will have to be carefully monitored." But, I also feel that given the uncertainty in whether children are import for ongoing transmission, there are other settings we should caveat.

4. The authors note that they, "use peer reviewed articles as a quality threshold," and, while I strongly disagree with the exclusion of pre-prints, I think the authors should at least provide some information on how many studies or clusters were excluded. Given the long (and increasing lag) between pre-print and publication, is this study missing half of all clusters that are currently published or in-review? 10% 95%? Providing information around what's been excluded is standard practice for such reviews and feels critical in this case.

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and is the work technically sound?
Partly

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are all the source data underlying the results available to ensure full reproducibility?
Partly

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Epidemiology

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Reviewer Report 05 June 2020

https://doi.org/10.21956/wellcomeopenres.17583.r38985

✔ **Joël Mossong**
Epidemiology and Microbial Genomics, Laboratoire National de Santé, Dudelange, Luxembourg

My comments and suggestions have been adequately addressed.

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and is the work technically sound?

Yes

Are sufficient details of methods and analysis provided to allow replication by others?

Yes

If applicable, is the statistical analysis and its interpretation appropriate?

Yes

Are all the source data underlying the results available to ensure full reproducibility?

Yes

Are the conclusions drawn adequately supported by the results?

Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Epidemiology of infectious diseases

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Version 1

Reviewer Report 18 May 2020

https://doi.org/10.21956/wellcomeopenres.17429.r38734

?

Joël Mossong

Epidemiology and Microbial Genomics, Laboratoire National de Santé, Dudelange, Luxembourg

This manuscript aims to provide a descriptive analysis of transmission settings of Covid19 based on published articles or media reports, which is of major interest for controlling the epidemic.

I have several major concerns:

1. Most settings reported herein are not representative of settings from a global perspective, most are from the initial epidemic in Asia (mainly from the Singapore dashboard and <20% of settings in the manuscript are outside of Asia). This needs to be added to the discussion as a major limitation.

2. Some important and widely reported outbreaks in particular settings are missing. e.g. the outbreak of the megachurch in Mulhouse France (https://www.dailymail.co.uk/news/article-8168819/French-megachurch-meeting-blamed-sparking- and the Ruby Princess outbreak (reported in

https://www1.health.gov.au/internet/main/publishing.nsf/Content/1D03BCB527F40C8BCA258503C [1]) or the cluster in the french ski resort (https://www.bbc.com/news/uk-51425702). This somehow questions the completeness of the systematic review. The authors could have widened their search terms to include the settings (church, ship, etc.) and outbreak when searching media reports.

3. Given that this manuscript from a team in the UK, it is surprising that only 4 outbreak settings were reported for the UK. The authors need to discuss why they were not able to find more reports from the local and national media outlets in English speaking countries like UK, Ireland, and possibly also Australia, Canada and the US.

4. The authors should discuss reasons for under reporting: public health surveillance systems in many countries were quickly overwhelmed to investigate transmission settings and chains of transmissions. Transmission clusters in elderly care and hospitals homes due to political sensitivity, linked to increased mortality, lack of adequate PPE equipment

5. Meat factories and slaughter houses have recently emerged as high risk setting in the US (https://edition.cnn.com/2020/04/08/business/meat-plant-closures-coronavirus/index.html) and Germany (https://www.dw.com/en/coronavirus-breaks-out-in-third-german-slaughterhouse/a-53389860). This setting should be included separately in Table 1.

Minor comments:

1. Add the sum of cases for all clusters per setting in table 1.

2. p.3.& p. 7 "the first 100 transmission events". While this is an interesting concept, it isn't really being addressed in this article. No country presented herein has collected more than 100 events. The paragraph in the discussion on this seems therefore irrelevant and could be deleted.

3. p. 7. The authors mention that there is increasing evidence for airborne transmission. The current consensus is that most transmission occurs via airborne droplets, which is different to aerosol transmission. I suggest to replace "be airborne" by "occur via airborne droplets".

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Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and is the work technically sound?
Partly

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Yes

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Epidemiology of infectious diseases

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 01 Jun 2020

Quentin Leclerc, London School of Hygiene & Tropical Medicine, London, UK

This manuscript aims to provide a descriptive analysis of transmission settings of Covid19 based on published articles or media reports, which is of major interest for controlling the epidemic.

Thank you for taking the time to review our article. Please note that we have now updated our analysis to include an additional 49 transmission events (201 events total) and 4 new settings type ("Food processing plant", "Prison", "Transport" and "Wedding"; 22 setting types total). Some of these new elements overlap with your suggestions. Our Discussion section has also been updated to reflect these new results.

I have several major concerns:

1. **Most settings reported herein are not representative of settings from a global perspective, most are from the initial epidemic in Asia (mainly from the Singapore dashboard and <20% of settings in the manuscript are outside of Asia). This needs to be added to the discussion as a major limitation.**

Thank you for raising this point. We already mentioned in the Discussion - Limitations section that many studies originated from the early outbreak in China, but have included an additional sentence there to clarify that this could prevent our results from being directly applicable to other countries. That said, please note that in our updated analysis, 98/201 (50%) events are from China and Singapore, compared to 92/152 (60%) in our original analysis, which improves the coverage of our results.
The added sentence is "The settings we identified here therefore might not be representative of settings from a global perspective."

1. **Some important and widely reported outbreaks in particular settings are missing. e.g. the outbreak of the megachurch in Mulhouse France (https://www.dailymail.co.uk/news/article-8168819/French-megachurch-meeting-blame(and the Ruby Princess outbreak (reported in https://www1.health.gov.au/internet/main/publishing.nsf/Content/1D03BCB527F40C8BC or the cluster in the french ski resort (https://www.bbc.com/news/uk-51425702). This somehow questions the completeness of the systematic review. The authors could have widened their search terms to include the settings (church, ship, etc.) and outbreak when searching media reports.**

Thank you for suggesting these additional clusters; we have now added the Ruby Princess and the French ski resort events.
Our initial analysis was focused on trying to find distinct *settings* in which transmission had occurred. Hence we were initially trying to prioritise examples of new *settings* linked to clusters rather than gathering all data on all outbreaks linked to all settings. This has changed somewhat with the open source database and we are happy to act as a gathering point for cluster data.
For the outbreak in Mulhouse, this falls into the category of events that we do not include in our analysis. This because we are interested in understanding transmission only within specific settings; for example, for a cruise ship, the cluster size we report corresponds to the number of people infected on that ship only, not the people that these might have infected after disembarking. If we included people infected by passengers after disembarking, this would not reflect the "cruise ship" setting, as this additional transmission could occur in a variety of other settings (household, meal etc…).
We had already highlighted this in the Methods – Outline section, but have now repeated that point at the beginning of the Discussion to hopefully make this distinction clearer ("Note that we restrict cluster size to only include individuals infected within a specific setting, and exclude secondary infections which occurred outside the settings.")

1. **Given that this manuscript from a team in the UK, it is surprising that only 4 outbreak settings were reported for the UK. The authors need to discuss why they were not able to find more reports from the local and national media outlets in English speaking countries like UK, Ireland, and possibly also Australia, Canada and the US.**

Our initial search was at the end of March. At that time, the number of confirmed cases in the UK was around 20,000, compared to more than 200,000 now. Therefore, there was little information at the time on clusters in these countries compared with Asia, which is why we were less likely to find media reports on that topic for the UK. For similar reasons, we had little information for English-speaking countries. In addition, because of the lack of widespread testing in the UK and/or follow-up of cases, information on clusters does not appear to be widely available in the UK.
As of 26/05/2020, we have now identified 39 transmission events in English-speaking countries (19% of all the transmission events we have identified so far). Therefore, our updated analysis is more geographically balanced.

1. **The authors should discuss reasons for under reporting: public health surveillance systems in many countries were quickly overwhelmed to investigate transmission settings and chains of transmissions. Transmission clusters in elderly care and hospitals homes due to political sensitivity, linked to increased mortality, lack of adequate PPE equipment**

Thank you for this suggestion. In line with your comments on the "first 100 transmission events" we have adapted the paragraph in the discussion to discuss reasons for under reporting.
We have also added a sentence to the paragraph on healthcare clusters in the discussion to reflect the likely increased reporting of clusters linked to these settings due to political sensitivity.

1. **Meat factories and slaughter houses have recently emerged as high risk setting in the US (https://edition.cnn.com/2020/04/08/business/meat-plant-closures-coronavirus/index.ht and Germany (https://www.dw.com/en/coronavirus-breaks-out-in-third-german-slaughterhouse/a-533 This setting should be included separately in Table 1.**

Thank you for raising this point. Our online database had been updated to reflect this, and we have now added the "Food processing plant" setting type in our analysis, and comment on this in the Results and Discussion sections of our article.

This also applies to our new "Prison", "Transport" and "Wedding" setting types.

Minor comments:

1. **Add the sum of cases for all clusters per setting in table 1.**

We have now implemented this suggestion in the revised article.

1. **p.3.& p. 7 "the first 100 transmission events". While this is an interesting concept, it isn't really being addressed in this article. No country presented herein has collected more than 100 events. The paragraph in the discussion on this seems therefore irrelevant and could be deleted.**

We agree it was frustrating not to find this data, which would have been an interesting angle, giving us "denominator" information. In line with the comments above we have adapted this paragraph to link to under reporting.

1. **p. 7. The authors mention that there is increasing evidence for airborne transmission. The current consensus is that most transmission occurs via airborne droplets, which is different to aerosol transmission. I suggest to replace "be airborne" by "occur via airborne droplets".**

Thank you for this suggestion, we have now rephrased this accordingly.

