Aerosol and Air Quality Research

ORIGINAL RESEARCH
https://doi.org/10.4209/aaqr.200495

Special Issue:
Special Issue on COVID-19 Aerosol Drivers, Impacts and Mitigation (XII)

Air Recirculation Role in the Spread of COVID-19 Onboard the Diamond Princess Cruise Ship during a Quarantine Period

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ABSTRACT

The Diamond Princess cruise ship is a unique COVID-19 transmission case because of the high testing capacity and the confined environment. This exploratory study aims to raise the hypothesis regarding the role of poor ventilation systems in the spread of COVID-19 by analysing count data collected by the onboard clinic during the outbreak, and considering the deck plan and design of the air conditioning system of the ship. Observed symptomatic infection rate after day 5 (incubation period median day) of the quarantine, in cabins without previous confirmed cases are compared to that in cabins with previous confirmed cases. Accordingly, the observed symptomatic infection rate in cabins without a previously confirmed case (1.2%) was higher than for cabins with a previously confirmed case (0.8%); however, the difference was not statistically significant. In addition, age did not appear to be a confounding variable. Airborne transmission of COVID-19 through the ventilation system onboard could explain the higher than expected virus spread into cabins without previously confirmed cases during the quarantine period; thus, this study provides further potential evidence of coronavirus transmission by aerosols. Conflicting results from other studies involving the Diamond Princess outbreak are also discussed in light of our results.

Keywords: Confined spaces, Ventilation, Airborne transmission, Filters, HVAC system

OPEN ACCESS

Received: July 31, 2020
Revised: December 22, 2020
Accepted: December 27, 2020

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Publisher:
Taiwan Association for Aerosol Research
ISSN: 1680-8584 print
ISSN: 2071-1409 online

1 INTRODUCTION

Unreported cases, and limited testing capabilities for the SARS-CoV-2 have led to uncertainty about the actual number of people that are infected, died, or recovered from COVID-19 around the world. As most of the people on Diamond Princess cruise ship were tested for COVID-19, the Diamond Princess ship has become an important case study for research about the COVID-19 outbreak.

Because of 10 lab-confirmed cases of COVID-19 on the 4th of Feb 2020, Diamond Princess was quarantined for a14-day period with 6th of Feb, as the first full day of quarantine. A total of 3711 individuals were on board at that first day of quarantine (2666 passengers and 1045 crew members) as described by the Japanese National Institute of Infectious Diseases (NIID, 2020). Crew members were provided with personal protective equipment and instructed to follow international guidance on Infection prevention and control. Passengers were given thermometers and instructions for self-monitoring of body temperature and requested to stay in their cabins and to call if they had a fever above 37.5°C (NIID, 2020). Passengers who showed symptoms (e.g., fever, cough) were tested for COVID-19. If their tests confirmed positive, they disembarked the ship and isolated. Then their cabinmates -if any- were consequently tested. If they were found to be positive cases too, they disembarked the ship and isolated. Otherwise, they remained on board. Up to Feb 16th, 2020, the median reproductive number (R0) of COVID-19 on the Diamond Princess cruise ship was around 2.28 (95% confidence interval: 2.06–2.52) as estimated by Zhang *et al.* (2020).

By the 20th of Feb, 619 COVID-19 positive cases were confirmed. Out of these cases, a total of 301 (49%) cases were symptomatic. Among these cases, there were 163 cases with recorded symptom onset dates during the quarantine period (NIID, 2020). Among these 163 cases, 115 were passengers, and 48 were crew. From the 20th Feb, over 1600 non-case, mainly passengers began to disembark the Diamond Princess ship. Criteria for disembarkation of non-cases included, completion of a 14-day period without sharing a cabin with a confirmed case, a negative test result, and no symptoms (NIID, 2020).

