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Review: What is the evidence for indoor transmission of SARS-CoV-2?

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[3]Conducted literature searches
[4]Coordination of screening, quality assessment and data extraction (epidemiology and microbiology)
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Introduction

It is well established that SARS-CoV-2 is readily transmitted in indoor environments; however questions remain about the relative importance of different transmission mechanisms, the risks associated with different indoor environments and activities and the role of ventilation and plumbing systems in mitigating or amplifying transmission.

These questions are complex and cannot be answered by one discipline in isolation. It is necessary to draw on a range of disciplinary knowledge and expertise in order to build a complete picture. We therefore sought to identify and integrate evidence from three distinct disciplines, each of which has distinct strengths and limitations: **mechanistic approaches** model the physical behaviour of small and large droplets under different climatic conditions. As modelling studies, they are based on assumptions and do not account for all aspects of the physical reality, and are limited in what they can tell us about the viability or infectivity of particles in 'real-world' conditions. Also included in this category are experiments which investigate particle emission during speech or breathing. These studies can help us understand the mechanisms of droplet and aerosol formation, but do not normally test for the presence or infectivity of viruses in such particles, and so are limited in what they can tell us about the role of these as routes of transmission. **Epidemiological approaches** interrogate descriptive data on case clusters from the early stages of the pandemic to try to identify the most likely routes of transmission. A limitation of these approaches is that data are limited and that observational findings have a high risk of bias. **Microbiological experiments** investigate the viability of the virus under different environmental and time periods under controlled laboratory conditions. The limitation of this sort of study is that the results may not be generalizable to the real world.

The purpose of this review is to integrate evidence from epidemiological, microbiological and fluid mechanics studies on the transmission of SARS-CoV-2 in indoor settings. We set out to answer ten specific questions:

1. What evidence is there for aerosolised transmission?
2. What evidence is there for faecal-oral transmission?
3. What evidence is there regarding the role of ventilation systems in indoor transmission?
4. What evidence is there regarding the role of plumbing systems in indoor transmission?
5. What evidence is there regarding transmission via different indoor surfaces (materials and specific objects)?
6. What evidence is there for the transmission in indoor residential settings?
7. What evidence is there for transmission in indoor workplace settings?
8. What evidence is there for transmission in other indoor settings (social, community, leisure, religious, public transport)?
9. Do particular activities convey greater risk (e.g. shouting, singing, eating together, sharing bedrooms)?
10. What evidence is there for the appropriate length of distancing between people?

Methods

We divided our search strategy into two searches to focus on indoor transmission. The first search focused on epidemiological and microbiological approaches. We searched PubMed and medRxiv between 20-05-2020 and 21-05-2020 (LG). The second search focused on mechanistic and numerical simulation approaches. We searched PubMed, medRxiv, arXiv, Scopus, WHO COVID-19 database, Compendex & Inspec between 20-05-2020 and 21-05-2020 (MD). Full search details are in Appendix 1.

We included articles reporting data on any indoor setting (e.g. domestic, workplace, leisure, public transport, healthcare); any indoor activities (e.g. singing, eating together, sharing living environments); any potential means of transmission (e.g. airborne transmission, surface transmission (fomites), faecal-oral transmission); mechanisms which may influence transmission in indoor environments (e.g. ventilation, air conditioning, plumbing systems). We excluded studies investigating transmission in healthcare settings; studies focusing purely on the clinical characteristics of cases; studies focusing on covid-19 prevention interventions and studies set in schools (transmission in schools and among children is the focus of a separate ongoing review which can be found here [insert link]). Screening criteria for mechanistic studies were adapted to include articles reporting data on any respiratory virus and numerical simulation studies focusing on the mechanisms of transmission.

Title and abstract screening was conducted by one reviewer (LG, GN, RM, PK, TH). Rejections were reviewed by a second reviewer (LG, GN, RM, PK, TH). Full text screening of each article was conducted by one reviewer (LG, GN, PK, TH, RN, KO). A second reviewer screened all excluded full texts (LG, GN, PK, TH, RN, KO). Data extraction and quality assessment for each article was conducted by a single reviewer (LG, GN, PK, TH, RN, KO).

Data extraction was limited to a minimal set of required data items. Due to the highly heterogeneous nature of the study types identified by the searches, it was not possible to assess quality using validated risk of bias tools. Instead, each study was critically appraised individually. Mechanistic and numerical simulation studies were appraised by an expert in the field (IMV, SBC, EP, SZ, MS). Data were synthesised narratively, and meta-analysis was conducted where indicated. Using the GRADE system (Guyatt et al., 2008) a single reviewer RM graded the certainty of the evidence overall.

In the absence of suitable existing tools, we developed a quality appraisal tool for numerical simulation studies from three sources (American Society of Mechanical Engineers, 2009, 2018; Roache, 2009). We developed a quality appraisal tool for experimental studies (microbiological and fluid mechanics) from several sources (CAMARADES, 2020; Public Health Agency of Canada, 2014; Young & Solomon, 2009). We adapted a quality assessment and data extraction tool for epidemiological outbreak cluster studies from the Joanna Briggs Institute checklist for critically appraising case series (Joanna Briggs Institute, 2020). For other epidemiological study designs, we used Critical Appraisal Skills Programme (CASP) checklists (Critical Appraisal Skills Programme, 2020). Critical appraisal tools are available in appendix 2.

Data on secondary attack rates in households were meta-analysed using a fixed effects model in R 3.6.3 (R Core Team, 2020) using the *rma.uni()* function in the metafor package (Viechtbauer, 2010). I^2 and Cochrane's Q were calculated to assess heterogeneity. For consistency, the same function was used to estimate confidence intervals for SAR in individual studies that were not included in pooled estimates.

Because most of the microbiological evidence on this topic was generated from hospital-based studies, we included microbiological studies which collected samples from both clinical and non-clinical settings. To maximise the transferability and generalisability of these findings to non-clinical indoor settings, we excluded results of samples collected in areas of the hospital such as operating theatres and ICU where aerosol-generating procedures are routinely carried out.

This is an update of two previous rapid reviews (UNCOVER 002-01 – focusing on indoor vs. outdoor transmission, full description of methods available here, literature search conducted 31 March 2020; and UNCOVER 002-02 – focusing on outdoor transmission, full description of methods available here, literature search conducted 30 April 2020). In summary, UNCOVER 002-01 sought publications of any study design providing data on indoor or outdoor transmission and of published or pre-published status, excluding publications from nosocomial settings, modelling data, animal models and articles providing commentary but no data. UNCOVER 002-02 re-examined articles identified by the initial review, using revised screening criteria to include articles that reported data on outdoor transmission, airborne transmission, surface transmission, environmental factors affecting virus transmission (e.g. virus viability and persistence on different surfaces and at different temperatures and levels of humidity). We excluded papers exclusively about indoor transmission. We also excluded statistical modelling studies. A specialist in fluid dynamics (IMV) joined our team to provide expert critical appraisal of the evidence on aerosol vs. droplet transmission through the air.

Results

After the removal of duplicates, a total of 1573 articles were identified. 1447 were rejected through title and abstract screening and a further 60 were rejected at the full-text screening stage and quality assessment stage. 33 did not provide data relevant to study questions, 26 were poor quality and 1 article could not be retrieved. 66 articles were retained for analysis. This information is summarised in the PRISMA diagram (Figure 1). The overall quality of the evidence was graded as low. We report the results on each of our review questions separately, integrating the epidemiological, microbiological and fluid mechanics evidence.

What evidence is there for aerosolised transmission?

We know that SARS-CoV-2 is transmitted through respiratory droplets ejected from the mouth or nose of an infected individual. Transmission occurs either when these droplets come into direct contact with mucosal membranes in the eyes, nose or mouth of a susceptible individual, or when deposited on a surface and successively transferred to a mucosal membrane through physical contact (i.e. touching a contaminated object and then touching one's nose, mouth or eyes). Respiratory droplets range in size from 0.1 µm (roughly the size of a dust particle) to 1 mm (Mittal, Ni, & Seo, 2020). They behave differently depending on their size.

Larger droplets (diameters of the order of 100 - 1000 µm) follow a ballistic trajectory (i.e. they fall mostly under the influence of gravity) and reach the ground within approximately 1 second and without time to evaporate (Bourouiba, 2020; Bourouiba, Dehandschoewercker, & Bush, 2014; Xie, Li, Chwang, Ho, & Seto, 2007). It is well-established that SARS CoV-2 is transmitted through larger respiratory droplets. The distance they travel before landing depends on (among other factors) how they were generated: those generated from speaking land 1 metre or closer to the speaker (Xie et al., 2007), droplets generated by coughing travel about 2 metres (Bourouiba et al., 2014) before landing, and those generated by sneezing can travel for 8 metres before falling to the ground (Bourouiba, 2020).

Smaller droplets (diameters of the order of 10 µm or smaller) fall so slowly through the air that they have time to evaporate. These very light, desiccated particles, or aerosols, can then remain suspended in the air, potentially indefinitely. Aerosolised particles are ejected in a jet-like flux which, within a few metres, increases in diameter from a few centimetres to tens of centimetres. This flux bends upwards because it is warmer than the surrounding air. Aerosolised particles can travel long distances on air flows – for example, from room to room or in and out of windows within a building or from coach to coach within a train - before eventually landing.

There are also intermediate-sized particles (diameters of the order of 10 – 100 µm), which share some properties of both large droplets and aerosols: being larger and heavier than aerosols, they will fall to the ground more quickly. They may carry a smaller infectious dose than large droplets (Tellier, Li, Cowling, & Tang, 2019).