Competing Interests: No competing interests were disclosed.

Comments on this article

Version 2

Reader Comment 23 Jun 2020

Barney Duncan, Ex-Wellcome Biotechnology Ltd, Abermaw, Gwynedd, UK

Back in the 1980's Wellcome Biotechnology Ltd (owned & operated by the Wellcome Trust) expended much effort in trying to eliminate the use of blood fractions from nutrient media used for growing and maintenance of animal & human cell lines prior to innoculation with virus in the making of rabies and foot & mouth disease vaccines as well as interferon. At the time, it was found that without blood, cell growth and virus titres were poorer.

I have recently observed locally in North Wales 2 major clusters from the 2 Sisters Poultry processing plant on Anglesey and a meat processing plant in Wrexham. This caused me to look further into commonality of Covid outbreaks in other meat processing plants. It resulted in me coming across your paper.

I am mindful of the fact that the first outbreak was traced back to a food market in Wuhan China. The *coronavirus* likely jumped to people in a wet *market* there where meat, seafood, and live animals were handled.

I believe there may be real signifcance in the quantities of blood on workers overalls and working surfaces in slaughterhouses & meat processing factories. Blood deposits would surely provide a site where virus impregnated droplets from an infected worker could act as inoculum and allow virus to replicate rapidly

In consequence of these facts I would suggest the following recommendations for the next update

1. Add wet/cattle markets to the transmission settings list
2. Split food processing plant into two fractions meat and non-meat

Thank you to all participants/contributors to your paper. It is most creditable & worthwhile and I believe will prove most valuable line of research.

Barney Duncan
Chemical Engineer (ret'd)

Competing Interests: None unless you consider being a Wellcome pensioner influences my judgement but I'm sure Bill Castell (former CEO of Wellcome Biotechnology and Chairman of Wellcome Trust) could & would readily dispel any such notions !

Reader Comment 08 Jun 2020

David Henry, Bond University, Gold Coast, Queensland, Australia

This is an important topic. I am concerned about your search. I may have missed it, but I think having done this scoping exercise that you should rerun your searches with specific terms (and synonyms) for the settings of interests: schools churches, weddings, meatworks (lots of synonyms) etc. I am guessing that you will get a lot more hits. I don't think that 'transmission cluster' is a sufficiently sensitive term. I'd also like to see a PRISMA flow diagram.

Competing Interests: None

Version 1

Reader Comment 21 May 2020

María Margarita Ronderos Torres, Independent Consultant in Epidemiology, Colombia

I would like to draw to your attention the football match between Atalanta from Bergamo and Valencia from Spain on the 19th Feb at the San Siro Stadium in Milan. Aprox 40,000 fans from the Region attended the match. 35% of the Valencia team delegation when returning to Spain tested positive for COVID19. The region only went into lockdown on the 4th of March. This gave ample time (1.5 t 2 incubation periods) for household transmission with high intergeneration mix and known high elderly population. Further study is needed but this could be very well explain the explosion of cases that followed and is in line with your proposed explanation for super spread of the virus.

Competing Interests: NO competing interests

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On the concentration of SARS-CoV-2 in outdoor air and the interaction with pre-existing atmospheric particles

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ABSTRACT

The spread of SARS-CoV-2 by contact (direct or indirect) is widely accepted, but the relative importance of airborne transmission is still controversial. Probability of outdoor airborne transmission depends on several parameters, still rather uncertain: virus-laden aerosol concentrations, viability and lifetime, minimum dose necessary to transmit the disease. In this work, an estimate of outdoor concentrations in northern Italy (region Lombardia) was performed using a simple box model approach, based on an estimate of respiratory emissions, with a specific focus for the cities of Milan and Bergamo (Italy). In addition, the probability of interaction of virus-laden aerosol with pre-existing particles of different sizes was investigated. Results indicate very low (<1 RNA copy/m^3) average outdoor concentrations in public area, excluding crowded zones, even in the worst case scenario and assuming a number of infects up to 25% of population. On average, assuming a number of infects equal to 10% of the population, the time necessary to inspire a quantum (i.e. the dose of airborne droplet nuclei required to cause infection in 63% of susceptible persons) would be 31.5 days in Milan (range 2.7–91 days) and 51.2 days in Bergamo (range 4.4–149 days). Therefore, the probability of airborne transmission due to respiratory aerosol is very low in outdoor conditions, even if it could be more relevant for community indoor environments, in which further studies are necessary to investigate the potential risks. We theoretically examined if atmospheric particles can scavenge virus aerosol, through inertial impact, interception, and Brownian diffusion. The probability was very low. In addition, the probability of coagulation of virus-laden aerosol with pre-existing atmospheric particles resulted negligible for accumulation and coarse mode particles, but virus-laden aerosol could act as sink of ultrafine particles (around 0.01 μm in diameter). However, this will not change significantly the dynamics behaviour of the virus particle or its permanence time in atmosphere.

1. Introduction

The COVID-19 is the disease associated to the SARS-CoV-2 virus, that was initially reported in Wuhan (China), and successively it spread all over the world and was declared Public Health Emergency of International Concern by the World Health Organization (WHO). COVID-19 produces an acute respiratory disease and the main clinical manifestations are fever, cough, and dyspnoea. The spread of SARS-CoV-2 by contact (direct or indirect through contaminated surfaces) is widely accepted (WHO, 2020), but the relative importance of airborne transmission is controversial (Asadi et al., 2020; Bontempi 2020; Domingo et al., 2020; Jiang et al., 2020; Klompas et al., 2020; Morawksa et al., 2020; Prather et al., 2020; Zhang et al., 2020).

Viral respiratory infections are an important cause of morbidity and mortality worldwide. They may range from asymptomatic to acute diseases, in some cases life-threatening. Breathing, talking, coughing or sneezing release droplets, which can contain viral particles, in case of infected individuals. Airborne transmission of disease could occur by means of large droplets (>5 μm) released during respiration, coughing, and sneezing by contagious persons, or by solid residuals (called droplet nuclei or aerosol) of small droplets (<5 μm). Generally large droplets settle faster than they evaporate, contaminating the immediate vicinity of the infected individuals. In contrast, small droplets evaporate faster than they settle, leaving a residual which might contain virus aggregates, proteins, and mineral salts (Bourouiba, 2020; Asadi et al., 2020). They have a longer permanence time in atmosphere and can be

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transported and dispersed, by winds, over longer distances compared to large droplets.

Probability of airborne transmission depends on several parameters, still rather uncertain, such as virus-laden aerosol concentrations, viability and lifetime, and minimum dose necessary to transmit the disease (Contini and Costabile, 2020; Buonanno et al., 2020). This probability could be significantly different in outdoor and indoor community environments (such as hospitals, quarantine areas, commercial centres and so on) because there could be more intense sources (number of infected individuals) and negligible dispersion and transport conditions. In addition, the influence of meteorological parameters, such as UV radiation, that could deteriorate the virus reducing its lifetime in atmosphere (Ratnesar-Shumate, 2020) is significantly different when indoors and outdoors are compared. The analysis of Nishiura et al. (2020) in eleven COVID-19 clusters in Japan showed that the odds that a primary case transmitted COVID-19 in a closed environment was 18.7 times greater compared to an open-air environment. The analysis of Arav et al. (2020) showed that indoor airborne transmission in pre-symptomatic cases has a minor role compared to other transmission mechanisms.

Some studies (Conticini et al., 2020; Setti et al., 2020a, 2020b) suggested that outdoor airborne transmission could have played an important role during COVID-19 outbreak in northern Italy in winter 2020. The mechanism hypothesized is that virus-laden aerosol could interact with atmospheric particles creating clusters with pre-existing particles acting as carriers enhancing the persistence of the virus in atmosphere. This lead to the suggestion that atmospheric particulate matter concentrations is a kind of proxy to track virus dispersion in the atmosphere. There are not, up to now, specific data on the interaction of SARS-CoV-2 with pre-existing particles. However, it is known that atmospheric aerosols could contain biological material (bacteria and viruses) in certain conditions (Verreault et al., 2008; Deprés et al., 2012) and that the interaction between viruses and atmospheric particles could influence (increasing or decreasing) their infectivity (Groulx et al., 2018). Concentration and size distribution of both virus-laden aerosol and pre-existing particles strongly influence the probability of interaction.

Measurements of SARS-CoV-2 concentration in air (in both outdoor and indoor conditions) are relatively limited and some contrasting results were observed. In Liu et al. (2020) outdoor air samples collected in public areas in Wuhan (China) during the COVID-19 pandemic gave negative results, when tested for the presence of SARS-CoV-2 RNA with the exclusion of some specific crowded areas. Similar results were obtained from the measurements reported in Hu et al. (2020). Outdoor air samples collected in northern Italy (in the city of Bergamo) during the COVID-19 outbreak were positive to the presence of SARS-CoV-2 RNA in 23% of the measurement days, but no determination of concentration was provided (Setti et al., 2020a). Outdoor air samples simultaneously collected in Venice (northern Italy) and in Lecce (southern Italy) in May 2020 tested negative for the presence of SARS-CoV-2 RNA (Chirizzi et al., 2020). In indoor conditions, larger concentrations of virus-laden aerosols, compared to outdoor environments, were measured in some hospitals and quarantine areas (Hu et al., 2020; Liu et al., 2020; Santarpia et al., 2020). However, other studies reported negative results for indoor SARS-CoV-2 RNA detection even near COVID-19 confirmed patients (Faridi et al., 2020; Ong et al., 2020). In none of these studies was possible to ascertain the viability of collected viral particles.