Although the virus was likely transmitted, in many cases, prior to the quarantine period due to close contact with a case within the same cabin, many new cases were also recorded with symptom onset dates during the quarantine period in cabins with no previous confirmed cases and in single-occupancy cabins. It is not possible to infer exactly when all cases on Diamond Princess were infected due to the variance in COVID-19 incubation periods among individuals and to the lack of symptom presentation in many cases. However, we assume that; firstly, the median time of the incubation period for COVID-19 is 5 days from exposure to symptoms onset. This assumption is based on the estimation for the incubation period median time for COVID-19 as reported by previous studies (Guan *et al*., 2020; Li *et al*., 2020; Lauer *et al*., 2020). And secondly, the infection risk is higher when there is a close contact with a sick person within a small space such as ships' cabins. Finally, the exposure to external COVID-19 transmission routes, such in the case of interacting with crew members while serving meals, is the same for all passengers' cabins during the quarantine period.

Consequently, an airborne transmission mode for COVID-19 -through the ship's central heating ventilation air conditioning (HVAC) filtration system- will be suspected, if the infection rate for cases with recorded symptom onset dates after day 5 (incubation period median day) of the quarantine, in cabins with previous confirmed cases is not higher than that in cabins with no previous cases.

The objectives of the study reported here are twofold. First, to test the null hypothesis that the observed infection rate of new confirmed cases with recorded symptom onset dates in cabins without previously confirmed cases of COVID-19, is less than or equal to that in cabins with previously confirmed cases. To eliminate the effect of pre-quarantine period exposure to the virus as much as possible, only infection rates of new confirmed cases with recorded symptom onset after the incubation period median day (day 5 of the quarantine) will be considered. We will investigate whether dissimilar age distributions among the cabins, could had been the reason for any difference. Second, to examine whether the HVAC system on the Diamond Princess cruise ship could have played a role in the spread of the infection to the cabins with no previous confirmed cases during the quarantine period.

2 METHODS

This is an exploratory study that uses mixed methods to: (a) calculate and compare the observed symptomatic infection rate with recoded symptom onset (**SIRR**) among the different passengers' cabins using published count data; (b) investigate whether different age distributions could explain the symptomatic infection rates' differences, using published count data; (c) retrieve and check the design of HVAC system, and deck plans of the Diamond Princess ship from the literature.

Count Data: This is a summary data that is collected on the Diamond Princess by the ship's onboard clinic, and published by the NIID (2020) on 21st of Feb 2020. The data consists of two tables; the first table includes COVID-19 cases with reported onset dates for the period of 6–17th of Feb. Numbers of new confirmed cases were given per date of quarantine day, per population aboard type (passengers or crew members), and per cabins' previous confirmed cases type (cabins with previous confirmed cases, cabins without previous confirmed cases) for a total of 163 symptomatic confirmed cases. As the focus of this study is on the infection rates of cases with known onset dates inside passengers' cabins, only data that relate to passengers, and have known onset dates –after the incubation period median day– have been analysed. The second table was organized according to 10 age group, each with a span of 10 years. For each age group, data included population aboard, total number of confirmed cases, and number of symptomatic confirmed cases.

Statistical Analysis: In this study, SIRR are calculated as followed:

$$SIRR_{QPM} = \frac{\text{Number of CCs with recorded symptom onset dates during the QPM}}{\text{The population at risk at the first day of the QPM}} \quad (1)$$

where QPM is the quarantine period after the incubation median day (day 5 of the quarantine period), and CCs are the confirmed cases. After calculating $SIRR_{QPM}$ in cabins with previous confirmed cases and in cabins without previous confirmed cases (Tables S1 and S2). Two-proportions z-test (one-tailed) was used to compare these infection rates, in which the null hypothesis was:

$$H_0: SIRR_{QPM2} \leq SIRR_{QPM1} \quad (2)$$

where $SIRR_{QPM2}$ is the infection rate in cabins without previous confirmed cases after the incubation period median day. And $SIRR_{QPM1}$ is the infection rate in cabins with previous confirmed cases after the incubation period median day.

Any age group that was found to be less than 5 people was merged with the closest age group to it. Chi-square test was used to check whether symptomatic, asymptomatic, non-case counts differ by ages. If a significant difference was found, relative contribution of each cell to the total chi-square score were used to check where the differences actually lie. The significance level for all tests is 0.05. R (version 3.6.1) was used to run the statistical analysis.