While the possibility of CoV-2 transmission through aerosol is still uncertain, Li et al demonstrated with numerical simulations that a COVID-19 outbreak in a restaurant in Guangzhou, China, is compatible with aerosol transmission (Y. Li et al., 2020). Furthermore, there is substantial evidence that virus-laden aerosol dispersion played a role in the 2003 SARS-CoV outbreak (Li, Duan, Yu, & Wong, 2005; Li Y., Huang X., & I.T., 2005; Wong et al., 2004; I. T. Yu et al., 2004; I. T. S. Yu, Wong, Chiu, Lee, & Li, 2005). One illustration of the potential risk posed by aerosols was an experiment which showed that aerosols emitted above mid-body height would tend to remain at vertical elevations corresponding to the breathing levels of seated passengers in an aircraft carriage (Poussou & Plesniak, 2012). Aerosol dispersal has also been shown to be possible within a train coach (Yang, Li, Li, & Tu, 2018), between buildings (I. T. Yu et al., 2004) and between floors of a building (Li et al., 2005; Niu & Tung, 2008).

Evidence from fluid mechanics experiments and simulations show that very small, virus-sized particles can remain suspended in the air in aerosols for long periods of time. This does not, however, tell us whether live virus can survive in this state. Laboratory-based microbiological studies have been conducted to explore this question. van Doremalen et al found that the virus remained viable for 3 hours in the aerosolised state (median half-life 1.09 hours, 95 % credible interval 0.64, 2.64), indicating that aerosolised transmission is theoretically possible (van Doremalen et al., 2020). To investigate whether aerosolisation of viral particles might actually be occurring, several hospital-based studies (Guo et al., 2020; Liu, Ning, et al., 2020; Santarpia et al., 2020; Wu et al., 2020; Zhou et al., 2020) and one study which considered modes of transmission in the Diamond Princess cruise ship (Yamagishi, 2020) collected and analysed environmental samples. Four studies found that SARS-CoV-2 RNA was detectable in the air using air sampling techniques, which is suggestive of aerosolised particles. Positive results included hospital hallways, patient rooms, and pharmacy areas, all of which were accessible by the general public, highlighting potential exposure and transmission risk (Guo et al., 2020; Liu, Ning, et al., 2020; Santarpia et al., 2020; Zhou et al., 2020). Interestingly, Liu et al sampled areas surrounding the two hospitals in their study and found virus RNA detection at the entrance of two department stores where patients frequently walked past to access the hospital, highlighting potential aerosol transmission from clinical to non-clinical areas (Liu, Ning, et al., 2020). However, two studies failed to detect SARS-CoV-2 via air samples (Wu et al., 2020; Yamagishi, 2020). It is also important to note that the detection of viral RNA does not necessarily imply the presence of live virus. Viral RNA can be either live virus, which poses an infectivity risk, but equally it can be fragmented dead virus which does not have the ability to cause infection. To establish whether environmental samples of SARS-CoV-2 pose an infection risk, it is not sufficient simply to detect viral RNA: we need to know whether the virus is viable, a question which can only be answered using laboratory culturing methods (Leland & Ginocchio, 2007).

Taking this evidence together, aerosolised transmission is theoretically possible. SARS-CoV-2 can survive in aerosolised form for up to 3 hours (van Doremalen et al., 2020) so it is *theoretically* possible for an uninfected person to inhale particles of aerosolised virus even after the source of the infection has departed the scene. Whether or not this poses an *actual* infection risk depends, among other factors, on the quantity of virus required to trigger infection, a question which currently remains unanswered. We examined observational epidemiological studies for evidence suggestive of aerosol transmission. The evidence is of poor quality and lacks detail. Most of the epidemiological evidence is compatible with droplet/fomite transmission through close contact. A large outbreak in Washington State, USA, linked to a choir practice is potentially consistent with aerosolised transmission. Xu et al conducted a careful analysis of the outbreak on the Diamond Princess cruise ship (Xu et al., 2020). After 6 February, when passengers were confined to their cabins, passenger transmission was limited to close contacts (sharing a cabin). The absence of any cross-room transmission among passengers after the quarantine period began supports the hypothesis that transmission was via droplets/fomites and not airborne via the air conditioning system.

What evidence is there for faecal-oral transmission?

Other human coronaviruses can be transmitted via the faeces of infected individuals, so it is important to establish whether SARS-CoV-2 can be transmitted in this way. We reviewed seven case series (Jiehao C, Jing X, & Daojiong L, 2020; Ling et al., 2020; W. Wang et al., 2020; Wölfel et al., 2020; Wu Y, Guo C, & Tang L, 2020; Zhang, Wang, & Xue, 2020; W. Zhang et al., 2020), two case reports (Holshue et al., 2020; Tang et al., 2020), and one non-systematic review article (L. Y. Li et al., 2020). Emerging evidence suggests that gastro-intestinal (GI) symptoms in SARS-CoV-2 may be the result of viral invasion of ACE2 expressing enterocytes of ileum and colon, as seen with SARS-CoV (Zhang H, Kang Z, & Gong H, 2020). However, GI symptoms are less common in SARS-CoV-2 than in SARS-CoV or MERS: a review of published studies found that compared to 30% patients with gastro-intestinal symptoms in SARS and MERS, diarrhoea and vomiting occurred in 5.6% (range of estimates 2 - 34), and 4.5 % (range 1 - 10) patients of COVID -19, respectively (L. Y. Li et al., 2020). All ten articles we reviewed reported detection of SARS-CoV-2 viral RNA in faecal samples using RT-PCR. Estimates of the proportion of adult cases with viral RNA detectable in faeces range from 29 % (Ling et al., 2020) to 82 % (W. Wang et al., 2020), although because the studies used different parameters and time frames, it is not possible to draw any firm conclusions from these data. Four case series (Jiehao C et al., 2020; Ling et al., 2020; Wu Y et al., 2020; J. Zhang et al., 2020), one case report (Tang et al., 2020) and one review article (L. Y. Li et al., 2020) reported that SARS-CoV-2 faecal samples still tested positive after throat swabs had turned negative, implying the potential for prolonged infectivity. Again, though, sample sizes are small and differences in the way that data were collected and reported makes direct comparison difficult. Four case series (Jiehao C et al., 2020; Wu Y et al., 2020; W. Zhang et al., 2020) and one case report (Tang et al., 2020) found that the presence of SARS-CoV-2 viral RNA or live virus in faecal samples was unrelated to the presence of gastro-intestinal symptoms. We also reviewed three studies which collected environmental samples, two in clinical settings (Liu, Ning, et al., 2020; Santarpia et al., 2020) and one in a cruise ship (Yamagishi, 2020), which suggest that aerosolisation of viral particles may occur through toilet flushing. Two studies highlighted the detection of SARS-CoV-2 RNA on the floor surrounding toilets used by confirmed cases, which is consistent with aerosolisation of virus particles through toilet flushing (Santarpia et al., 2020; Yamagishi, 2020). The highest concentration of SARS-CoV-2 RNA detected in air samples by (Liu, Ning, et al., 2020) was in a patient toilet cubicle.

Taken together, these results suggest that there is potential for transmission via the faeces of an infected person, either through the contamination of surfaces or through aerosolisation; however they should be interpreted with caution. The detection of SARS-CoV-2 viral RNA in faecal samples does not mean that live virus is present or that patients are infectious. Two studies tested faecal samples for the presence of live virus. One detected live virus in all four samples tested (W. Wang et al., 2020); however in a virological analysis of nine cases of COVID-19 who were all part of a single epidemiological cluster in Munich, Germany, Wölfel et al were able to isolate infectious virus from samples taken from patients' throats and lungs, but not from faecal samples, even though these samples had high concentrations of viral RNA (Wölfel et al., 2020).

Conclusions – Transmission mechanisms

Based on the evidence available to date, the most common transmission route for SARS-CoV-2 is person-to-person, short-range spread via mostly respiratory droplets that directly reach recipients either through the air or through touching contaminated surfaces and then transferring the virus on the hands to mucosal membranes. Evidence from numerical simulation and fluid mechanics studies, microbiological laboratory studies and environmental sampling studies suggest that aerosol transmission is theoretically possible and is another potential source of transmission. Evidence from an outbreak linked to a choir practice is also consistent with this. SARS-CoV-2 is potentially transmissible via the faecal-oral route but there is no direct evidence of this.

What evidence is there regarding the role of ventilation systems in indoor transmission?

Air currents, amplified by ventilation systems, are responsible for the dispersal of both aerosols and large droplets within buildings. This can happen in various ways. For example, a study by Chen et al showed that even small differences of temperature between two rooms can cause a two-way flow between the rooms (Chen, Zhao, & Yang, 2011). Li et al conducted a real-scale experiment and a computational fluid dynamics simulation in a restaurant, which showed that there was higher particle concentration in the presence of air recirculation, generated by cold air injected into the room by the air conditioning unit and warm air generated by the people eating in the restaurant (Y. Li et al., 2020). A study by Sung et al discovered that tracer gas was efficiently distributed from room to room along a building corridor, aided by strong air currents entering through open windows (Sung et al., 2018). In a study showing that an upper apartment can contain up to 7 % of the air from the one beneath it, Niu and Tung provide evidence that airborne transmission through ventilation is possible (Niu & Tung, 2008). A study by Li et al showed that during the 2003 SARS outbreak in Hong Kong the ventilation system in the densely populated Amoy Gardens apartment complex contributed to the dispersal of the virus among flats and across different floors and buildings in the complex (Li et al., 2005).

However, ventilation systems are also likely to decrease the concentration of viral particles in the air: the above study on the role of ventilation systems in the SARS outbreak at the Amoy Gardens complex also suggested that the ventilation system played a fundamental role in mitigating the outbreak by diluting the concentration of virus particles (Li et al., 2005). Yu et al demonstrated, through numerical simulations, that increasing air exchange rates decreases the risk of contamination in a semi-open hospital ward (H. C. Yu, Mui, Wong, & Chu, 2017). In short, ventilation is likely to decrease virus concentration but increases aerosol dispersal, therefore it is likely to decrease virus transmission risk near the source and increase virus transmission risk further away from the source.

What evidence is there regarding the role of plumbing systems in indoor transmission?