This demonstrates that further studies, also using multidisciplinary approaches (Bontempi et al., 2020), are needed to investigate the role of virus airborne transmission in the spread of COVID-19. This work presents a study, using simple box models, of the average concentration of virus-laden aerosol due to respiratory emissions, in outdoor air in Lombardia region (northern Italy, severely hit by COVID-19) during winter 2020. In addition, the probability of interactions of virus-laden aerosol with pre-existing particles, an aspect previously not addressed in published papers, is investigated.

2. Characterisation of emissions

Sneezing, coughing, and respiration lead to release of large droplets and smaller aerosols. Conventionally, a distinctive size of 5 μm is used (Anderson et al., 2020) to separate droplets and aerosols. These emissions are saliva and secretions expelled (atomisation) from the upper airway, through the mouth or the nose (Morawska et al., 2009; Han et al., 2013; Bourouiba et al., 2014; Asadi et al., 2019; Bake et al., 2019; Hsiao et al., 2020; Martano, 2020). Large droplets tend to be removed quickly by dry deposition processes, and this is the reason of the suggested physical distance to minimise the risk of short distance contagion. Instead, small aerosols have a relevant fraction in the size range of the accumulation mode and they, or the droplet nuclei after evaporation (Asadi et al., 2020), could remain in suspension in air for longer time span compared to large droplets (Stadnytskyi et al., 2020).

Sneezing, mainly associated to symptomatic individuals, produces relevant number of large droplets. In Han et al. (2013) sneezing tests from human participants were performed and two size distributions including unimodal (aerosol geometric mean: 360.1 μm) and bimodal (aerosol geometric mean: 74.4 μm) were observed. Coughing is mainly associated to symptomatic individuals; however, it could also involve occasional coughs from asymptomatic individuals. Lindsley et al. (2012) showed that the amount of particles emitted in a cough varies widely from patient to patient in a range between 900 and 300,000 particles/cough with an average of 75,400 particle/cough (standard deviation 97,300) in patients with influenza and an average of 52,200 particles/cough (standard deviation 98,600) after recovery from influenza. In general, 63% of droplets emitted during coughing are in the respirable size range (Lindsley et al., 2012). Respiration and speaking, that are relevant also for asymptomatic individuals, are a source of fine aerosol (Morawska et al., 2009; Asadi et al., 2019), even if the intensity of the source is more limited compared to singing, shouting, coughing or sneezing. In Asadi et al. (2019), measurements during breathing showed a typical emissions from mouth and nose, in normal and fast breathing, lower than 3000 particles/h, with geometric mean diameter around 0.8 μm. Emissions during speaking and vocalisations are larger, between 3000 and 36,000 particles/h, with a geometric mean diameter (around 1 μm). Furthermore, emission intensity increases during loud speaking compared to whispering (Morawska et al., 2009; Asadi et al., 2019).

Respiratory droplets and aerosols released by infected individuals could contain viral particles. There are limited experimental evidences for the SARS-CoV-2, however, viral RNA in respiratory droplets and aerosols was observed for other respiratory viruses including other coronavirus (Milton et al., 2013; Yan et al., 2018; Leung et al., 2020). Milton et al. (2013) found a median emission of about 1200 RNA copies/h in respiration of influenza infected individuals, at one day from the onset of the disease, in aerosols (<5 μm) and about 50 copies/h in the coarse fraction (>5 μm) with a decrease in the successive days. Leung et al. (2020) found emissions, in the aerosol size fraction (<5 μm), in the range 4–4000 copies/h for other coronaviruses (NL63, OC43, 229E, and HKU1), 4–2000 copies/h for influenza, and 4–1200 copies/h for rhinovirus.

Another important aspect is the fraction of these respiratory virus-laden particles that are effectively viable and able to transmit the contagion. There are no information regarding SARS-CoV-2. However, the study of Yan et al. (2018) for the influenza virus found a small but statistically significant correlation among viable virus counting and RNA copies concentration in respiratory aerosols. The only study relative to the lifetime of SARS-CoV-2 in air is from van Doremalen et al. (2020) that found a half-life of about 1 h and that the virus can remain viable in air for about 3 h in laboratory controlled conditions. In outdoor conditions, the effective lifetime could depend from meteorological conditions, like temperature, humidity, and solar radiation that could degrade the virus (Ratnesar-Shumate et al., 2020).

The emissions of viral RNA copies can be estimated following the approach proposed in Buonanno et al. (2020): using mass balance between the viral load in mouth (sputum) and the volume of particles emitted during respiration and speaking. Specifically, the emission rate (E) is evaluated as:

$$E = C_V I_R \sum_{j=1}^{4} N_j V_j \quad (1)$$

where I_R is the inspiration rate, C_V the viral load in the mouth (in sputum), N_j the particle number concentration in the size range j, and V_j the volume of particle in the same size range. We considered four aerosol size ranges, as done in Morawska et al. (2009), and reported in Table 1. These were differentiated for diurnal and nocturnal hours. In diurnal hours, the particle concentrations are the average between unmodulated vocalization and voiced counting as done in Buonanno et al. (2020), instead, in nocturnal hours the particle concentrations refer to breathing activity.

The inhalation rates, averaged between females and males, are equal to 0.49 (resting), 0.54 (standing), 1.38 (light exercise), 2.35 (moderate exercise), and 3.30 m^3/h (heavy exercise) (Adams, 1993). For nocturnal hours the value at rest (0.49 m^3/h) was used, while, for diurnal hours the values of light exercise 1.38 m^3/h was used. The average of the two conditions (i.e. the daily average considering 12 h at rest and 12 h of activity) was 0.94 m^3/h. In order to develop a worst case scenario (WCS from now on), an increased inhalation rate (1.08 m^3/h) obtained considering 8 h per day at rest and 16 h per day of activity was also used.

Recent research studies investigated values of viral load in the mouth of COVID-19 confirmed patients finding highly variability, also related to the number of days from the onset of the disease. Wölfel et al. (2020) found an average viral load in sputum (C_V) of 7×10^6 copies/mL, with a maximum of 2.35×10^9 copies/mL in COVID-19 patients. Rothe et al. (2020) investigate one case of transmission from an asymptomatic individual, finding a high viral load in sputum of 10^8 copies/mL, confirming that asymptomatic individuals could be a potential source. A study on 82 SARS-CoV-2 infected individuals (Pan et al., 2020) found highly variable viral load in sputum with several cases having values between 10^8 copies/mL and 10^9 copies/mL and one case arriving up to 10^{11} copies/mL. Therefore, in this work, we consider a median value of C_V equal to 10^9 copies/mL.

With the assumptions discussed, the probability that a 10 μm droplet, prior to dehydration, contains one RNA copy is about 52% and this probability decrease to about 0.05% for a 1 μm droplet. The average estimated emission is 3613 RNA copies/h per infected individual. With the WCS assumptions, the estimated emission is 4770 RNA copies/h.

3. Estimate of outdoor concentrations using a box model

We used a simple box model approach to estimate average outdoor atmospheric concentrations of RNA copies of SARS-CoV-2 in the Region Lombardia as function of the number of infected individuals and using the average emissions estimated in Section 2. This model could give information regarding long-term averages and the effect of mixing height and ventilation (wind speed). Sophisticated models are available for analysis of pollutant transport and dispersion with high spatial and temporal resolution. However, they need, as input, data on emissions with high details on spatial and temporal resolutions. These details are not available for virus-laden aerosol emissions released during respiration and speaking, for this reason we choose to apply a simple box model. The box model is based on a large square of 150 km by 150 km covering almost all region Lombardia (Fig. 1) and having a height equal to the average mixing layer height. The mixing layer over the city of Milan (the largest city of Lombardia) was analysed in Ferrero et al. (2010) for the period 2005–2008 showing values, in winter, between 50 m and 500 m with typical median values around 250 m. The vertical profiles of particulate matter showed that 70% (for PM_1) and 80% (for PM_{10}) of particles were inside the mixing layer with rather uniform profiles. The analysis of the mixing layer height in Milan, done using measurements taken with the Sonic Detection and Ranging (SODAR) approach (Argentini et al., 1999), showed similar figures for the mixing layer height generally between 200 m and 300 m. Data provided by Arpa Lombardia, at the Milano Linate airport for the period February–April 2020, showed a median value of the mixing height of 240 m in February and an increase in March and April. Therefore, for the modelling purposes, we assumed an average mixing layer height of 250 m containing 75% of the RNA copies as a uniform profile. For the sake of simplicity and as precaution, coagulation and deposition processes were neglected.

Wind velocity near the ground (at 10 m height) in the area near Milan could be relatively small. Average winter value of 0.84 m/s was observed in Ferrero et al. (2010) and values between 0.5 m/s and 2.5 m/s were observed in Silibello et al. (2008). The analysis of the data from three meteorological stations in Milan, managed by the Regional Environmental Agency (Arpa Lombardia), gave a median wind velocity near the ground of 1.1 m/s in the period February–April 2020. Therefore, for the model, we assumed an average wind velocity of 2.2 m/s at a height of 125 m above the ground (i.e. in the middle of the mixing layer). This was obtained using the typical factor 2 for the ratio between the wind velocity at 125 m and that at 10 m in long-term average wind velocity profile in suburban areas (Contini et al., 2009). For the worst case scenario, we used a lower mixing height (60 m), about the minimum values (range 50 m–70 m) observed over Milan (Ferrero et al., 2010) in winter period, and a lower wind velocity of 1.2 m/s. The latter obtained as the first quartile (25th percentile) of the wind velocities measured at the different stations (0.9 m/s) multiplied by a factor 1.36 for the ratio between the middle of the mixing height (30 m) and the measurement height (10 m). A best case scenario (BCS from now on) was also analysed. This refers to better dispersion conditions compared to average or to WCS values. Specifically, in this case the mixing height selected was 400 m corresponding to the third quartile (75th percentile) of the measurements at the Milano Linate airport in February and roughly around the maximum values measured in Ferrero et al. (2010) and in Argentini et al. (1999). The wind speed selected was 4 m/s chosen as the third quartile of the wind velocities measured at the different stations (1.7 m/s) multiplied by a factor 2.35 for the ratio between the middle of the mixing height (200 m) and the measurement height (10 m).