Literature review: The Diamond Princess's HVAC filtration system design was examined by checking the Diamond Princess's website (Princess, 2020) and referencing Kosako and Shiiyama (2008) that extensively described the air conditioning system design for large cruise ships of the Princess Cruise Mitsubishi Grand implementation. This Grand series consists of two similar cruise ships; Diamond Princess and its sister Sapphire Princes. Moreover, the deck plan of Diamond princess cruise ship was checked to assess the percentage of cabins that depends totally on the supplied air by the ship's HVAC system (Cruise Deck Plan, 2020).

As this study was secondary retrospective analysis of anonymised published count data, formal Research Ethics approval was not required.

3 RESULTS AND DISCUSSION

The number of new symptomatic confirmed cases in all cabins continued to decline as the quarantine continued (Table 1, Fig. 1). This may have been due to the strict infection prevention and control measures that were put in place during the quarantine period onboard the ship (Mizumoto and Chowell, 2020; Zhang *et al.*, 2020) resulting in a substantial decline of the dominant transmission mode onboard, i.e., passenger-to-passenger transmission, as a result of passengers staying inside their cabins (Mizumoto and Chowell, 2020). Alternatively, a large proportion of asymptomatic cases may have remained undetected (Plucinski *et al*., 2002; Emery *et al*., 2020).

Based on the assumptions that the exposure to external COVID-19 transmission routes during the quarantine period was the same for all passengers' cabins, and the infection risk was higher when there was a close contact with a sick person, a lower infection rate after the incubation period median day was expected in cabins without previous confirmed cases than that in cabins with previous confirmed cases. Remarkably, $SIRR_{QPM}$ in cabins without previous cases (1.2%) was found higher than that in cabins with previous cases (0.8%) after the incubation median day. However, there was not sufficient evidence to reject the null hypothesis at 0.05 level of significance, in which difference in $SIRR_{QPM}$ was 0.4% (p value = 0.2, 95% lower confidence interval bound: –0.3%). This, in part, may have been due to the small numbers of cases with recorded symptom onset dates after day 5 of the quarantine resulting in the test being underpowered to detect a significant difference. In addition, the day-to-day contribution of asymptomatic cases to symptomatic infection rates in cabins during the quarantine period was not known. Other studies (Emery *et al*., 2020; Mizumoto *et al*., 2020; Plucinski *et al*., 2020) have estimated that the proportion of asymptomatic infections could range from 17.9 to 74%. The asymptomatic proportion was defined as the proportion of asymptomatically infected individuals among the total number of infected individuals (Mizumoto *et al*., 2020).

Table 1. COVID-19 symptomatic confirmed cases with known onset during the quarantine period.

Onset dates	Cumulative sum of the new confirmed cases among passengers	
	In cabins with previously confirmed cases	In cabins without a previously confirmed case
06/02/2020	1	14
07/02/2020	5	39
08/02/2020	6	55
09/02/2020	12	68
10/02/2020 (median day)	15	72
11/02/2020	18	80
12/02/2020	18	85
13/02/2020	22	90
14/02/2020	23	91
15/02/2020	23	92
16/02/2020	23	92
17/02/2020	23	92