There is no direct evidence that SARS-CoV-2 is transmissible via infected faeces; however until this is demonstrated definitively, it is important to understand the potential role of defective plumbing systems, which are thought to have played a role in the transmission of SARS-CoV in a large outbreak in the Amoy Gardens residential complex in Hong Kong in 2003. During this outbreak, 321 cases in the apartment complex were linked to faecal-oral transmission (L. S. Hung, 2003) and there is compelling evidence that this was exacerbated by deficient indoor plumbing systems. Subsequent simulations have demonstrated that aerosols can be generated in vertical soil stack pipes when toilets are flushed and can enter a room due to the suction generated by the ventilation system (Gormley, Aspray, Kelly, & Rodriguez-Gil, 2017; H. C. K. Hung, Chan, Law, Chan, & Wong, 2006; Jack, Cheng, & Lu, 2006; I. T. Yu et al., 2004). In this context, contaminated aerosols originating from breath or sewage are more likely to be warmer than the surrounding air, and so are more likely to travel from the lowest to the highest floors of a building than vice versa. The lower the environmental air temperature, the more significant the aerosol transmission from the lowest floors to the highest floors (Lim, Cho, & Kim, 2011). The study by Gormley et al implies that a functioning U-trap is the only mechanism preventing transportation of aerosolised particles (Gormley et al., 2017). Yet this study states that U-trap failure/depletion can result from a variety of mechanisms and is not unusual. The authors report that most of the buildings where defective U-traps have been found are high occupancy and that two such buildings in the UK are hospitals.

Conclusions: Role of ventilation and plumbing systems in transmission

Air currents are responsible for the dispersal of both aerosols and large droplets within buildings, between different rooms and even between different floors. This dispersal can be amplified by a variety of factors, including ventilation and air conditioning systems, differences of temperature between rooms and air currents entering through open windows.

However, ventilation systems are also likely to dilute the concentration of viral particles in the air and thereby to play a potential role in decreasing transmission. Ventilation systems are likely to decrease virus transmission risk near the source but to increase virus transmission risk further away from the source.

There is no direct evidence that SARS-CoV-2 is transmissible via infected faeces; however until this route of transmission is definitively ruled out, it is important to note that aerosolised particles can be generated in vertical soil stack pipes when toilets are flushed. These particles can then enter a room via ventilation systems and defective plumbing systems – specifically U-trap failure/depletion. This is of particular relevance in high occupancy and high-rise buildings.

What evidence is there regarding transmission via different indoor surfaces (materials and specific objects)?

A fomite is any object that may be contaminated with infectious agents and serve in their transmission. Virus particles from aerosols, droplets or people's hands can contaminate surfaces in this way. If they are then touched by a susceptible person and transported by hands into mucosal membranes, they can cause infection. We looked at the research evidence for fomite transmission in order to establish the length of time live virus survives on different surfaces and under different environmental conditions and to identify the sorts of objects and surfaces commonly contaminated.

Microbiological evidence on the persistence of live virus on different surfaces or materials comes from two sources: laboratory-based studies which investigate the survival of live virus under carefully controlled environmental conditions ((Chin et al., 2020; Sun et al., 2020; van Doremalen et al., 2020) and studies which collect environmental samples using swabbing techniques and then test them for detection of viral RNA using reverse transcription polymerase chain reaction (RT-PCR) (V. C. C. Cheng et al., 2020; Hirotsu, Maejima, Nakajima, Mochizuki, & Omata, 2020; Jiang et al., 2020; Santarpia et al., 2020; Wu et al., 2020; Yamagishi, 2020; Ye et al., 2020; Zhou et al., 2020). As highlighted above, viral RNA can be either live virus, which poses an infectivity risk, but equally it can be fragmented dead virus which does not have the ability to cause infection. To establish whether environmental samples of SARS-CoV-2 pose an infection risk, it is not sufficient simply to detect viral RNA: we need to know whether the virus is viable. Live virus can be detected through laboratory culturing methods, which give an indication of the presence of live virus in suitable cell lines (Leland & Ginocchio, 2007). Three of the studies attempted to culture live virus from environmental swabs (Santarpia et al., 2020; Yamagishi, 2020; Zhou et al., 2020).

In a laboratory-based study, van Doremalen et al investigated the persistence of SARS-CoV-2 on a variety of different surfaces (van Doremalen et al., 2020). The researchers found that the virus persisted for up to 72 hours after application to plastic (median half-life 6.81 hours, 95 % credible interval5.62, 8.17) and up to 48 hours after application to stainless steel (median half-life 5.63 hours, 95 % credible interval 4.59, 6.86). The virus was found to be more stable on these surfaces than on copper (median half-life 0.774 hours, 95 % credible interval 0.427, 1.19) and cardboard (median half-life 3.46 hours, 95 % credible interval 2.34, 5). After 4 hours, no viable SARS-CoV-2 was detectable on copper and after 24 hours no viable SARS-CoV-2 was detectable on cardboard. Chin et al found that SARS-CoV-2 was more stable on smooth surfaces. No infectious virus could be detected on day 4 (glass and banknote) or day 7 (stainless steel and plastic) (Chin et al., 2020). In the same study the researchers investigated stability at different temperatures and found SARS-COV-2 to be highly stable and able to survive for long periods at low temperatures (4°C), but sensitive to heat: at 4°C, there was only around a 0·7 log-unit reduction of infectious titre on day 14, whereas at 22°C it was detectable at 7 days but not at 14 days. With the incubation temperature increased to 70°C, the time for virus inactivation was reduced to 5 minutes. Using a strain from the nasal-pharyngeal swab of a clinically confirmed COVID-19 patient in Shanghai, Sun et al measured the stability of SARS-CoV-2 in wet (in 100 uL culture medium) and dry (10 uL supernatant on filter paper) environments at room temperature (22°C) each day for 7 days, as well as its stability under acidic conditions to mimic the gastric environment (pH2.2) (Sun et al., 2020). Although the virus survived for 3 days in both the wet and dry environments, the dry environment was less favourable for virus survival. Viable virus was not observed after 4 days in either the wet or dry condition. The authors concluded that COVID-19 virus is highly infectious and high concentrations can also survive under an acidic condition, such as the stomach. Overall, these studies indicate that under highly controlled laboratory conditions, low temperatures and wet environments are most conducive to persistence of SARS-COV-2.

We examined evidence from six hospital-based studies in China (Wu et al., 2020; Ye et al., 2020), Hong Kong (V. C. C. Cheng et al., 2020), Japan (Hirotsu et al., 2020), UK (Zhou et al., 2020) and USA (Santarpia et al., 2020) and two studies from non-clinical settings: a cruise ship moored in Japan (Yamagishi, 2020) and a quarantine hotel in China (Jiang et al., 2020). All eight studies used real-time PCR methods for detection of SARS-CoV-2 from surface samples. This involved detection of viral RNA through targeting different parts of the virus (Sironi et al., 2020). Studies utilised different target genes, all specific for SARS-CoV-2. The RdRp gene assay has been reported to have the highest analytical sensitivity (H. Wang et al., 2020). Furthermore, some studies reported the quantities of viral RNA in each sample, which gives an indication of the amount of virus present. This is relevant for assessing viral load.

The six hospital-based studies collected swab samples from patient rooms and high-touch surfaces. Telephones, keyboards, doorknobs, elevator buttons, TV controls, water dispenser buttons and toilet floors were the most common areas of SARS-CoV-2 contamination in the hospital-based studies. Zhou et al detected viral RNA in both clinical and public areas of the hospital, although this was significantly more likely to be found in areas of the hospital occupied by covid-19 patients (OR 0.5, 95 % confidence interval 0.2-0.9, p=0.025) (Zhou et al., 2020). They detected viral RNA on 114/218 (52.3 %) of surfaces. These swabs were taken from several different objects, including chairs, computer keyboards and alcohol hand sanitiser dispensers. Hirotsu et al collected 15 environmental samples from rooms occupied by an infected patient (Hirotsu et al., 2020). The samples were collected after thorough cleaning of the area. They did not detect any viral RNA, which provides evidence on the effectiveness of cleaning to reduce transmission. Ye et al also suggested that because they collected samples after new environmental cleaning protocols were introduced, environmental contamination of SARS-CoV-2 may have been previously higher in this Wuhan hospital at the earlier stages of the pandemic and could have contributed to the initial high transmission rate amongst healthcare workers and visitors (Ye et al., 2020).

Two studies investigated virus detection in non-clinical settings: a quarantine hotel in China (Jiang et al., 2020) and a cruise ship in Japan (Yamagishi, 2020), both of which had confirmed SARS-CoV-2 cases in the rooms/cabins. In the cruise ship cabins viral RNA was present on highly touched surfaces in cabins such as the room phone, TV remote and the doorknob before and after spraying with 5 % hydrogen peroxide solution, indicating that wiping surfaces may be more effective at disinfection than only spraying surfaces (Yamagishi, 2020). High virus detection was also observed on bed pillows. Furthermore, Jiang et al detected high viral load on the pillowcase and bed sheet in the room of one confirmed case (Jiang et al., 2020). The results from the cruise ship study also found no difference ($p > 0.05$) in virus detection between symptomatic and asymptomatic case cabins (Yamagishi, 2020). These studies highlight hotspots of virus detection in hospitality settings used to quarantine suspected cases and could be important for infection control in non-clinical settings, to avoid future transmission/outbreaks.

Three studies quantified the amount of virus present by reporting viral load/gene copy data. All three found minimal amounts of viral material, indicating that although the virus was present, there were low levels of contamination in the environment (V. C. C. Cheng et al., 2020; Santarpia et al., 2020; Yamagishi, 2020).