Estimated average concentrations are reported in Fig. 2 as function of the number of infected individuals (including asymptomatic) for the entire region Lombardia (about 23,844 km^2 and 10 million inhabitants). These results have been used as boundary condition for the application of two other box models (Fig. 1): one of 10 km by 10 km covering the earth of the Milan town (about 1.4 million inhabitants); the second with an extension of 2 km by 2 km centred above the town of Bergamo (about 120,000 inhabitants) in which there was an epidemic outbreak. The results are reported in Fig. 3, again including the average, the WCS, and the BCS results. To put in perspective these results, it is useful to consider the officially counted cases furnished by the Italian Ministry of Health (www.salute.gov.it). It must be said that the numbers could be underestimated because they are related to the capacity of performing nasal/mouth swabs and to the absence of systematic testing on asymptomatic individuals. In the region Lombardia, the maximum number of active cases (i.e. the currently positive individuals) was 37,305 achieved on May 04, 2020. At the same date, the total number of cases in the region was 78,105. Data was not available at city level but total number of cases is available for each Italian province. The total number of cases in the

Table 1
Particle concentrations (cm^{-3}) for different size ranges separated for diurnal and nocturnal hours.

	Diam. 0.8 μm	Diam. 1.8 μm	Diam. 3.5 μm	Diam. 5.5 μm
Diurnal hours	0.4935	0.1035	0.073	0.035
Nocturnal hours	0.084	0.009	0.003	0.002

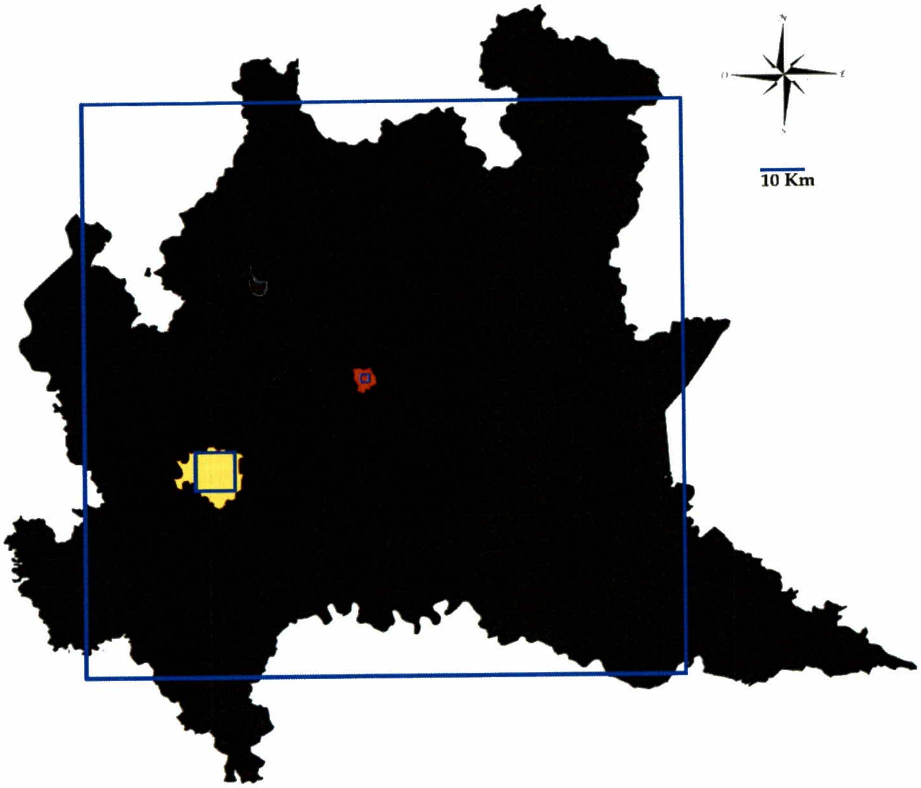

Fig. 1. Map of the region Lombardia with indication of the box model domain. In yellow the area of the city of Milan with the second box domain and in red the location of the city of Bergamo with the third box domain. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

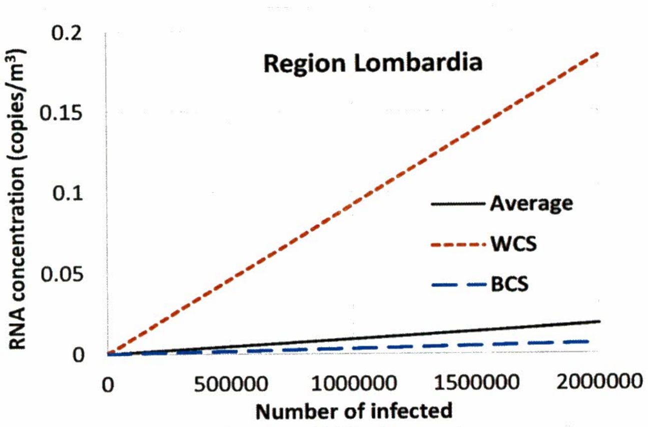

Fig. 2. Estimated average outdoor concentration as function of the number of infected individuals for the Region Lombardia. WCS is the worst case scenario calculated with larger emissions and lower wind speed and mixing height compared to average. BCS is the best case scenario calculated with larger wind speed and mixing height compared to average.

province of Milan at May 04, 2020 was 20,254 and in the province of Bergamo 11,538 cases were counted on the same date.

Estimated outdoor average concentrations are relatively small; this is in agreement with the few measurements available. Aerosols samples were collected in Wuhan (China) in February 2020 and found no detectable concentration of SARS-CoV-2 (<3 copies/m^3) with the exclusion of crowded sites, in which concentrations up to 11 copies/m^3 were observed. In the preprint of Hu et al. (2020), aerosol samples were collected in Wuhan (China) in outdoor public areas and in different hospitals (indoor), and no virus copies were found in outdoor samples in residential and public areas. In a recent work (Setti et al., 2020a), it is reported that traces of viral RNA were observed in 8 cases out of 34 (about 23% of positive cases) in PM_{10} daily samples collected in Bergamo (Northern Italy) during the spread of COVID-19 in the period between February and March 2020 even if concentrations were not quantified.

According to the data reported in Fig. 3, considering the average inspiration rate discussed in the previous Section and a number of infected individuals equal to 10% of the population (about 140,000 people for Milan and 12,000 people for Bergamo), it would be necessary, on average, 38 h in Milan (range calculated from BCS and WCS scenarios: 3.2–109 h) and 61 h in Bergamo (range 5.3–179 h) to inspire a single virus particle. Furthermore, it must be considered that a single virus particle could be not sufficient to transmit the infection. It can be used the concept of quantum, defined as the dose of airborne droplet nuclei required to cause infection in 63% of susceptible individuals. The conversion factor C_i defined as the ratio between one infectious quantum and the infectious dose expressed in viral RNA copies is not defined for SARS-CoV-2 in current scientific literature. However, referring to SARS-CoV-1, that has similar characteristics (van Doremalen et al., 2020), Watanabe et al. (2010) estimated the SARS-CoV-1 infectious doses received by residents in Hong Kong, corresponding to a C_i between 0.01 and 0.1 (Li et al., 2005; Yu et al., 2004). An average value equal to 0.05 was used for this work, as done in Buonanno et al. (2020). In the conditions stated above, the average time necessary to inspire a quantum would be 31.5 days in Milan (range calculated using BCS and WCS scenarios: 2.7–91 days) and 51.2 days in Bergamo (range 4.4–149 days). Therefore, the possibility to have airborne transmission in outdoor is low, almost negligible, if crowded areas and large gatherings of people are avoided.

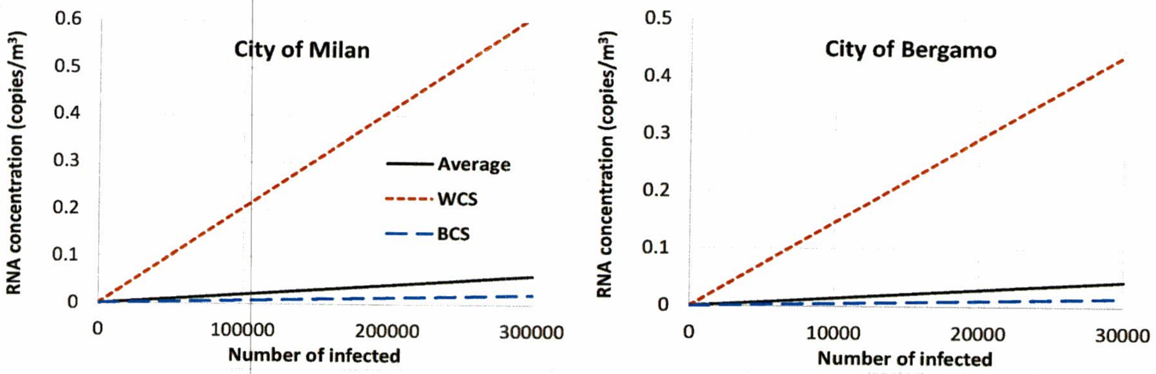

Fig. 3. Estimated average outdoor concentration as function of the number of infected individuals for the Milan and Bergamo cities. WCS is the worst case scenario calculated with larger emissions and lower wind speed and mixing height compared to average. BCS is the best case scenario calculated with larger wind speed and mixing height compared to average.