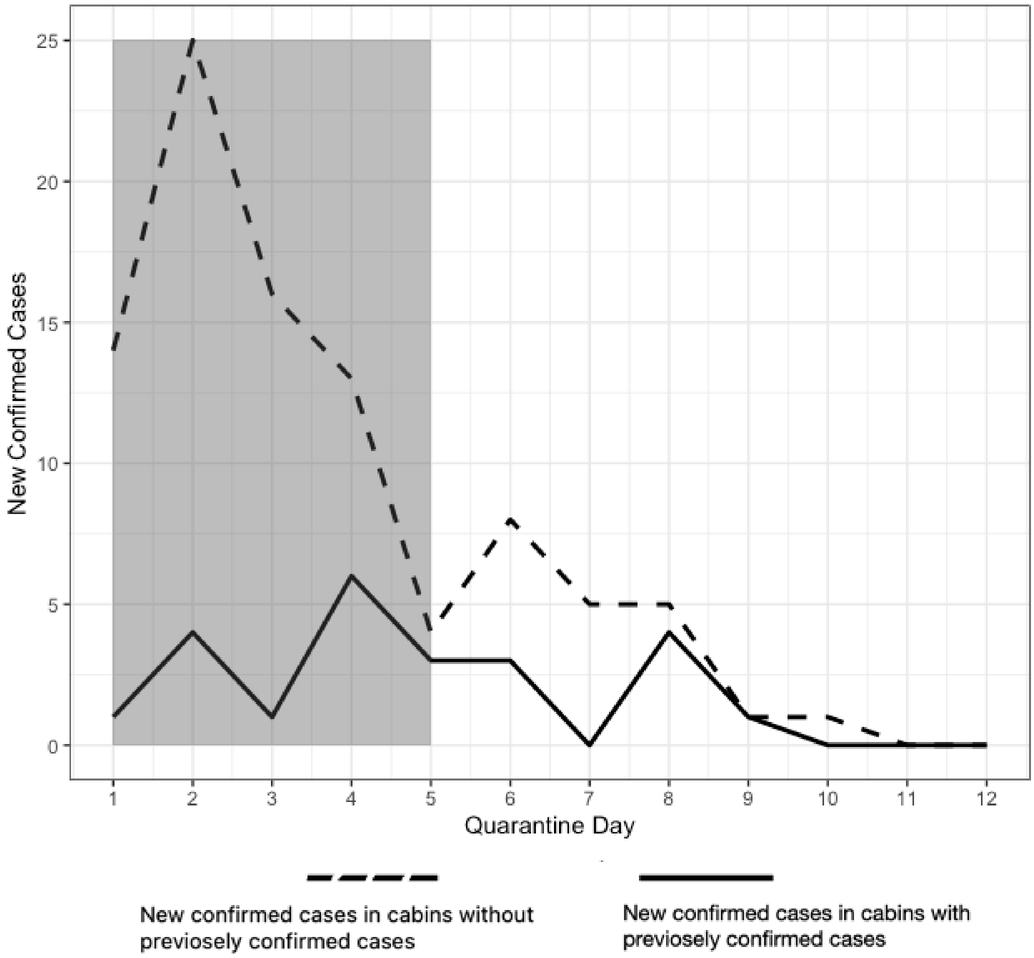

Fig. 1. Observed number of new confirmed cases by quarantine day and per cabins type (data in the grey area was not used in the statistical calculation).

Analysis of the second prepared dataset (Table 2) where children and young people under 20 years of age were excluded due to small sample sizes, 80–89 and 90–99 age groups were combined, and the sums of confirmed case were divided by the population at risk per age group, showed that the highest infection rate was in the age group of “80–99” (23%) (Fig. 2). Chi-squared test showed that case distributions differed significantly by age group (df = 12, $P < 0.0001$).

Table 2. Distribution of cases per age group.

Age group	Symptomatic confirmed case	Asymptomatic confirmed case	Non-cases
20–29	25	3	319
30–39	27	7	394
40–49	19	8	307
50–59	28	31	339
60–69	76	101	746
70–79	95	139	781
80+	29	25	173