Three studies attempted to culture live virus from environmental samples. Zhou et al were unable to culture any live virus from either air or surface samples and the results in the other two studies were inconclusive (Santarpia et al., 2020; Yamagishi, 2020; Zhou et al., 2020). In these studies, it is not known what time had elapsed between environmental contamination and sample collection: if there was a considerable delay, this could potentially explain the difficulties in isolating live virus. Transport time to the laboratory (Yamagishi, 2020), methodological errors (Yamagishi, 2020), low RNA levels in the samples (Zhou et al., 2020), or virus that is infectious but not culturable in the laboratory (Zhou et al., 2020) have all been suggested as potential reasons for the failure to culture live virus from viral RNA samples. Three studies highlighted the absence of viral culturing methods as an obstacle in demonstrating the infectivity of SARS-CoV-2 positive samples (Guo et al., 2020; Jiang et al., 2020; Liu, Ning, et al., 2020).

Sze-To et al investigated the indirect contact infection risk associated with fabric and non-fabric surfaces (Sze-To, Yang, Kwan, Yu, & Chao, 2014). The researchers used a technique called Lagrangian simulations, which is a method of tracking the trajectories of particles. They concluded that non-fabric fomites (e.g. hard floors or tables) present higher risk than fabric ones (e.g. carpets).

There is very limited epidemiological evidence on this subject. A contact tracing report on a church outbreak in Singapore reported by Pung et al found that one of the three secondary cases did not have direct contact with the presumed index cases, but occupied the same seat as one of them at a prayer meeting directly following the service but not attended by the index cases (Pung et al., 2020).

Conclusions: transmission via different surfaces and objects

Laboratory-based experiments demonstrate that the length of time SARS-CoV-2 remains viable on surfaces depends on the type of surface and the environmental conditions. Evidence suggests that the virus prefers smooth, non-fabric surfaces, low temperatures and damp conditions. It survives for longer on plastic (detectable for up to 72 hours, with a half-life of approximately 7 hours) and stainless steel (detectable for up to 48 hours, with a half-life of approximately 6 hours) than on cardboard (detectable for up to 24 hours, with a half-life of approximately 3.5 hours). Copper has strong anti-viral properties, with no viable virus detectable after 4 hours and a half-life of less than an hour. Experiments investigating the impact of temperature on the virus show that it highly stable at 4° C (still detectable at 14 days). At 22° C it is detectable at 7 but not at 14 days. At 70° C it is undetectable after 5 minutes. Although the virus persists in both the wet and dry environments, experiments have shown that the dry environment is less favourable for survival. It can also survive under acidic conditions, such as the stomach.

Studies analysing swabs taken from various surfaces and high-touch objects in clinical and non-clinical settings occupied by infected cases detected viral RNA on telephones, keyboards, doorknobs, elevator buttons, TV controls, water dispenser buttons, chairs, toilet floors, bedding and hand sanitiser dispensers. However all three studies which quantified the amount of virus present found minimal amounts of viral material. We found only one epidemiological study which reported explicitly on fomite transmission: a case of secondary transmission through occupying the same seat as the index case, without the infected person coming into direct contact with the index case.

What evidence is there for the transmission of COVID-19 in indoor residential settings?

Twelve studies included data on transmission in residential settings (Bi et al., 2020; Burke et al., 2020; Chan et al., 2020; Chaw et al., 2020; H. Y. Cheng et al., 2020; Fan et al., 2020; Hu et al., 2020; Kim & Jiang, 2020; McMichael et al., 2020; Roxby et al., 2020; Tobolowsky et al., 2020; Xu et al., 2020). These can be split into those focusing on private households and those focusing on communal living facilities, such as care homes and shelters for people experiencing homelessness. Six studies reported on household transmission, with 4 providing data on secondary attack rates (defined as the probability that an infection occurs among susceptible people within a specific group, such as a household or close contacts (Liu, Eggo, & Kucharski, 2020)) (SARs) (Table 1). We conducted a meta-analysis of the SARs for these four studies. The pooled SAR for people living in the same household was 11 % (95 % CI 9, 13) (figure 2).

We found six studies reporting data on transmission in settings with some degree of communality (e.g. communal dining rooms, bathrooms, dormitories or social spaces; food prepared communally or served by staff; staff providing assistance with daily living). These studies involved very different types of population, so it was not appropriate to conduct a meta-analysis. Two articles reported on outbreaks in nursing homes in USA (McMichael et al., 2020) and South Korea (Kim & Jiang, 2020). Tobolowsky et al reported on an outbreak in three affiliated day/overnight shelters for people experiencing homelessness in USA (Tobolowsky et al., 2020); Xu et al described the outbreak on the Diamond Princess cruise ship quarantined off Japan (Xu et al., 2020); Roxby et al reported on an outbreak in an assisted and independent living community in Washington State, USA (Roxby et al., 2020); and Fan et al reported on Chinese nationals repatriated from Iran in early March 2020 (Fan et al., 2020). Four of the studies provided data for estimating SARs amongst residents (Table 2 - data are reported separately in table 3 for staff working in these settings). The SARs for people living in communal settings were significantly higher than the SARs for households. The highest - 62.3 % (95 % confidence interval 54.0, 70.6) - was in the US care home (although ascertainment of the denominator was not precise). SARs amongst residents of the homeless shelters and passengers on the cruise ship were similar to each other (18 %; 95 % CI 12.6, 23.3 and 19.6 %; 95 % CI 17.6, 20.3 respectively). The lowest SAR - 3.8 %, 95 % confidence interval 0, 7.9 - was in the senior assisted and independent living community in the USA, where elderly residents lived largely independently in separate apartments. The study by Fan et al on Chinese nationals repatriated from Iran provided very little information on potential exposures; however it reported a significant positive correlation between the incidence of COVID-19 infection and residing in a dormitory ($\chi2 = 4.088$, $p = 0.043$) (Fan et al., 2020).

What evidence is there for the transmission of COVID-19 in indoor workplaces?

Ten studies reported on transmission among workers or at workplaces: care home workers (McMichael et al., 2020), cruise ship crew (Kakimoto et al., 2020; Xu et al., 2020), staff at a shelter for people experiencing homelessness (Tobolowsky et al., 2020), staff at an assisted and independent living community for the elderly (Roxby et al., 2020), workers at meat/poultry processing plants (Dyal et al., 2020); shop workers (Pung et al., 2020); workers at a customer call centre (Kim & Jiang, 2020); workers at a government ministry (Kim & Jiang, 2020) and unspecified workplaces or schools (Burke et al., 2020; Chaw et al., 2020). Five of these studies provided data for the estimation of SARs among staff (Table 3). They range from 3.2 % (95 % CI 0, 7.6) for staff working in the assisted and independent living community to 21 % (95 % CI 8.1, 34.0) for staff working in the shelters for people experiencing homelessness. SARs for staff and residents were not significantly different in the assisted and independent living community or in the shelter; however SARs were significantly higher for residents than for staff on the cruise ship ($p = 0.000017$) and in the care home ($p < 0.00001$). The final study reported in table 3 is from a US contact tracing study, in which the close contacts of travel-related cases at the beginning of the pandemic were traced. No detail about the types of workplace or occupations is provided. There were no secondary cases. We found three workplace studies which did not present sufficient data to estimate SARs but nevertheless provide insight into workplace transmission. Dyal et al present data collected by the US Centers for Disease Control (CDC) on workplace outbreaks in meat and poultry processing facilities across the USA (Dyal et al., 2020). The article presents data from 17 of 23 US states reporting at least one such outbreak, expressing the number of cases in each state as a proportion of all meat and poultry workers employed in the state. In other words, the denominator includes workers in facilities which have not experienced an outbreak, thus under-estimating the impact of such an outbreak on an individual facility. By April 2020 there had been a total of 4913 cases in a total workforce of 130578 in the 17 states who provided full data (3.8 %, 95 % CI 3.7, 3.9). CDC identified a range of key drivers: difficulty in maintaining the 2 metre social distance on the production line at break times and while entering/exiting the facility; difficulty implementing covid-19-specific disinfection guidelines; socioeconomic challenges related to poverty, such as people continuing to work whilst ill, especially where attendance is incentivised and workers living in overcrowded, multigenerational households; communication challenges such as the inaccessibility of health and safety training to non-English speakers and to non-literate workers; sharing of transportation to work; and adherence to correct usage of face coverings. Kakimoto et al report data from part-way through the outbreak among crew of the Diamond Princess cruise ship anchored off Japan (Kakimoto et al., 2020). Results point to the role of close living and working conditions in transmission. Fifteen out of the initial 20 cases among the crew were in food service workers and 16 lived on the same deck. Eight of the 20 shared cabins with fellow crew members and as of 4 March 2020 five of these had developed covid-19. Pung et al conducted a small contact tracing study of an outbreak in Singapore connected with the visit of a tour group of around 20 tourists from China to a complementary health products shop and to a jewellery shop (Pung et al., 2020). Four assistants in the complementary health products shop and one assistant in the jewellery shop were subsequently confirmed to have COVID-19. Finally, Kim and Jiang report limited information on two workplace outbreaks in South Korea: one in a customer call centre, where 164 people became ill and another in the Ministry of Oceans and Fisheries, where there were 30 cases (Kim & Jiang, 2020). No information is provided about the numbers of close contacts working in these environments, nor on the nature of the workplace involved in the Ministry of Oceans and Fisheries outbreak.

What evidence is there for the transmission of COVID-19 in other indoor settings (social, community, leisure, religious, public transport)?

We found six epidemiological studies reporting on transmission related to social, religious, community or leisure settings. Four studies report on a total of eight outbreaks related to religious gatherings or churches (Chaw et al., 2020; Kim & Jiang, 2020; Pung et al., 2020; Yong et al., 2020). One study reports on two outbreaks in gyms (Kim & Jiang, 2020) and one investigated evidence for transmission in a clinic waiting room (Burke et al., 2020).