The situation is different in specific community indoor environments in which there is the possibility to have several infected individuals in restricted spaces. In these environments, the transport and dispersion, and consequently the dilution of airborne viral particles is more limited so that concentrations could be larger. In addition, the indoor environmental conditions (temperature, humidity, and absence of solar radiation) could be more suitable for virus survival compared to outdoors. Santarpia et al. (2020) observed the presence of viral RNA in the air in isolation rooms where patients with SARS-CoV-2 were treated. The analysis by Liu et al. (2020) of aerosol samples in two hospitals in Wuhan (China), during COVID-19 outbreak, showed high concentrations in patient care areas (up to 19 copies/m^3 in toilet facility) as well as in medical staff areas (18–42 copies/m^3). Liu et al. (2020) also performed size-segregated analysis of indoor virus in air showing that a relevant fraction of these virus-laden aerosols was in the fine size range (0.2–1 μm) that could remain in air for a longer time compared to the coarse fractions, thus being more suitable for airborne transmission. Faridi et al. (2020) collected ten air samples in the major hospital in Iran but detection of SARS-CoV-2 in air inside patient rooms was unsuccessful. In Hong Kong (Cheng et al., 2020) air samples taken near the mouth of an established COVID-19 patients tested negative for the presence of SARS-CoV-2, although the statistics was very limited. In Singapore, in an isolation area (with 12 air changes per hour) that housed three COVID-19 patients, samples were collected from surfaces and in the air (for 2 days). The air samples were negative even if traces of SARS-CoV-2 were found on the surfaces (Ong et al., 2020). Therefore, there are contrasting results that could likely arise also from the different measurement conditions and the different methodological approaches used. However, community indoor environments could represent a larger risk compared to outdoor (Contini and Costabile, 2020; Buonanno et al., 2020) and further studies are necessary to ascertain this aspect. It is advisable to use masks and frequent ventilation in these indoor environments to minimise risks.

In Setti et al. (2020b) it is hypothesized that the presence of SARS-CoV-2 RNA in outdoor air samples could represent a potential early indicator of COVID-19 diffusion. According to the results presented here, to have a probability of 50% of collecting a RNA copy in a standard 24 h air sample (55 m^3), it would be necessary a number of infected individuals, including asymptomatic, equal to about 45,000 in the city of Milan (3.2% of the population) and to about 6300 in the city of Bergamo (5.2% of population). Sporadically, RNA copies could be detected on filters for periods with low dispersion conditions as those of the worst case scenario. Therefore, it is doubtful that this approach could be efficiently used as an early indicator of COVID-19 diffusion or an early indicator of a recrudescence of the pandemic.

4. Interaction of virus-laden aerosol with pre-existing atmospheric particles

Johnson et al. (2011) showed that droplets size distribution emitted via coughing, sneezing, speaking and breathing are multimodal, with modes diameters around 200 μm and 2 μm. The small droplets evaporate rapidly leaving droplet residuals (virions) consisting of virus aggregates, proteins and mineral salts. At 50% relative humidity (RH), a 10 μm pure water droplet evaporates in about 0.15 s (Hinds, 1999). Xie et al. (2007) numerically calculated the evaporation and dispersion of respiratory droplets with a salinity of 0.9% w/v at ambient air temperature and different RH. A 20 μm droplet evaporates in less than 1 s. Redrow et al. (2011) carried out simulations on sputum droplets and numerical results indicate that a 10 μm sputum droplet will evaporate to become a droplet nucleus (3.5 μm) in 0.55 s at 80% RH and in 0.3 s at 50% RH. These virions have low sedimentation velocities and can remain suspended in atmosphere and, eventually, interact with pre-existing atmospheric particulate matter (PM). Setti et al. (2020a) suggested that SARS-CoV-2 RNA can be present on outdoor PM and in conditions of atmospheric stability and high concentrations of PM, SARS-CoV-2 could create clusters with outdoor PM and, by reducing their diffusion coefficient, enhance the persistence of the virus in the atmosphere. However, this preliminary result must be confirmed. We theoretically examined if atmospheric particles can scavenge virions.

4.1. Selected atmospheric particles and virions number concentrations and sizes

We estimate the atmospheric particles number concentration in winter in Bergamo, one of the most relevant COVID-19 outbreak in northern Italy, through the air quality measurements carried out by the Regional Protection Agency (ARPA-Lombardia). In winter 2020, the highest PM_{10} (94 μg/m^3) and $PM_{2.5}$ (70 μg/m^3) concentrations were measured in Bergamo at Via Garibaldi and Via Meucci air quality monitoring stations, respectively (Supplement information S1 shows daily PM_{10} and $PM_{2.5}$ concentrations). Unfortunately, the PM_1 fraction were not available for that period. However, Vecchi et al. (2008) measured in winter (December 2003–March 2004) a $PM_1/PM_{2.5}$ ratio of 0.6–0.9 and PM_1/PM_{10} ratio of 0.4–0.6 in three cities (Milano, Genoa, and Florence) with an average PM_1 value 0f 48.8 μg/m^3 in Milan, which would give an average estimate of $PM_{2.5}$ of 65 μg/m^3 (average ratio $PM_1/PM_{2.5}$ of 0.75) and a PM_{10} of 94 μg/m^3 (average ratio PM_1/PM_{10} of 0.5). Therefore, the obtained concentration values are in agreement with the highest measured concentrations obtained by ARPA in the 2020 winter period.

Rodriguez et al. (2007) obtained the particle number concentration in the ultrafine size range in Milan in the period November 2003–December 2003 with a Differential Mobility Analyzer connected to a Condensation Particle Counter. They found, in the ultrafine mode (N_{10}–N_{100}), about 1.5 × 10^{10} #/m^3 and about 5.5 × 10^9 #/m^3 in the accumulation mode (N_{100}–N_{800}) in agreement with results from Lonati et al. (2011) obtained during the cold season. The particle number concentration in the coarse fraction is obtained by adapting particle size distributions collected by an OPC (Grimm 107, Envirocheck model) in the urban area of Milan during 2011 and 2012 in winter and summer months (Cugerone et al., 2018) (see Fig. S2). Table 2 shows the estimated particle number concentrations in the three size modes: ultrafine, accumulation, and coarse. The last column gives the size intervals considered in each mode.

We consider the following sizes representative of the virions: 200 μm (large droplets), 2 μm (dry evaporated residuals) and 0.1 μm (single virus aerosol). Liu et al. (2020) detected peaks both in sub-micrometric and super-micrometric regions of virus particle concentrations in Wuhan (China). We also assume a number concentration of viral particles in the atmosphere of 10 copies/m^3 in each mode, which was the maximum concentration observed in crowded public areas in Wuhan (Liu et al., 2020).

4.2. Collision process

We theoretically examined if PM atmospheric particles can scavenge virus aerosol, through inertial impact, interception, and Brownian diffusion. We calculated the scavenging coefficients of a 10 μm settling particle by using Fuchs' formula (Fuchs, 1964) for the interception and Brownian diffusion scavenging efficiencies, and Park et al. (2005) formulation for impaction. The probability of the virions to be scavenged due to coarse PM_{10} settling particles resulted negligible because the total scavenging kernel was very low. In addition, the volume swept by falling atmospheric coarse particles will contain a limited number of virions particles, thereby lowering the probability of collisions to a negligible value even in the unrealistic condition of a fall of 1000 m. Detailed information is provided in Supplemental Information S2.

Attachment of virions to PM_{10} particles could also be possible by thermal coagulation (governed by Brownian diffusion) or by kinematic coagulation (governed by external forces). We will consider only thermal coagulation. The dry residual droplets of the second mode (2 μm) could be a sink for PM aerosols from the accumulation and ultrafine modes, because of thermal coagulation. The rate of collision of an atmospheric particle of size d_i with a fixed particle of size d_j (the dry residual droplet, which is supposed to have a negligible Brownian displacement) in the stationary case, is given by (Friedlander, 2000):

$$F = 2\pi D(d_i + d_j)N_0 \quad (2)$$

where F is the number of particles colliding per second, N_0 is the PM aerosol number concentration, d_i is the PM aerosol size (assumed 0.1 μm for accumulation mode and 0.01 μm for ultrafine mode), d_j is the droplet residual (2 μm) and D is the PM diffusion coefficient (5.2 10^{-8} m^2/s and 6.8 10^{-10} m^2/s for particle size of 0.01 μm and 0.1 μm respectively – Hinds (1999)). Results show a collision rate of about 5 × 10^{-5} collisions per second in the accumulation mode and 10^{-2} in the ultrafine mode. It would take more than one day for a collision to take place between a virion and an atmospheric aerosol particle in the accumulation mode, and only about 100 s for an ultrafine particle (0.01 μm). However, in this case the added mass to the virion would be negligible, as well as the changes in its size.

Finally, we consider the monodisperse coagulation of a single virus particle (0.1 μm) in the accumulation mode. For a monodisperse aerosol, the rate of change in number concentration is given by the Smoluchowski equation (Supplemental Information S2). The coagulation kernel of a 0.1 μm monodisperse aerosol is about 7.2 × 10^{-16} m^3/s, considering also the Fuchs correction (Hinds, 1999). Figure S4 (supplementary material) shows the particle size increase as a function of time. Even after 8000 s the particle diameter increase would be only 1.2% without consequences in the dynamic behaviour of virus-laden aerosol in the atmosphere.