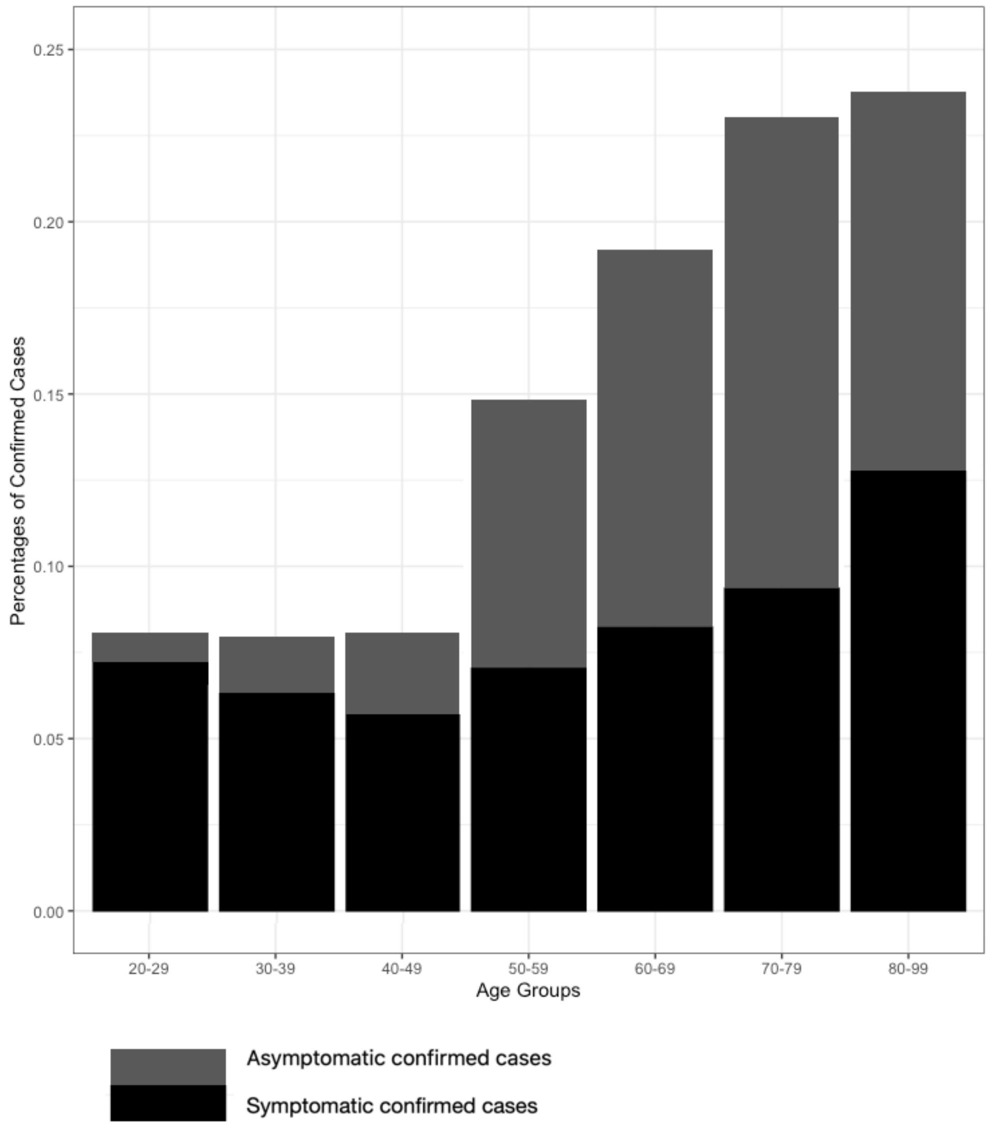

Fig. 2. Infection rates per age group.

However, asymptomatic confirmed cases in the age groups: "70–79", "20–29", "30–39", "40–49" (in descending order of contribution) contributed approximately 71% of the total chi-square score and thus account for most of the difference. Symptomatic confirmed cases contributed to only 10% of the difference. Accordingly, a hypothetical difference in age distributions among the cabins cannot explain why the symptomatic infection rate in cabins with previous confirmed cases was not higher than that in cabins without previous cases. Plucinski *et al.* (2020) verified the association between age and presenting with symptoms.

In their paper about the central HVAC system design in the Diamond Princess cruise ship, Kosako and Shiiyama (2008) stated that although cruise ships should be able to use 100% fresh air as a design condition; it is a part of energy-saving measures to mix outside air with that inside. Cabin temperature regulation happens through a combination of reheating and variable airflow (Kosako and Shiiyama, 2008). It is ordinary practice to use only 30% of fresh air inside passengers' cabins (Kosako and Shiiyama, 2008). As a result, air from different cabins can gather in one air duct, mixed with fresh air, be filtered then re-circulated to cabins.