Chaw et al report on outbreaks related to the Tablighi Jama'at religious gathering in Malaysia and a subsequent similar gathering in Brunei (Chaw et al., 2020). Both were extended, communal overnight gatherings. Estimated SARs were 25.3 % (95 % CI 15.5, 35.2) and 14.8 % (95 % CI 5.3, 24.3) respectively. Pung et al describe a contact tracing study in a church in Singapore (Pung et al., 2020). The presumed index cases were a couple visiting from China who had attended a service at the church. Three of the 142 contacted attendees at the service subsequently tested positive for SARS-CoV-2 (SAR 2.1; 95 % CI 0, 4.4). Two further articles report on transmission via church services but do not provide sufficient data to estimate SARs. Yong et al describe linked outbreaks in two churches in Singapore (Yong et al., 2020). The presumed index cases at the first church were two Chinese national travellers from Wuhan who attended a service. Five people subsequently became ill. The index case at the second church was a church employee, who is presumed to have contracted the virus whilst hosting a family celebration attended by a symptomatic case from the first church outbreak. Sixteen people became ill. Finally, Kim and Jiang describe four outbreaks linked to churches in South Korea: Shincheonji church (149 cases at the time of publication), River of Grace community church (67 cases), Onchun church (43 cases) and Dongan church (29 cases) (Kim & Jiang, 2020).

This study also reports on two outbreaks connected with gyms in South Korea. At the first, Cheonan-si gym facility, 63 people were reported as contracting the virus. At the second, Cheonan/Asan-si gym, there were 35 reported cases. No further details are provided (Kim & Jiang, 2020).
The study of early travel-related cases in USA by (Burke et al., 2020) followed up 95 people who spent time in clinic waiting rooms with affected individuals. No cases were detected.

Conclusions: transmission in different indoor settings

We found evidence of transmission in domestic, workplace and community/leisure settings. Most of the studies we found were conducted early in the pandemic, when effective and accurate contact tracing was possible. We found higher secondary attack rates in communal residential contexts (care homes, shelters for homeless people, cruise ship) than in households.

We found evidence of workplace outbreaks in a care home, an assisted and independent living community, shelters for homeless people, shops, meat and poultry processing factories, a cruise ship, a business conference, a customer call centre and a government ministry; however few of the studies provided enough detail to allow meaningful comparison of the risks in different settings. Nevertheless, many of the workplace settings where outbreaks have occurred are characterised by close physical contact and prolonged time spent in crowded indoor spaces. Evidence from the study by Dyal et al on outbreaks in meat and poultry processing plants also highlights the role health inequalities and inadequate social protection play in relation to people continuing to work whilst ill, overcrowded housing and transportation to and from work and inadequate health and safety communication and training, particularly for non-English speakers and non-literate workers (Dyal et al., 2020).

Do particular activities convey greater risk (e.g. shouting, singing, eating together, sharing bedrooms)?

Because SARS-CoV-2 is transmitted through respiratory droplets, activities that increase the emission of droplets convey greater risk. Evidence from fluid mechanics experiments enables us to partition activities into four levels of risk based on the number of droplets ejected (Asadi, Wexler, & Cappa, 2019; Chao et al., 2009; Duguid, 1946; Xie, Li, Sun, & Liu, 2009; Zayas et al., 2012), the least risky being quiet breathing. The next riskiest level is heavy breathing or singing, followed by coughing and finally sneezing. There is a very significant (orders-of-magnitude) difference in risk between each of these levels and the next. There is also evidence that pronouncing some sounds (e.g. need, see) results in the emission of more droplets than others (e.g. hot, mood); however these risk differences are relatively small compared to the risks between, for example, coughing and singing (Asadi S, Wexler AS, Cappa CD, Barreda S, & Bouvier NM, 2020).

We found six descriptive epidemiological studies which describe transmission via daily living activities among people living together in households, although none of the studies provides sufficient detail to pinpoint the risks associated with specific activities. In a contact tracing study of 9 travel-related cases in USA early in the pandemic, Burke et al report on 2 cases resulting from household transmission, both in the spouses of cases (Burke et al., 2020). They suggest that daily living activities such as sharing beds, bathrooms, eating together, face to face contact and spending time in the car together are likely to increase the risk of transmission. Family members cohabiting during case isolation were advised where possible to use separate bedrooms and bathrooms, limit time in same room and affected family members were advised to wear a mask when in the same room as others. The study reported strong compliance in general with these measures, with some evidence that there was higher compliance with isolation measures and less time spent with affected family members in households where there was no transmission. In a high quality, well-conducted study Chaw et al investigated attack rates for different relationships living together in households (Chaw et al., 2020). They found that the highest secondary attack rate was amongst spouses, at 41.94 % (95 % CI, 26.42, 59.24). This compares with 14.12 % (95 % CI, 8.27, 23.08) for children and 2.03 % (95 % CI, 0.69, 5.79) for other relatives (parents, siblings, grandparents, housekeepers, etc.). Cheng et al compared secondary attack rates in household members with non-household family members (H. Y. Cheng et al., 2020). The secondary attack rate in people living in the same household was 19.44 % (95 % CI 9.75, 35.02) compared to 10.64 % (95 % CI 4.63, 22.6) in relatives living apart, although the difference is not significant. Bi et al investigated factors associated with transmission for 391 primary cases in Shenzhen, China (Bi et al., 2020). They tested and followed up 1286 close contacts for 14 days and then retested. Close contacts were defined as people living in the same apartment, sharing a meal, travelling together, or interacting socially with the index case from 2 days before the onset of symptoms. A multivariate regression analysis estimated the OR for household contacts as 6.3 (95 % CI 1.5, 26.3), travelling together 7.1 (95 % CI 1.4, 34.9) and eating meals together 7.13 (95 % CI 0.73, 69.32). The OR for having contact "often" with the index case (compared to having rare or moderate contact) was 8.8 (95 % CI 2.6, 30.1). Two studies (Chan et al., 2020; Hu et al., 2020) did not provide sufficient data to estimate SARs but nevertheless provided narrative evidence on transmission within families living together and on the risks of transmission within households when cases are asymptomatic, and thus not aware of the need for enhanced hygiene and social distancing at home.

The six studies we found which report on transmission in communal contexts are consistent with the conveyance of risk through close contact daily living activities, although again, insufficient detail is provided to identify risks associated with specific activities. It is striking that the SAR reported in the care home (McMichael et al., 2020) is an order of magnitude higher than that reported in the senior assisted and independent living community (Roxby et al., 2020), a much less communal setting, where elderly residents lived largely independently in separate apartments. It is important to note, however, that although the age profile in the two settings is likely to be similar, the residents of the nursing home were likely frailer. Also, ascertainment of the denominator in the care home study was not precise, so these results are uncertain.

Conclusions: transmission risk associated with different activities

Our study found evidence that within households, the risk of transmission was higher between spouses than between other types of relative. We found evidence that effective social distancing to prevent transmission within households is possible, particularly if the isolated person is able to use a separate bathroom, a separate bedroom, minimise time in the same room as other family members and wear a mask where this is unavoidable. However, such measures are challenging in overcrowded housing and do not take into account that many cases are asymptomatic so individuals will be unaware that they are sick and potentially transmitting the virus to others.

We found evidence that activities associated with a higher risk of transmission are those where people gather in close proximity indoors for prolonged periods. Churches and religious gatherings, sharing meals and bathing facilities, close physical contact and activities such as singing together have all been reported in conjunction with outbreaks. In contrast, there have been fewer reports of transmission in relation to more casual, short term social contact, although this may be because such contacts are subject to recall bias and harder to track and trace. Risks associated with travelling with an affected case are difficult to evaluate – the evidence from these studies was limited and non-specific.

What evidence is there for the appropriate length of distancing between people?

There is a general consensus that the main route of CoV-2 transmission is through person-to-person short-range transmission, which occurs through large respiratory droplets ejected while speaking, coughing and sneezing. These droplets land within less than 1 metre, 2 metres and 8 metres from the source, respectively.

There is clear evidence that aerosolised transmission played a role in the 2003 SARS-CoV outbreak (Li et al., 2005; Li Y. et al., 2005; Wong et al., 2004; I. T. Yu et al., 2004; I. T. S. Yu et al., 2005). The evidence is less clear for SARS-CoV-2; however viral RNA has been detected in aerosols (Liu, Ning, et al., 2020) and laboratory studies suggest live virus can survive in this form for up to 3 hours (van Doremalen et al., 2020). Numerical studies have demonstrated that aerosol can travel significant distances, including across different rooms, floors, and also from one building to another. Epidemiological evidence from a large outbreak linked to a choir practice is also compatible with aerosolised transmission across longer distances indoors. However, the longer the travelled distance, the lower the likelihood that the concentration of virus is above the threshold needed to transmit the disease.

Discussion

This review integrates current evidence from epidemiological, microbiological and fluid mechanics perspectives on the transmission of covid-19 in indoor settings.

Most of the epidemiological studies it draws on were conducted early in the pandemic, when effective and accurate contact tracing was possible. We found higher secondary attack rates in communal residential contexts (care homes, shelters for homeless people, cruise ship) than in households. Within households, the risk of transmission was higher between spouses than between other types of relative. This study suggests that effective social distancing to prevent transmission within households is possible, particularly if the isolated person is able to use a separate bathroom, a separate bedroom, minimise time in the same room as other family members and wear a mask where this is unavoidable. However, such measures are challenging in overcrowded housing and do not take into account that many cases are asymptomatic so individuals will be unaware that they are sick and potentially transmitting the virus to others.

We found evidence of workplace outbreaks in a care home, an assisted and independent living community, shelters for homeless people, shops, meat and poultry processing factories, a cruise ship, a business conference, a customer call centre and a government ministry; however few of the studies provided enough detail to allow meaningful comparison. Nevertheless, many of the workplace settings where outbreaks have occurred are characterised by close physical contact and prolonged time spent in crowded indoor spaces. Evidence from the study on outbreaks in meat and poultry processing plants (Dyal et al., 2020) also highlights the role health inequalities and inadequate social protection play in relation to people continuing to work whilst ill, overcrowded housing and transportation to and from work and inadequate health and safety communication and training, particularly for non-English speakers and non-literate workers.