Therefore, scavenging and thermal coagulation processes have negligible effect in the attachment of virions to atmospheric aerosol particles in the considered conditions. Other processes, like electrostatic attractive forces or turbulent coagulation, not taken into account in this study, could eventually be responsible for inclusion of virions into atmospheric particles.

Table 2
Atmospheric particle number concentrations for different size ranges: ultrafine, accumulation and coarse modes.

Mode	Urban particle number concentration (m^{-3})	Size range
Ultrafine	2 × 10^{10}	0.01–0.1 μm
Accumulation	6 × 10^9	0.1–0.8 μm
Coarse	3 × 10^6	1–3 μm

5. Conclusions

Average outdoor SARS-CoV-2 virus-laden aerosol concentrations, due to respiratory emissions of infected individuals in the Lombardia region (Northern Italy, Po valley pollution hot-spot), were investigated as function of the number of infected individuals (including asymptomatic). This was done using three simple box models: one covering all region, the second centred on the city of Milan, and the third centred on the city of Bergamo, where a COVID-19 outbreak was observed in March 2020. Emissions were estimated using a mass balance model for respiratory droplets and aerosols and the typical values of viral load observed in sputum. Calculations were done for average conditions and for best and worst case scenarios using different dispersion and ventilation assumptions compared to the average.

Outdoor concentrations in public area, excluding crowds, were very low, < 1 RNA copy/m^3, even in the worst case scenario and assuming a number of infects up to 25% of local population. In average terms, assuming a number of infects equal to 10% of the population, the time necessary to inspire a quantum would be 31.5 days in Milan (range calculated using BCS and WCS scenarios: 2.7–91 days) and 51.2 days in Bergamo (range 4.4–149 days). Therefore, the probability of airborne transmission due to respiratory aerosol is very low in outdoor conditions excluding public crowded areas. This transmission mechanism could be more relevant for indoor community environments, in which further studies are necessary to investigate the potential risks. Therefore, it is advisable to mitigate the risk for vulnerable people via frequent ventilation, air exchanges, and disinfection of exposed surfaces including those of air conditioning systems.

The probability of the viral particles to be scavenged from atmospheric aerosol particles, due to inertial, interception and Brownian capture mechanisms, was negligible. The probability of coagulation of virus-laden aerosol with pre-existing particles was very low for accumulation and coarse mode particles, even considering the maximum RNA copies concentrations observed in crowded public areas, and large concentrations of pre-existing particles typically observed in winter conditions in the Lombardia area. The virus-laden aerosol particles eventually present in atmosphere are dry residual of evaporated droplets (i.e. droplet nuclei) rather than agglomerate with pre-existing particles. There is a small, but not negligible, probability that virus-laden aerosol could act as sink of ultrafine particles (around 0.01 μm in diameter). However, this will not change significantly the dynamics of the virus particles or their permanence time in atmosphere.

Authors credit statement

F. Belosi and D. Contini conceptualized the study design; M. Conte,

G. Santachiara, and V. Gianelle contributed to data post-processing and calculations. All authors collaborated to interpretation of results, wrote, read, commented, and approved the final manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2020.110603.

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SARS-CoV-2 concentrations and virus-laden aerosol size distributions in outdoor air in north and south of Italy

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ABSTRACT

The COVID-19 disease spread at different rates in the different countries and in different regions of the same country, as happened in Italy. Transmission by contact or at close range due to large respiratory droplets is widely accepted, however, the role of airborne transmission due to small respiratory droplets emitted by infected individuals (also asymptomatic) is controversial. It was suggested that outdoor airborne transmission could play a role in determining the differences observed in the spread rate. Concentrations of virus-laden aerosol are still poorly known and contrasting results are reported, especially for outdoor environments. Here we investigated outdoor concentrations and size distributions of virus-laden aerosol simultaneously collected during the pandemic, in May 2020, in northern (Veneto) and southern (Apulia) regions of Italy. The two regions exhibited significantly different prevalence of COVID-19. Genetic material of SARS-CoV-2 (RNA) was determined, using both real time RT-PCR and ddPCR, in air samples collected using PM_{10} samplers and cascade impactors able to separate 12 size ranges from nanoparticles (diameter $D < 0.056$ µm) up to coarse particles ($D > 18$ µm). Air samples tested negative for the presence of SARS-CoV-2 at both sites, viral particles concentrations were <0.8 copies m^{-3} in PM_{10} and <0.4 copies m^{-3} in each size range investigated. Outdoor air in residential and urban areas was generally not infectious and safe for the public in both northern and southern Italy, with the possible exclusion of very crowded sites. Therefore, it is likely that outdoor airborne transmission does not explain the difference in the spread of COVID-19 observed in the two Italian regions.

1. Introduction

The pandemic of COVID-19 disease, due to the novel coronavirus SARS-CoV-2, was firstly reported in a cluster in Wuhan (China) in December 2019 and it rapidly spread all around the World. By June 27 (2020), infected cases reached 9,660,902 individuals and 491,195 deaths worldwide (https://covid19.who.int/). Starting from February 2020 it was clear that spread of the disease happened in specific outbreak areas and that significant differences were observed in COVID-19 prevalence and fatality rate in different countries and in different regions of the same country. In Europe, Italy was the first country severely hit, with the majority of cases observed in northern Italy and a much smaller number of cases observed in central and, especially, southern Italy. The rapid spread of SARS-CoV-2 and these spatial differences raised important questions regarding the mechanisms of transmission and the role potentially played by airborne transmission. It has also been suggested that airborne transmission could be responsible of the different COVID-19 prevalence observed in northern and southern Italy because of the different dispersion conditions in the two areas (Conticini et al., 2020; Setti et al., 2020). The Po Valley area in northern Italy is characterised, especially during winter period, by low wind speed accompanied to long periods of stable conditions with shallow mixing layers (Ferrero et al., 2010) and this limit both transport (because of limited ventilation) and dispersion of pollutants (because of limited turbulence) favouring large pollutant concentrations near the ground. Venice area, in the northeast of Italy is located near the sea and it has a typical circulation of air masses (Contini et al., 2015) with prevalent winds coming from NNE-NE directions (from the Alps

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mountains) mainly during the night and winds coming from SSE-SE during the day (from the Adriatic Sea). In contrast, Apulia region in southern Italy has a local meteorology characterised by greater solar radiation, compared to the Po Valley, increasing thermal turbulence and strong winds that favour transport and dilution of pollutants (Cesari et al., 2018). This difference in dispersion conditions could, in principle, influence the concentrations of virus-laden particles in outdoor air.

The spread of SARS-CoV-2 by contact (direct or indirect through contaminated surfaces) is widely accepted, however, the relative importance of airborne transmission is still controversial (Contini and Costabile, 2020; Domingo et al., 2020; Klompas et al., 2020; Morawska and Cao, 2020; Prather et al., 2020). Particles are emitted during sneezes, cough, respiration, speaking, singing, and shouting. In case of infected individuals, these particles could contain viable virus as happens for other respiratory viruses (Milton et al., 2013; Yan et al., 2018), including other coronaviruses such as NL63, OC43, 229E, and HKU1 (Leung et al., 2020). Sneezing and coughing are mainly associated with symptomatic individuals, however, emissions during respiration and speaking could happen also for asymptomatic individuals that have typically a viral load comparable to that of symptomatic patients (Lavezzo et al., 2020). Large respiratory droplets (conventionally with diameter $D > 5$ μm) settle faster than they evaporate, contaminating the immediate vicinity of the infected individuals. In contrast, small droplets (i.e. $D < 5$ μm) evaporate faster than they settle, leaving dry residuals (also called droplet nuclei) which might contain virus aggregates, proteins, and mineral salts (Asadi et al., 2020; Bourouiba, 2020). Droplet nuclei can remain suspended in air for longer time compared to large droplets and potentially contribute to airborne transmission (Allen and Marr, 2020; Morawska and Cao, 2020; Martano, 2020).

The probability of airborne transmission is different in outdoor and indoor environments and depends on several parameters; the most important are: (i) concentration and size distribution of virus-laden particles in air; (ii) the fraction of viable viral particles; (iii) the minimum viral load necessary to transmit the infection by inhalation in susceptible individuals. The lifetime of aerosolized SARS-CoV-2 could be 3 h under laboratory controlled conditions (van Doremalen et al., 2020), but it could be less in outdoors depending on the degradation of the virus due to local meteorology conditions (Ratnesar-Shumate et al., 2020). The minimum infectious dose, expressed in viral RNA copies inhaled, is not defined for SARS-CoV-2 in current scientific literature. However, referring to the studies on SARS-CoV-1, the dose of airborne virus copies (i.e. the quantum) necessary to cause infection in 63% of susceptible individuals is variable between 10 and 100 and it is possible to assume an average of 20 for SARS-CoV-2 (Buonanno et al., 2020). Current knowledge of concentration and size distribution of virus-laden aerosol in air is extremely scarce and contrasting results have been observed. In outdoors, measurements in Wuhan (Hu et al., 2020; Liu et al., 2020) showed concentrations below the detection limit, except for crowded areas; while, a study conducted in Bergamo (north of Italy) identified traces of viral RNA in 23% of the analysed PM_{10} samples without quantifying the concentrations (Setti et al., 2020). Concentrations of viral particles in indoor environments (mainly measured in hospitals and quarantine areas) seems to be higher (Hu et al., 2020; Liu et al., 2020; Santarpia et al., 2020) than those observed in outdoors. However, other studies showed no detectable concentrations even in proximity of quarantined COVID-19 patients (Faridi et al., 2020; Ong et al., 2020).