Diamond Princess' deck plans showed that about 30% of the cabins onboard are interior cabins and with no access to the natural fresh air (Cruise Deck Plans, 2020). Furthermore, given the COVID-19 outbreak on the Diamond Princess cruise happened during winter, meant even passengers in cabins with balconies were dependent on the HVAC system. On their website (Princess, 2020), and when they were asked about whether COVID-19 can be spread through the ship's ventilation system, Princess did not declare, in their answer, that they had stopped the HVAC during the quarantine period, nor they had operated the HVAC system on 100% fresh air supply. They only had confirmed that the HVAC filtration system on the Diamond Princess ship is comparable to those used by land-based hotels, resorts and casinos (Princess, 2020).

HVAC systems in commercial setting have a minimum efficiency reporting value (MERV) of 5–8 (Table S3), in which MERV refer to the effectiveness of air filters in HVAC. And even in superior residential, commercial, and industrial spaces HVAC systems usually have a minimum efficiency reporting value (MERV) of 9–12 (Table S3). MERV 5–8 air filters are used to collect particles with size range of 3–10 µm. MERV 9–12 air filters are used to collect particles with size range of 1–3 µm (Miao and Xin, 2017). Since SARS-CoV-2 has a diameter of approximately 0.06–0.14 µm (Cascella *et al*., 2020), this suggests the HVAC ventilation system on the Diamond Princess cruise ships was completely unable to filter viruses as small as SARS-CoV-2 virus. Thus, the central HVAC system could have carried SARS-CoV-2 virus from one cabin to another through the air recirculation between cabins. Such a probable airborne transmission mode of SARS-CoV-2 virus on the Diamond Princess ship could, at least partially, explain why the infection rate in cabins without previous confirmed case was not lower than that in cabins with previous confirmed case (and also could explain the infections with COVID-19 in single-occupancy cabins) after day 5 (incubation period median day) of the quarantine.

Interestingly, Plucinski *et al*. (2020) established that, even after excluding cabinmates who tested positive within 5 days of their cabinmate, the transmission rate for passengers in single-person cabins or in multi-person cabins with uninfected cabinmates was lower than that among passengers in multi-person cabins with at least one symptomatic COVID-19 positive cabinmate, indicating a pattern of intra-cabin transmission. However, unlike the definition of confirmed cases in our study that is restricted to passengers who tested positive for COVID-19 during the quarantine period, Plucinski *et al*. (2020), considered passengers who had positive results onboard Diamond Princess, who had negative results onboard Diamond Princess and tested positive in the United States, and those who were never tested onboard Diamond Princess and had a positive result in the United States, all as positive cases.

Similarly, one preprint study (Xu *et al*., 2020) that predicted the dates of infections on the Diamond Princess cruise ship reached an opposite result to ours, in which they, using their predicted data concluded that "the ship central air conditioning system did not play a role in the transmission" and "the long-range airborne route was almost totally absent in the outbreak". The differences in our studies are as follows; firstly, they have claimed that infection among passengers after 6^{th} of Feb was limited to those who stayed in the same cabin with an infected passenger. Though the published data (NIID, 2020), clearly stated that among the confirmed COVID-19 cases with recorded symptom onset, 92 cases occurred among passengers in cabins without a previously confirmed cases during the quarantine period. Moreover, in the period after the incubation median day during the quarantine, 71% of the new cases occurred in cabins without a previous confirmed case, and 29% occurred in cabins with a previous confirmed case. And secondly, Xu *et al*. (2020) claimed that "It was also reported that the maximum outdoor air supply was operated during the quarantine period," but did not provide a reference to support this claim, and still to date, we could find no evidence that the Diamond Princess cruise ship had actually operated its HVAC on a maximum air supply during COVID-19 outbreak. Finally, the authors reported that "During the quarantine period, passengers stayed in their rooms, and the outer cabins had access to balcony doors" and they did not reveal that at least 30% of the cabins onboard, and which are usually the most occupied cabins due to their lower price, had no access to fresh air and were totally dependent on the ship' HVAC because they are interior cabins.