We found evidence that community and social settings associated with a higher risk of transmission are again those where people gather in close proximity indoors for prolonged periods. Churches and religious gatherings, sharing meals and bathing facilities, close physical contact and activities such as singing together have all been reported in conjunction with outbreaks. In contrast, there have been fewer reports of transmission in relation to more casual, short term social contact, although this may be because such contacts are subject to recall bias and harder to track and trace. Risks associated with travelling with an affected case are difficult to evaluate – the evidence from these studies was limited and non-specific.

Most of the studies featured in this review were conducted early in the pandemic (January to April 2020 – see figure 3). During these early stages, before transmission was widely disseminated in communities, it was easier to track discrete outbreaks and to identify chains of transmission with a degree of confidence. The period of lockdown which then followed in many countries effectively reduced transmission in most workplace, social and non-residential community settings. At the time of writing (August 2020) many countries have suppressed the virus to the extent that lockdown measures can be relaxed, and economic and social activity can resume, albeit with strict social distancing measures in place. As this happens, we can anticipate the re-emergence of outbreaks in workplace and social settings. There will be new lessons to learn about high-risk activities and environments and it will be important to update the evidence as it emerges over the coming months. There will inevitably be a time lag whilst the scientific evidence emerges, during which news media can provide a useful early warning system. For example, on 2 July 2020, the Guardian newspaper reported on a spike in workplace outbreaks across England as the lockdown eased (Barr, 2020). A later article in the same newspaper reported on numerous outbreaks in food processing factories during the summer months (Mohdin, 2020) and a 30 June article linked a spike in cases in the English city of Leicester, which resulted in the re-imposition of a local lockdown, to garment and food processing factories in the city (Bland & Campbell, 2020). Many of the factors – workers continuing to come to work whilst sick, workplace and residential overcrowding, a disproportionate impact on minority communities and the failure of employers to institute effective physical distancing – echo the findings of the report into outbreaks in US meat processing plants (Dyal et al., 2020).

Evidence from microbiological and fluid mechanics studies suggest that aerosolised transmission is theoretically possible and epidemiological evidence from a large outbreak linked to a choir practice is compatible with aerosolised transmission across longer distances indoors. However, many questions remain unanswered and there is some conflicting evidence. We still do not know what quantity of live virus is required to present an infection risk or whether live virus is present sufficient quantities in aerosolised particles to present a risk. Although the investigation of the outbreak amongst choir members was consistent with airborne transmission created by aerosolised droplets generated in the act of singing, the absence of any cross-cabin transmission among passengers on the Diamond Princess cruise ship after the quarantine period began and passengers were confined to their cabins supports the hypothesis that transmission was via droplets/fomites and not airborne via air conditioning in this context.

This review has a number of limitations. Although the focus of this study is transmission of SARS-CoV-2 in indoor, non-clinical settings, most of the microbiological and environmental evidence was generated in clinical contexts because this is where most of this type of study have been conducted to date. Clearly such settings are very different from non-clinical, community contexts: for example, there is a higher risk of transmission via aerosol generating procedures (AGP) and greater numbers of individuals infected with SARS-CoV-2, so virus detection in these settings is likely higher than in non-clinical indoor settings. To maximise the transferability and generalisability of these findings to community settings, we attempted to extract and report only on samples taken from areas of hospitals accessible to visitors and the general public; however this was not always possible, as the studies did not provide information on the extent to which AGPs were carried out in patient rooms. Therefore, these results must be treated with caution in applying them to non-clinical settings.

Although we excluded evidence from animal studies in this review, such studies should perhaps be included in future reviews, as they can potentially provide direct experimental evidence on modes of transmission in a way that is impossible from observational human studies. For example, (Richard M, Kok A, & de Meulder D, 2020) conducted an experiment with ferrets to ascertain whether SARS-CoV-2 could be transmitted efficiently through the air. Donor ferrets were inoculated with a high dose of SARS-CoV-2 taken from a human subject. Each donor ferret was then put into a cage with a healthy ferret ("direct contact"). A second healthy ferret ("indirect recipient") was housed in a second cage, separated from the first by a space of 10 cm. Air flowed from the infected cage to the initially uninfected cage. The researchers found that the virus was transmitted efficiently by direct contact (from the inoculated ferret to the direct contact ferret) and through the air (from the inoculated ferret to the indirect recipient in a separate cage). The patterns of virus shedding and infectivity in all three types of ferret were similar. This study provides evidence that transmission is possible via direct contact or through the air. Because the indirect recipients were only 10 cm distant from the inoculated ferrets, this study cannot distinguish between droplet and aerosolised transmission but it is possible to envisage an extension of this study which could address such a question by extending the distance separating the infected from the recipient ferret such that any observed transmission would have to occur via aerosolisation of the virus.

Our study also has methodological limitations. Title and abstract and full text screening was conducted by only one reviewer, with a second reviewer screening rejected articles only. Thus this may have biased the studies included in the review. Similarly, the data extraction and quality assessment of each article was conducted by one reviewer only. The quality of the available epidemiological evidence was graded as low, so this makes any conclusions uncertain. In particular, there is significant variability in contact tracing approaches across different countries and even different regions within countries. Contact tracing of rapidly evolving infectious diseases inevitably contains case ascertainment biases, non-homogenous sampling over time and location, and uncontrolled correlation (Kim & Jiang, 2020). There may be publication bias, with large outbreaks potentially more likely to be reported and investigated than household studies. This review draws on evidence from a wide variety of populations and so not all the results will be directly applicable to a given population. Finally, this review was conducted at particular stage of the pandemic and as such is a snapshot in time: social contexts and drivers of behaviour and transmission will likely evolve and change as the pandemic progresses.

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Key references

American Society of Mechanical Engineers. (2009). *Standard for Verification and Validation in Computational Fluid Dynamics and Heat Transfer* (Vol. VV 20): American Society of Mechanical Engineers.

American Society of Mechanical Engineers. (2018). *Assessing Credibility of Computational Modeling through Verification and Validation: Application to Medical Devices* (Vol. VV 40): American Society of Mechanical Engineers.

Asadi S, Wexler AS, Cappa CD, Barreda S, & Bouvier NM, e. a. (2020). Effect of voicing and articulation manner on aerosol particle emission during human speech. *PLOS ONE 15*, e0227699. Retrieved from https://doi.org/10.1371/journal.pone.0227699

Asadi, S., Wexler, A. S., & Cappa, C. D. e. a. (2019). Aerosol emission and superemission during human speech increase with voice loudness. *Sci Rep, 9*. Retrieved from https://doi.org/10.1038/s41598-019-38808-z

Barr, C. (2020). Suspected Covid-19 outbreaks in English workplaces double in a week. *The Guardian*. Retrieved from https://www.theguardian.com/society/2020/jul/02/suspected-covid-19-outbreaks-in-english-workplaces-double-in-a-week

Bi, Q., Wu, Y., Mei, S., Ye, C., Zou, X., Zhang, Z., . . . Feng, T. (2020). Epidemiology and Transmission of COVID-19 in Shenzhen China: Analysis of 391 cases and 1,286 of their close contacts. doi:10.1101/2020.03.03.20028423

Bland, A., & Campbell, D. (2020). Some Leicester factories stayed open and forced staff to come in, report warns. . *The Guardian* Retrieved from https://www.theguardian.com/uk-news/2020/jun/30/some-leicester-factories-stayed-open-and-forced-staff-to-come-in

Bourouiba, L. (2020). Turbulent Gas Clouds and Respiratory Pathogen Emissions: Potential Implications for Reducing Transmission of COVID-19. *Jama*. doi:10.1001/jama.2020.4756

Bourouiba, L., Dehandschoewercker, E., & Bush, J. (2014). Violent expiratory events: On coughing and sneezing. *Journal of Fluid Mechanics, 745*, 537-563. doi:10.1017/jfm.2014.88

Burke, R. M., Balter, S., Barnes, E., Barry, V., Bartlett, K., Beer, K. D., . . . Hunte. (2020). Enhanced Contact Investigations for Nine Early Travel-Related Cases of SARS-CoV-2 in the United States. doi:10.1101/2020.04.27.20081901

CAMARADES. (2020). Protocols. Retrieved from http://syrf.org.uk/protocols/

Chan, J. F., Yuan, S., Kok, K. H., To, K. K., Chu, H., Yang, J., . . . Yuen, K. Y. (2020). A familial cluster of pneumonia associated with the 2019 novel coronavirus indicating person-to-person transmission: a study of a family cluster. *Lancet, 395*(10223), 514-523. doi:10.1016/S0140-6736(20)30154-9. Epub 2020 Jan 24.

Chao, C., Wan, M. P., Morawska, L., Johnson, G. R., Ristovski, Z. D., Hargreaves, M., . . . Katoshevski, D. (2009). Characterization of expiration air jets and droplet size distributions immediately at the mouth opening. *Journal of aerosol science, 40*, 122–133

Chaw, L., Koh, W. C., Jamaludin, S. A., Naing, L., Alikhan, M. F., & Wong, J. (2020). SARS-CoV-2 transmission in different settings: Analysis of cases and close contacts from the Tablighi cluster in Brunei Darussalam. doi:10.1101/2020.05.04.20090043

Chen, C., Zhao, B., & Yang, X. (2011). *Significance of two-way airflow effect due to temperature difference in indoor air quality*.

Cheng, H. Y., Jian, S. W., Liu, D. P., Ng, T. C., Huang, W. T., Taiwan Covid-19 Outbreak Investigation, T., & Lin, H. H. (2020). High transmissibility of COVID-19 near symptom onset. doi:10.1101/2020.03.18.20034561

Cheng, V. C. C., Wong, S. C., Chen, J. H. K., Yip, C. C. Y., Chuang, V. W. M., Tsang, O. T. Y., . . . Yuen, K. Y. (2020). Escalating infection control response to the rapidly evolving epidemiology of the coronavirus disease 2019 (COVID-19) due to SARS-CoV-2 in Hong Kong. *Infect Control Hosp Epidemiol, 41*(5), 493-498. doi:10.1017/ice.2020.58. Epub 2020 Mar 5.