This work tries to fill the gap in knowledge regarding atmospheric concentrations of virus-laden particles in Italy. It is focused on the analysis of concentration and size distribution of SARS-CoV-2 virus-laden aerosol in outdoor air, comparing data collected in the Veneto region (north Italy) and Apulia region (south Italy), to asses a possible role of outdoor airborne transmission in the difference of COVID-19 spread rate observed in north and south of Italy. Measurements were performed simultaneously in the two regions, collecting air samples using both PM_{10} samplers and cascade impactors. SARS-CoV-2 presence was determined looking for genetic material (RNA) using both real-time RT-PCR and droplet digital PCR (ddPCR) methods (Corman et al., 2020; Suo et al., 2020).

2. Methods

2.1. Samples collection

Aerosol sampling was simultaneously carried out from 13th to 27th of May 2020, in two different Italian regions: Veneto (in the northeaster Italy) and Apulia (in the southeaster Italy). In Veneto, samples were collected at the Scientific Campus of Ca' Foscari University (45°28′47″N, 12°15′12″E, Mestre-Venice, Italy). The site is located in a working/residential area of Mestre, characterized by some major potential sources of particulate matter: high density residential areas; heavily trafficked roads; the industrial area of Porto Marghera, and an international airport (Squizzato et al., 2016). In Apulia, measurements were performed at the Lecce Environmental-Climate Observatory (ECO, 40.3°N 18.1°E; 36 m a.s.L.), located at the Institute of Atmospheric Sciences and Climate of the National Research Council (ISAC-CNR), inside the University Campus, at about 4 km (WSW) from the urban area of Lecce (Dinoi et al., 2020). The area, considered an urban background site, is affected by the integrated contribution of local anthropogenic sources (mainly road traffic and biomass burning) and by the long-range transport of natural and anthropogenic dust (Cesari et al., 2016, 2018).

During both sampling campaigns, two different samplers were used. In Venice, PM_{10} samples were collected using a low volume aerosol sampler (Skypost PM-TCR Tecora) equipped with a sequential sampler (Charlie) that operates at flow rate of 38.3 L min^{-1}. The sampling period for each sample was about 48 h, with a total average air volume of 110 m^3 per sample. A second simultaneous sampling was performed using a model 110 MOUDI cascade impactor with an average flow of 30 L min^{-1}. The inlet of the impactor has a nominal cut-off size of 18 μm, and the nominal cut-off sizes of the 10 impaction stages are: 10, 5.6, 3.2, 1.8, 1.0, 0.56, 0.32, 0.18, 0.10 and 0.056 μm. A back-up filter collected particles with aerodynamic diameter <0.056 μm. The sampling period for each impactor sample was about 6 days, with a total average air volume of about 250 m^3 per sample. This setup for data collection with the impactor was already successfully used in other measurement campaigns (Cesari et al., 2020).

In Lecce, the 48-h PM_{10} samples were collected using a low volume (38 L min^{-1}) sampler (SWAM 5a Dual Channel Monitor-FAI Instruments). Size-segregated samples were collected with a rotating model 120 MOUDI-II™ cascade impactor, operating at 30 L min^{-1} for about 6 days for each sample, to separate particles of different aerodynamic diameters in the same twelve intervals used in the Venice site.

At both sites, quartz fibre filters were used, after a decontamination process with a 4 h pre-combustion at 400 °C in a muffle furnace. In total, 12 PM_{10} filters (6 for each site) and 48 impactor filters (24 for each site) were collected. In addition, 4 field blank filters were obtained for each site, 2 for the PM_{10} sampler and 2 for the cascade impactor. All samples were vacuum packed in sealed sterile petri dishes and frozen at −25 °C immediately after sampling for conservation until the successive analysis. Laboratory analysis started within four days from the end of collection period.

It has been chosen to use both, PM_{10} samplers and cascade impactors, because it is important to know the size distribution of virus-laden particles to effectively understand the risk of airborne transmission. Sub-micrometric particles (in the accumulation mode <1 μm) could remained suspended in atmosphere for longer time compared to larger particles that have a greater deposition velocity. Therefore, particles in the accumulation mode could contribute to airborne transmission more than coarse particles and there are limited indication on this aspect in current studies. In Liu et al. (2020) in indoor environments in hospitals in China SARS-CoV-2 RNA was detected also in the size range 0.25–1 μm, instead, in the indoor measurements in Singapore hospitals (Chia et al., 2020) the smallest aerodynamic size fraction that contained detectable levels of SARS-CoV-2 was 1–4 μm.

2.2. Analytical method for RNA detection

RNA extraction for PCR experiments was achieved using Total RNA Purification Kit (Norgen Biotek Corp.) with a modified protocol to increase yield. Each filter was cut and placed inside a 2 mL centrifuge tube containing 1 mL of Phosphate Buffer Solution (PBS) pH 7.4. The tube was sealed and put in a sonicator water bath (Elmasonic S10H) for 30 min. Aerosol particles were separated from the quartz filter by centrifugation using a mini syringe placed in a collection tube. The obtained pellet, for each filter processed, was resuspended by 350 μL of supernatant, according to the manufacturer's protocol. The final eluted solutions (about 70 μL in total) were stored frozen at −80 ± 2 °C until PCR analysis that was performed within four days from extraction.

Molecular analysis for the detection of SARS-CoV-2 was carried out using real-time RT-PCR and Droplet Digital PCR (ddPCR) technologies. According to World Health Organization (WHO), real-time RT-PCR represents the gold standard for the diagnosis of SARS-CoV-2. Recently, ddPCR has demonstrated the best performance to detect SARS-CoV-2, because it reduces the false negatives (Suo et al., 2020).

Real-time RT-PCR for SARS-CoV-2 was carried out on a CFX96™ Real-Time system (Bio-Rad, Italy) using COVID-19 PCR DIATHEVA Detection kit (Diatheva, Cartoceto, PU, Italy) based on the WHO guideline (Corman et al., 2020). The COVID-19 PCR DIATHEVA Detection kit is a One-Step real-time reverse transcription (RT-PCR) multiplex assay based on fluorescent-labelled probe used to confirm the presence of SARS-CoV-2-RNA by amplification of RdRp and E gene. The kit provides all the reagents required for the analysis, PCR positive and PCR negative controls included. 5 μL of extracted RNA were added to 15 μL of Master mix for each sample and analysed according to kit instructions. Undiluted and 1:10 diluted samples were tested. In each run, two negative controls (molecular grade water) and a positive control were added. The interpretation of the sample results was done according to kit instructions. The limit of detection (LOD) of the COVID-19 PCR DIATHEVA Detection kit was previously defined through analysis of standard material RNA of SARS-CoV-2 and was equal to 10 copies/μL.

The ddPCR assays were performed using Bio-Rad SARS-CoV-2 ddPCR kit on QX200™ Droplet Digital™ PCR system (Bio-Rad, Italy). The Bio-Rad SARS-CoV-2 ddPCR is a reverse transcription (RT) droplet digital PCR (ddPCR) test designed for the qualitative detection of RNA from SARS-CoV-2. The assay includes the 2019-nCoV CDC ddPCR Triplex Probes and the One-Step RT-ddPCR Advanced Kit for Probes. The 2019-nCoV CDC ddPCR Triplex Probes contains specific oligonucleotide primers and probes for SARS-CoV-2 (N1 and N2), the same as those reported by Center for Disease Control and Prevention (CDC), mapping on regions of the virus nucleocapsid (N) gene into a single assay multiplex to enable a one-well reaction. The reaction mixtures were partitioned into approximately 20,000 droplets using a QX200 Droplet Generator™ (Bio-Rad, Italy) with the random dispersal of target nucleic acids into the droplets. The PCR assays were conducted in a C1000 Touch™ Thermal Cycler (Bio-Rad, Italy), according to kit instructions. After amplification, the droplets were individually assayed using the QX200™ Droplet Reader™. The fluorescence data were then analysed by the QuantaSoft v1.7 Software and QuantaSoft Analysis Pro v1.0 Software (Bio-Rad, Italy) to determine the presence of SARS-Cov-2 N1 and N2 in the specimen. The LOD of the Bio-Rad SARS CoV-2 ddPCR test was declared by the manufacturer in 0.625 copies/μL for targets N1 and N2.

The efficiency of the extraction procedure was evaluated through the recovery of a process control, a virus added prior to acid nucleic extraction. Mengo virus strain MC_0, supplied by Istituto Superiore di Sanità (ISS, Rome, Italy), is a murine virus of the *Picornaviridae* family, a non-enveloped positive-sense ssRNA virus. The efficiency of the extraction method was evaluated comparing the Ct values obtained for Mengovirus on samples extracts. In detail, 10 μL of Mengovirus was added prior to extraction to (i) 1 mL of PBS (reference sample); (ii) 1 mL of PBS with a blank filter and (iii) 1 mL of PBS with an exposed environmental filter. Each condition was run in duplicate. The detection of Mengovirus was carried out on a CFX96™ Real-Time system (Bio-Rad, Italy) using amplification conditions, primers and probe and reagents RNA UltraSense™ One-Step Quantitative RT-PCR System (Life Technologies, Carlsbad, California, US) (Pintó et al., 2009). Results indicate an average recovery of 49% (±5%).