Nonetheless, and close to our results, a study that analysed two COVID-19 outbreaks on buses and places of worship has strongly suggested that the conditioning system on a re-circulating mode may have facilitated the spread of COVID-19 virus during outbreaks (Shen, 2020). The same study showed that passengers sitting closer to the index case on the exposed bus did not have statistically higher risks of COVID-19 as those sitting further away. The study also showed that all passengers sitting close to a window remained healthy which may be due to better airflow (Shen, 2020).

Likewise, the authors in another study; Correia *et al*. (2020), have addressed HVAC as major source for indoor and environmental contamination that can explain the swift viral spread of COVID-19. The authors of this study believed that airborne transmission is possible, and that HVAC systems, when not adequately used, may contribute to the transmission of COVID-19 virus.

In fact, airborne transmission mode plays a significant role on cruise ships (Zheng *et al*., 2016) and researchers have often warned about the potential for cruise ship viral outbreaks (Saginur and Birk, 2005; Ferson *et al.*, 2005; Fernstrom and Goldblatt, 2013; Zheng *et al*., 2016; Rogers *et al.*, 2017). Ruby Princess is another cruise ship that had 576 cases of COVID-19 in 2020 (The Guardian, 2020). Other cruise ships which have witnessed COVID-19 in 2020 are Westerdam, and Voyager of the Sea (CDC, 2020).

With a large number of people sharing facilities, same stocks of food and water, and air conditioning systems (Ferson and Ressler, 2005), such close and crowded quarters promote transmission of airborne pathogens (Ferson and Ressler, 2005; Hadjichristodoulou *et al*., 2011). Viruses onboard can be easily transmitted from one person to another by inhalation of air that contains aerosols or droplets from the infected person who cough or sneeze (Mouchtouri *et al*., 2009). It has been suggested that coughing may produce as many as 3000 droplet nuclei (droplets with a size of ≤ 5 µm) (Cole and Cook, 1998; Fitzgerald and Haas, 2005; Tang *et al*., 2006). Besides infectious persons, airborne transmission can be released from heating, ventilation, and air conditioning (HVAC) systems (Cole and Cook, 1998). Airborne transmission happens when viruses are carried by dust or droplet nuclei suspended in air (Remington *et al*., 1985). Airborne dust can be resuspended by air currents after settling on any surface and droplet nuclei could remain suspended in the air for a long time and may travel long distances (Remington *et al*., 1985). COVID-19 was detectable in aerosols for up to three hours (Doremalen *et al*., 2020), and viral COVID-19 viable virus was isolated for up to 28 days at 20°C from common surfaces such as glass, stainless steel and both paper and polymer banknotes (Riddell *et al.*, 2020). COVID-19 viable RNA was also identified from air sampling of airborne infection isolation rooms in a general ward (Chia *et al*., 2020).

Actually, any enclosed space with dense population such as aircrafts, hospitals, etc, is susceptible to airborne transmission (Ferson and Ressler, 2005; Marks *et al*., 2000; Fernstrom and Goldblatt, 2013; Lu *et al*., 2020). One study; Kim *et al*. (2016), has found evidence to support the distant airborne transmission of Middle East respiratory syndrome coronavirus (MERS-CoV) in hospitals, in which MERS-CoV particles have been concentrated in exhaust air grills. In cruise ships, researchers have concluded that a higher ventilation rate could lead to a lower number of transmitted virus cases (Zheng *et al*., 2016). In a simulation study, HEPA filters and ultraviolet germicidal irradiation (UVGI) devices in ventilation systems were the most effective measures to control influenza on cruise ships ((Zheng *et al.*, 2016). They are shown to be more effective than masks worn by crew members and quarantining procedures (Zheng *et al.*, 2016).

A systematic review has shown strong evidence regarding the association between ventilation, airflow in buildings and the transmission of infectious diseases such as tuberculosis, influenza, and SARS (Li *et al*., 2007). The study showed that air flow and ventilation can affect how diseases spread indoors (Li *et al*., 2007). In an outbreak of COVID-19 in a restaurant in Guangzhou, China, transmission was prompted by air-conditioned ventilation and the key factor for infection was the direction of the airflow (Lu *et al*., 2020). One of the recommendations from the Lu *et al*. (2020) study was to prevent the spread of the viruses through improving ventilation. Even speech droplets, which can remain suspended for tens of minutes or longer and are eminently capable of transmitting disease in confined spaces, are influenced by the air flow and dominated by the ventilation rate (Stadnytskyi *et al*., 2020).