Chin, A. W. H., Chu, J. T. S., Perera, M. R. A., Hui, K. P. Y., Yen, H.-L., Chan, M. C. W., . . . Poon, L. L. M. (2020). Stability of SARS-CoV-2 in different environmental conditions. *The Lancet Microbe* Retrieved from https://doi.org/10.1016/S2666-5247(20)30003-3

Critical Appraisal Skills Programme. (2020). CASP checklists. Retrieved from https://casp-uk.net/casp-tools-checklists/

Duguid, J. (1946). The size and the duration of air-carriage of respiratory droplets and droplet-nuclei. *Epidemiology and Infection, 44(*471-479. doi:10.1017/S0022172400019288

Dyal, J. W., Grant, M. P., Broadwater, K., Bjork, A., Waltenburg, M. A., Gibbins, J. D., . . . Honein, M. A. (2020). COVID-19 Among Workers in Meat and Poultry Processing Facilities - 19 States, April 2020. *MMWR Morb Mortal Wkly Rep, 69*(18). doi:10.15585/mmwr.mm6918e3

Fan, J., Liu, X., Shao, G., Qi, J., Li, Y., Pan, W., . . . Bao, S. (2020). The epidemiology of reverse transmission of COVID-19 in Gansu Province, China. *Travel Med Infect Dis*, 101741. doi:10.1016/j.tmaid.2020.101741

Gormley, M., Aspray, T. J., Kelly, D. A., & Rodriguez-Gil, C. (2017). Pathogen cross-transmission via building sanitary plumbing systems in a full scale pilot test-rig. *PLoS One, 12*(2), e0171556. doi:10.1371/journal.pone.0171556

Guo, Z. D., Wang, Z. Y., Zhang, S. F., Li, X., Li, L., Li, C., . . . Chen, W. (2020). Aerosol and Surface Distribution of Severe Acute Respiratory Syndrome Coronavirus 2 in Hospital Wards, Wuhan, China, 2020. *Emerg Infect Dis, 26*(7). doi:10.3201/eid2607.200885

Guyatt, G. H., Oxman, A. D., Vist, G. E., Kunz, R., Falck-Ytter, Y., Alonso-Coello, P., . . . Group, G. W. (2008). GRADE: an emerging consensus on rating quality of evidence and strength of recommendations. *Bmj, 336*(7650), 924-926. doi:10.1136/bmj.39489.470347.AD

Hirotsu, Y., Maejima, M., Nakajima, M., Mochizuki, H., & Omata, M. (2020). Environmental cleaning is effective for the eradication of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) in contaminated hospital rooms: A patient from the Diamond Princess cruise ship. *Infect Control Hosp Epidemiol*, 1-8. doi:10.1017/ice.2020.144

Holshue, M. L., DeBolt, C., Lindquist, S., Lofy, K. H., Wiesman, J., Bruce, H., . . . Washington State - nCo, V. C. I. T. (2020). First Case of 2019 Novel Coronavirus in the United States. *N Engl J Med, 382*(10), 929-936. doi:10.1056/NEJMoa2001191

Hu, Z., Song, C., Xu, C., Jin, G., Chen, Y., Xu, X., . . . Shen, H. (2020). Clinical characteristics of 24 asymptomatic infections with COVID-19 screened among close contacts in Nanjing, China. *Sci China Life Sci, 63*(5), 706-711. doi:10.1007/s11427-020-1661-4. Epub 2020 Mar 4.

Hung, H. C. K., Chan, D. W. T., Law, L. K. C., Chan, E. H. W., & Wong, E. S. W. (2006). Industrial experience and research into the causes of SARS virus transmission in a high-rise residential housing estate in Hong Kong. *Building Services Engineering Research and Technology, 27*(2), 91-102. doi:10.1191/0143624406bt145oa

Hung, L. S. (2003). The SARS epidemic in Hong Kong: what lessons have we learned? *Journal of the Royal Society of Medicine, 96*, 374-378. Retrieved from https://doi.org/10.1258/jrsm.96.8.374

Jack, L. B., Cheng, C., & Lu, W. H. (2006). Numerical simulation of pressure and airflow response of building drainage ventilation systems. *Building Services Engineering Research and Technology, 27*(2), 141-152. doi:10.1191/0143624406bt152oa

Jiang, F. C., Jiang, X. L., Wang, Z. G., Meng, Z. H., Shao, S. F., Anderson, B. D., & Ma, M. J. (2020). Detection of Severe Acute Respiratory Syndrome Coronavirus 2 RNA on Surfaces in Quarantine Rooms. *Emerg Infect Dis, 26*(9). doi:10.3201/eid2609.201435

Jiehao C, Jing X, & Daojiong L, e. a. (2020). A case series of children with 2019 novel coronavirus infection: clinical and epidemiological features. . *Clin. Infect. Dis. , pii: ciaa198*.

Joanna Briggs Institute. (2020). Checklist for case series. In: Joanna Briggs Institute.

Kakimoto, K., Kamiya, H., Yamagishi, T., Matsui, T., Suzuki, M., & Wakita, T. (2020). Initial Investigation of Transmission of COVID-19 Among Crew Members During Quarantine of a Cruise Ship - Yokohama, Japan, February 2020. *MMWR Morb Mortal Wkly Rep, 69*(11), 312-313. doi:10.15585/mmwr.mm6911e2

Kim, Y., & Jiang, X. (2020). Evolving Transmission Network Dynamics of COVID-19 Cluster Infections in South Korea: a descriptive study. doi:10.1101/2020.05.07.20091769

Leland, D. S., & Ginocchio, C. C. (2007). Role of cell culture for virus detection in the age of technology. *Clin Microbiol Rev, 20*(1), 49-78. doi:10.1128/CMR.00002-06

Li, L. Y., Wu, W., Chen, S., Gu, J. W., Li, X. L., Song, H. J., . . . Cai, Q. (2020). Digestive system involvement of novel coronavirus infection: Prevention and control infection from a gastroenterology perspective. *J Dig Dis, 21*(4), 199-204. doi:10.1111/1751-2980.12862

Li, Y., Duan, S., Yu, I. T., & Wong, T. W. (2005). Multi-zone modeling of probable SARS virus transmission by airflow between flats in Block E, Amoy Gardens. *Indoor Air, 15*(2), 96-111. doi:10.1111/j.1600-0668.2004.00318.x

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

Li Y., Huang X., & I.T., Y. (2005). Role of air distribution in SARS transmission during the largest nosocomial outbreak in Hong Kong. . *Indoor Air, 15*, 83-95.

Lim, T., Cho, J., & Kim, B. S. (2011). Predictions and measurements of the stack effect on indoor airborne virus transmission in a high-rise hospital building. *Build Environ, 46*(12), 2413-2424. doi:10.1016/j.buildenv.2011.04.015

Ling, Y., Xu, S. B., Lin, Y. X., Tian, D., Zhu, Z. Q., Dai, F. H., . . . Lu, H. Z. (2020). Persistence and clearance of viral RNA in 2019 novel coronavirus disease rehabilitation patients. *Chin Med J (Engl), 133*(9), 1039-1043. doi:10.1097/CM9.0000000000000774

Liu, Y., Eggo, R. M., & Kucharski, A. J. (2020). Secondary attack rate and superspreading events for SARS-CoV-2. *Lancet, 395*(10227), e47. doi:10.1016/S0140-6736(20)30462-1

Liu, Y., Ning, Z., Chen, Y., Guo, M., Liu, Y., Gali, N. K., . . . Lan, K. (2020). Aerodynamic analysis of SARS-CoV-2 in two Wuhan hospitals. *Nature*. doi:10.1038/s41586-020-2271-3

McMichael, T. M., Clark, S., Pogosjans, S., Kay, M., Lewis, J., Baer, A., . . . Duchin, J. S. (2020). COVID-19 in a Long-Term Care Facility - King County, Washington, February 27-March 9, 2020. *MMWR Morb Mortal Wkly Rep, 69*(12), 339-342. doi:10.15585/mmwr.mm6912e1

Mittal, R., Ni, R., & Seo, J.-H. (2020). The flow physics of COVID-19. *Journal of Fluid Mechanics, 894*. doi:10.1017/jfm.2020.330

Mohdin, A. (2020). Nearly 300 workers test positive at M&S sandwich supplier in Northampton. *The Guardian*. Retrieved from https://www.theguardian.com/world/2020/aug/13/nearly-300-workers-test-positive-at-ms-sandwich-factory-in-northampton

Niu, J., & Tung, T. C. (2008). On-site quantification of re-entry ratio of ventilation exhausts in multi-family residential buildings and implications. *Indoor Air, 18*(1), 12-26. doi:10.1111/j.1600-0668.2007.00500.x

Poussou, S. B., & Plesniak, M. W. (2012). Vortex dynamics and scalar transport in the wake of a bluff body driven through a steady recirculating flow. *Exp Fluids, 53*(3), 747-763. doi:10.1007/s00348-012-1325-1

Public Health Agency of Canada. (2014). Infection prevention and control guidelines: critical appraisal toolkit. In: Public Health Agency of Canada.

Pung, R., Chiew, C. J., Young, B. E., Chin, S., Chen, M. I., Clapham, H. E., . . . Lee, V. J. M. (2020). Investigation of three clusters of COVID-19 in Singapore: implications for surveillance and response measures. *Lancet, 395*(10229), 1039-1046. doi:10.1016/S0140-6736(20)30528-6. Epub 2020 Mar 17.

R Core Team. (2020). R: A language and environment for statistical computing. : R Foundation for Statistical Computing, Vienna, Austria. . Retrieved from https://www.R-project.org/.