3. Results and discussion

The outbreak of COVID-19 in Italy has resulted in 239,961 confirmed cases and 34,708 fatalities as of 27th June 2020. The transmission of SARS-CoV-2 was exceptionally severe in Veneto region (Fig. 1), with maximum active cases (i.e. currently infected individuals) of 10,800 on 16th April (about 10% of the overall Italian cases) over a population of 4.9 million people. Apulia region (southern Italy) reached the maximum of active cases on the 3rd of May with 2,955 cases (3% of the overall Italian cases) over a population of 4.0 million people. At the beginning of sampling period (13th May) Veneto and Apulia regions were affected by 5,020 and 2,322 active cases, respectively. These official numbers likely underestimate the real contagions. In Italy, cumulatively, 2.2–3.5 million individuals seem to have been infected as of May 4th, giving an attack rate of 3.6%-5.8% of the population (Flaxman et al., 2020).

During sampling, the average temperature was 19.6 °C (±1.4 °C) in Venice and 21.0 °C (±1.9 °C) in Lecce; the average relative humidity was 69% (±9.5%) in Venice and 56% (±9.8%) in Lecce. No precipitations were observed at the two sites during the sampling period.

PM_{10} and $PM_{2.5}$ concentration levels at the two sites are shown in Fig. 2. The national lockdown in Italy (indicated as phase I) included the period between 10th March and 17th May, even if there were some differences of restrictive measures during this period. Successively, there was the post-lockdown divided in what we called phase II and phase III in Fig. 2. Phase II was from 18th May until 3rd June and it was a re-opening with several limitations (cinema and theatres closed, travels among different regions were interdict, employees of public administrations remained diffusely on smart working). During phase III it was removed the restriction of travels among different regions and a significant fraction of employees of public administrations started to work on offices again. Our measurements started near the end of the phase I and continued during phase II of the post-lockdown period. The concentrations of PM_{10}, averaged over the whole measurement period, were 17.2 ± 5.2 μg m^{-3} (average ± standard deviation) in Venice, as provided by the Regional Agency of Environmental Prevention and Protection of Veneto (ARPAV) and 27.0 ± 14.8 μg m^{-3} in Lecce. The average concentrations of $PM_{2.5}$ were 9.8 ± 2.5 μg m^{-3} in Venice and 8.3 ± 2.3 μg m^{-3} in Lecce. High PM_{10} concentration are determined in Lecce at the beginning of sampling period (13–18 May 2020), while the values of $PM_{2.5}$ were comparable at the two sites (Fig. 2). This was due to a contribution of coarse particles due to African dust advection, that influenced only southern regions of Italy, contributing mainly to PM_{10} but not significantly to $PM_{2.5}$.

The existence of SARS-CoV-2 in aerosol samples was determined through the detection of its genetic material (RNA) in collected samples. Air samples were extracted at the Istituto Zooprofilattico Sperimentale della Puglia e della Basilicata (IZSPB), COVID-19 laboratory for the Apulia region. All extracts were firstly analysed using real-time RT-PCR and were negative showing no detectable presence of SARS-CoV-2 RNA. The detection limit of the method, referred to the extracted solutions, was 10 genome copies μL^{-1}. Successively, the same extracts were also analysed using the most sensitive technique available in the laboratory, the ddPCR, lowering the detection limit to 0.625 genome copies μL^{-1} and all samples tested negative for the presence of viral RNA.

The LODs (genome copies μL^{-1}) were transformed in thresholds for atmospheric concentrations of viral particles (expressed in copies/m^3)

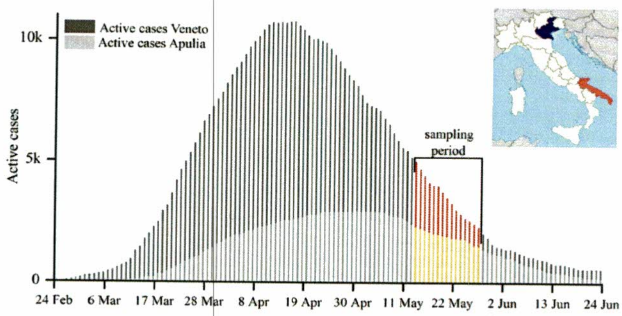

Fig. 1. Daily number of infected individuals observed in Veneto and Apulia regions during COVID-19 outbreak in Italy. The measurement sites are shown together with sampling period.

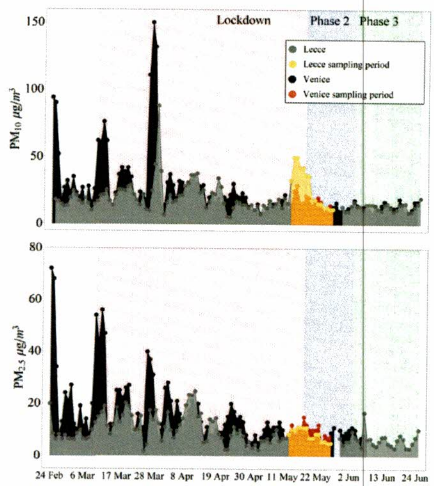

Fig. 2. Comparison of PM_{10} (top) and $PM_{2.5}$ (bottom) concentrations at the two sites evidencing the sampling period. The lockdown period (phase I) and the post-lockdown (phase II and II) are reported.

using the same approach employed for determination of concentration threshold of a chemical component of aerosol samples. Specifically, the LOD was transformed in a threshold of viral particles contained in a single filter (i.e. RNA copies per filter) considering the total volume of extraction solutions (about 70 µL) and the efficiency of the methodology (i.e. the recovery). These numbers were then normalised using the sampled volume to obtain the concentration threshold in copies m^{-3}. The concentration of virus-laden aerosol in PM_{10} samples was <0.8 copies m^{-3} at both sites during the sampling period. The size-segregated concentrations from nanoparticles ($D < 0.056$ µm) up to coarse particles ($D > 18$ µm) were <0.4 copies m^{-3} at both sites.

These results are comparable with those found in outdoor residential area in Wuhan (China) during the pandemic (Liu et al., 2020). Liu et al. (2020) collected air samples suing both samplers and cascade impactors, between February and March 2020, in public areas in outdoor as well as in indoor in quarantine areas. Samples collected in outdoor residential areas tested negative (<3 copies m^{-3}) with the exclusion of crowded zones in proximity of hospitals in which concentrations up to 11 copies m^{-3} were detected. Hu et al. (2020) found no viral RNA in air samples collected in residential community and an open public area (not crowded sites) in Wuhan (China). The analysis reported by Setti et al. (2020) shows that 23% of the 34 PM_{10} samples collected between February and March in outdoor in northern Italy (Bergamo) tested positive for SARS-CoV-2 RNA, however, concentrations of virus-laden particles were not evaluated. Results reported here suggest that in outdoor conditions, and excluding crowded areas, it is unlikely a role of airborne transmission of COVID-19.

The risk could be larger in community indoor environments where a certain number of infected individuals could be present in closed environments with limited ventilation. In this case, concentrations of virus-laden aerosol seems to be larger compared to outdoor, even if some contrasting results have been obtained. Liu et al. (2020) found SARS-CoV-2 RNA concentrations up to 42 copies m^{-3} in hospitals and quarantine areas in Wuhan (China) with a fraction of these viral particles in the fine size range (0.25–1 µm). Chia et al. (2020) found detectable SARS-CoV-2 genetic material in air in indoor COVID-19 patient care areas in Singapore in the size range >1 µm. Lednicky et al. (2020) found viable SARS-CoV-2 was isolated from air samples collected 2 to 4.8 m away from the patients in samples collected at the Student Health Care Center (SHCC, University of Florida, USA). Santarpia et al., 2020 found detectable concentrations of viral RNA in 63% of the samples collected in indoor at the Medical Center of the University of Nebraska (where COVID-19 patients were quarantined) with concentrations up to 2.86 copies L^{-1}). Instead, Faridi et al. (2020) did not detect SARS-CoV-2 in ten air samples collected in patient rooms of the largest hospital in Iran. In Singapore, air samples collected in a quarantine area with three patients tested negative for the presence of SARS-CoV-2 RNA (Ong et al., 2020). The possible larger risk of community indoor environments compared to outdoors could be mitigated by the use of face masks and the ventilation of closed spaces with outdoor air.

4. Conclusions

The results found indicate that outdoor atmospheric concentrations of SARS-CoV-2 were very small (<0.8 copies m^{-3}) in both northern and southern Italy. The same applies for each size range investigated with the impactor, which gave virus-laden aerosol concentrations <0.4 copies m^{-3}. The measurements were taken in a period when the number of active cases (i.e. infected individuals) in the two regions were not at the maximum values (Fig. 1), thereby, it is possible to assume that higher concentrations (up to a factor 2 on average for Venice) were likely be present during the period of maximum spread of contagion. The average typical threshold of about 20 virus copies is necessary (Buonanno et al., 2020) to make a quantum of virus (i.e. the dose of airborne droplet nuclei that, if inhaled, is able to cause infection in 63% of susceptible persons). Considering a typical inhalation rate of about 1 m^3/h, as average between rest and light exercise (Adams, 1993), the concentrations would be low to spread the contagion via airborne transmission even assuming the mentioned increase of a factor 2.

Therefore, it is possible to conclude that outdoor air in residential and urban areas was generally not infectious and safe for the public in both northern and southern Italy, with the possible exclusion of very crowded sites. In addition, outdoor airborne transmission of SARS-CoV-2 was likely not the main cause of the difference in diffusion rates of COVID-19 observed during outbreaks in north and south of Italy.

Author contributions

D. Contini, A. Gambaro, G. La Salandra conceptualized the study design; E. Barbaro, E. Gregoris, M. Feltracco collected samples in Venice and contributed to data post-processing; M. Conte, A. Dinoi collected samples in Lecce and contributed to data post-processing; D. Chirizzi, G. Ciccarese, G. La Salandra, and G. La Bella carried out the laboratory tests. All authors collaborated to interpretation of results, wrote, read, commented, and approved the final manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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