Although Yamagishi *et al*. (2020) detected SARS-CoV-2 RNA in a ceiling vent on the Diamond

Princess, they assumed this was likely to be the result of a projectile droplet and concluded that they did not find evidence of airborne transmission on the ship. They attributed all the detected RNA in case cabins to environmental surfaces transmission only in spite of lower rates of SARS-CoV-2 RNA detected in samples from surfaces with high frequency of hand-touching such as doorknobs. They proposed this result may have been due to conducting air sampling only after the case left the cabin resulting in lower viral load in the air, and the relatively short sampling time (20 minutes). Nonetheless, Yamagishi *et al*. (2020) highlighted the need for further studies to examine the possibility of airborne transmission of SARS-CoV-2 and the effect of stopping air recirculation in the cruise ship during the COVID-19 outbreak.

Morawska and Cao (2020) have emphasised the importance of national authorities and international institutions acknowledging the reality of airborne transmission mode of COVID-19, and recommend that adequate control measures should be implemented to prevent further spread of the COVID-19. The study (Morawska and Cao, 2020) quoted another study (Qian and Zheng, 2018) when mentioning all the possible precautions that should be taken against airborne transmission in indoor settings. These precautions include increased ventilation rate, using natural ventilation, avoiding air recirculation, avoiding staying in another person's direct air flow, and minimizing the number of people sharing the same environment (Qian and Zheng, 2018).

Our current study has several limitations. First and foremost, the incompleteness and quality of the published data used to compare the infection rates. Only summary data were available, and some counts were given as approximations. Data were not available on relevant factors such as the spatial distribution of passengers in the interior and outer cabins, and passengers' prior health conditions. Second, assumptions such as interaction levels with the crew members were the same for all passengers regardless whether their cabins had or had not previous confirmed cases may not be accurate. Third, though we are not discounting other important transmission modes such as close-contact droplets and fomites, in this study, we only considered the airborne transmission mode to explain why the infection rate with COVID-19 in passengers' cabins with previous cases was not higher than in cabins without previous confirmed cases after day 5 (incubation period median day) of the quarantine. Finally, we have not conducted an experiment to test the proposed airborne transmission mode through the HVAC system.

4 CONCLUSIONS

Airborne transmission of COVID-19 through poorly filtered and poorly ventilated, recirculated air onboard ship could explain the higher than expected virus spread into cabins without previously confirmed cases during the quarantine period.

There is accumulating evidence of COVID-19 spreading widely in confined settings such as restaurants, hospitals, care homes, shops, gyms, public transport, offices, schools, prisons, etc. Ventilation system design, filters, and upgrades; natural ventilation (just using outside air and not recirculating it); and airflow (direction/speed) should be all considered and evaluated when deciding what intervention measure(s) is appropriate to reduce exposure and limit the transmission of COVID-19 in a confined setting. Keeping two meters distance between customers in a shop, for instance, is not an effective measure without considering the air flow inside the shop. Self-isolating residents of a care home inside the rooms is not an effective measure if the ventilation system in the care home does not have highly-efficient filters that can capture a virus as small as COVID-19, especially if the HVAC system is working on a save-energy mode and the air is kept recirculated inside the residence.

ACKNOWLEDGEMENTS

I would like to acknowledge Professor Peter Thomas (retired), Doctor Jonathon Snook at Poole hospital (UK), Professor Brendan Murphy in the Mathematics and Statistics school at University College Dublin (UCD, Ireland), and Doctor Sharon Docherty, in the Medical Science and Public Health at Bournemouth University (UK) for their kind contributions in this study. I also thank the two anonymous reviewers for their critical readings, insightful comments, and useful suggestions which led to improving and clarifying this manuscript substantially.

SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at https://doi.org/10.4209/aaqr.200495

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