Richard M, Kok A, & de Meulder D, e. a. (2020). SARS-CoV-2 is transmitted via contact and via the air between ferrets. . *Nat Commun., 11*, 3496. doi:10.1038/s41467-020-17367-2

Roache, P. J. (2009). *Fundamentals of verification and validation*: hermosa publ.

Roxby, A. C., Greninger, A. L., Hatfield, K. M., Lynch, J. B., Dellit, T. H., James, A., . . . Neme, S. (2020). Detection of SARS-CoV-2 Among Residents and Staff Members of an Independent and Assisted Living Community for Older Adults - Seattle, Washington, 2020. *MMWR Morb Mortal Wkly Rep, 69*(14), 416-418. doi:10.15585/mmwr.mm6914e2

Santarpia, J. L., Rivera, D. N., Herrera, V., Morwitzer, M. J., Creager, H., Santarpia, G. W., . . . Lowe, J. J. (2020). Transmission Potential of SARS-CoV-2 in Viral Shedding Observed at the University of Nebraska Medical Center. doi:10.1101/2020.03.23.20039446

Sironi, M., Hasnain, S. E., Rosenthal, B., Phan, T., Luciani, F., Shaw, M. A., . . . Evolution. (2020). SARS-CoV-2 and COVID-19: A genetic, epidemiological, and evolutionary perspective. *Infect Genet Evol, 84*, 104384. doi:10.1016/j.meegid.2020.104384

Sun, Z., Cai, X., Gu, C., Zhang, R., Han, W., Qian, Y., . . . Qu, D. (2020). Stability of the COVID-19 virus under wet, dry and acidic conditions. . *MedRxiv, 2020.04.09.20058875*. Retrieved from https://doi.org/10.1101/2020.04.09.20058875

Sung, M., Jo, S., Lee, S. E., Ki, M., Choi, B. Y., & Hong, J. (2018). Airflow as a possible transmission route of middle east respiratory syndrome at an initial outbreak hospital in Korea. *International Journal of Environmental Research and Public Health, 15*(12). doi:10.3390/ijerph15122757

Sze-To, G. N., Yang, Y., Kwan, J. K., Yu, S. C., & Chao, C. Y. (2014). Effects of surface material, ventilation, and human behavior on indirect contact transmission risk of respiratory infection. *Risk Anal, 34*(5), 818-830. doi:10.1111/risa.12144

Tang, A., Tong, Z. D., Wang, H. L., Dai, Y. X., Li, K. F., Liu, J. N., . . . Yan, J. B. (2020). Detection of Novel Coronavirus by RT-PCR in Stool Specimen from Asymptomatic Child, China. *Emerg Infect Dis, 26*(6), 1337-1339. doi:10.3201/eid2606.200301

Tellier, R., Li, Y., Cowling, B. J., & Tang, J. W. (2019). Recognition of aerosol transmission of infectious agents: a commentary. *BMC Infectious Diseases, 19*(1), 101. doi:10.1186/s12879-019-3707-y

Tobolowsky, F. A., Gonzales, E., Self, J. L., Rao, C. Y., Keating, R., Marx, G. E., . . . Kay, M. (2020). COVID-19 Outbreak Among Three Affiliated Homeless Service Sites - King County, Washington, 2020. *MMWR Morb Mortal Wkly Rep, 69*(17), 523-526. doi:10.15585/mmwr.mm6917e2

van Doremalen, N., Bushmaker, T., Morris, D. H., Holbrook, M. G., Gamble, A., Williamson, B. N., . . . Munster, V. J. (2020). Aerosol and Surface Stability of SARS-CoV-2 as Compared with SARS-CoV-1. *N Engl J Med, 382*(16), 1564-1567. doi:10.1056/NEJMc2004973. Epub 2020 Mar 17.

Viechtbauer, W. (2010). Conducting meta-analyses in R with the metafor package. *Journal of*

Statistical Software., 36, 1-48. Retrieved from https://www.jstatsoft.org/v036/i03.

Wang, H., Li, X., Li, T., Zhang, S., Wang, L., Wu, X., & Liu, J. (2020). The genetic sequence, origin, and diagnosis of SARS-CoV-2. *Eur J Clin Microbiol Infect Dis*. doi:10.1007/s10096-020-03899-4

Wang, W., Xu, Y., Gao, R., Lu, R., Han, K., Wu, G., & Tan, W. (2020). Detection of SARS-CoV-2 in Different Types of Clinical Specimens. *Jama*. doi:10.1001/jama.2020.3786

Wölfel, R., Corman, V. M., Guggemos, W., Seilmaier, M., Zange, S., Muller, M. A., . . . Wendtner, C. (2020). Virological assessment of hospitalized patients with COVID-2019. *Nature, 581*(7809), 465-469. doi:10.1038/s41586-020-2196-x

Wong, T. W., Lee, C. K., Tam, W., Lau, J. T., Yu, T. S., Lui, S. F., . . . Outbreak Study, G. (2004). Cluster of SARS among medical students exposed to single patient, Hong Kong. *Emerg Infect Dis, 10*(2), 269-276. doi:10.3201/eid1002.030452

Wu, S., Wang, Y., Jin, X., Tian, J., Liu, J., & Mao, Y. (2020). Environmental contamination by SARS-CoV-2 in a designated hospital for coronavirus disease 2019. *Am J Infect Control*. doi:10.1016/j.ajic.2020.05.003

Wu Y, Guo C, & Tang L, e. a. (2020). Prolonged presence of SARS-CoV-2 viral RNA in faecal samples. . *Lancet Gastroenterol Hepatol, 5*, 434-435. doi:10.1016/S2468-1253(20)30083-2

Xie, X., Li, Y., Chwang, A. T. Y., Ho, P. L., & Seto, W. H. (2007). How far droplets can move in indoor environments – revisiting the Wells evaporation–falling curve. . *Indoor Air, 17*, 211-225. doi:10.1111/j.1600-0668.2007.00469.x

Xie, X., Li, Y., Sun, H., & Liu, L. (2009). Exhaled droplets due to talking and coughing. *J. R. Soc. Interface*, 6S703–S714. Retrieved from http://doi.org/10.1098/rsif.2009.0388.focus

Xu, P., Qian, H., Miao, T., Yen, H. L., Tan, H., Cowling, B. J., & Li, Y. J. (2020). Transmission routes of Covid-19 virus in the Diamond Princess Cruise ship. doi:10.1101/2020.04.09.20059113

Yamagishi, T. (2020). *Environmental sampling for severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) during a coronavirus disease (COVID-19) outbreak aboard a commercial cruise ship.* . Retrieved from https://doi.org/10.1101/2020.05.02.20088567

Yang, L., Li, M., Li, X., & Tu, J. (2018). The effects of diffuser type on thermal flow and contaminant transport in high-speed train (HST) cabins–a numerical study. *International Journal of Ventilation, 17*(1), 48-62. doi:10.1080/14733315.2017.1351736

Ye, G., Lin, H., Chen, L., Wang, S., Zeng, Z., Wang, W., . . . Wang, X. (2020). Environmental contamination of the SARS-CoV-2 in healthcare premises: An urgent call for protection for healthcare workers. doi:10.1101/2020.03.11.20034546

Yong, S. E. F., Anderson, D. E., Wei, W. E., Pang, J., Chia, W. N., Tan, C. W., . . . Lee, V. J. M. (2020). Connecting clusters of COVID-19: an epidemiological and serological investigation. *Lancet Infect Dis*. doi:10.1016/s1473-3099(20)30273-5

Young, J., & Solomon, M. (2009). How to critically appraise an article. . *Nature Clinical Practice Gastroenterology & Hepatology, 6*(2), 82-91.

Yu, H. C., Mui, K. W., Wong, L. T., & Chu, H. S. (2017). Ventilation of general hospital wards for mitigating infection risks of three kinds of viruses including Middle East respiratory syndrome coronavirus. *Indoor and Built Environment, 26*(4), 514-527. doi:10.1177/1420326X16631596

Yu, I. T., Li, Y., Wong, T. W., Tam, W., Chan, A. T., Lee, J. H., . . . Ho, T. (2004). Evidence of airborne transmission of the severe acute respiratory syndrome virus. *N Engl J Med, 350*(17), 1731-1739. doi:10.1056/NEJMoa032867

Yu, I. T. S., Wong, T. W., Chiu, Y. L., Lee, N., & Li, Y. (2005). Temporal-Spatial Analysis of Severe Acute Respiratory Syndrome among Hospital Inpatients. *Clinical Infectious Diseases, 40*(9), 91237–91243. Retrieved from https://doi.org/10.1086/428735

Zayas, G., Chiang, M. C., Wong, E., MacDonald, F., Lange, C. F., Senthilselvan, A., & King, M. (2012). Cough aerosol in healthy participants: fundamental knowledge to optimize droplet-spread infectious respiratory disease management. *BMC Pulm Med, 12*, 11. doi:10.1186/1471-2466-12-11

Zhang H, Kang Z, & Gong H, e. a. (2020). Digestive system is a potential route of COVID-19: an analysis of single-cell coexpression pattern of key proteins in viral entry process. *Gut, 69*, 1010-1018.

Zhang, J., Wang, S., & Xue, Y. (2020). Fecal specimen diagnosis 2019 novel coronavirus-infected pneumonia. *J Med Virol, 92*(6), 680-682. doi:10.1002/jmv.25742

Zhang, W., Du, R. H., Li, B., Zheng, X. S., Yang, X. L., Hu, B., . . . Zhou, P. (2020). Molecular and serological investigation of 2019-nCoV infected patients: implication of multiple shedding routes. *Emerg Microbes Infect, 9*(1), 386-389. doi:10.1080/22221751.2020.1729071

Zhou, J., Otter, J. A., Price, J. R., Cimpeanu, C., Garcia, D. M., Kinross, J., . . . Barclay, W. S. (2020). Investigating SARS-CoV-2 surface and air contamination in an acute healthcare setting during the peak of the COVID-19 pandemic in London. *Clin Infect Dis*. doi:10.1093/cid/ciaa905