Can Ship Travel Contain COVID-19 Outbreak After Re-Opening: A Bayesian Meta-analysis

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Summary

Large gatherings of people on cruise ships and warships are often accompanied by an increase in the risk of COVID-19 infections. To assess the transmissibility of SARS-CoV-2 on warships and cruise ships and to quantify the effectiveness of containment measures. The transmission coefficient ($\beta$), basic reproductive number ($R_0$), and time to deploy containment measures were estimated by the Bayesian Susceptible-Exposed-Infected-Recovered model. A meta-analysis was conducted to predict vaccine protection with or without non-pharmaceutical interventions. NPIs during the voyage could reduce the transmission coefficients of SARS-CoV-2 by 50% estimated from the meta-analyses. Two weeks into the voyage of a cruise that begins with 1 infected passenger out of 3711, we estimate there would be 45 (95% CI:25-71), 33 (95% CI:20-52), 18 (95% CI:11-26), 9 (95% CI:6-12), 4 (95% CI:3-5), and 2 (95% CI:2-2) final cases under 0%, 10%, 30%, 50%, 70% and 90% vaccines protection without NPIs, respectively. Timeliness of strict NPIs accompanied by quarantine and isolation is imperative when COVID-19 cases are introduced into cruise ships. The spread of COVID-19 on ships was predicted to be limited in scenarios corresponding to at least 70% protection from prior vaccination across all passengers and crew.

Keywords: COVID-19; cruise ship; warship; basic reproductive number; the Bayesian SEIR model
Introduction

Large gatherings of people in semiconfined settings, such as on cruise ships and warships, are often accompanied by an increase in the risk of infections. [1] Previous studies have already shown high attack rates in the COVID-19 outbreak on cruise ships [2, 3] where the complex and frequent movements of passengers on a cruise ship, and high levels of direct and indirect personal contact facilitate the spread of SARS-CoV-2. [4] High population density on warships and also cruise ship renders these settings susceptible to pathogens harbored in the respiratory tract and digestive lumen. [5-7]

The first cruise ship to have a major Severe Acute Respiratory Syndrome Coronavirus (SARS-CoV-2) outbreak on board was the Diamond Princess in February 2020 [8] in the wake of the original community-acquired outbreak identified in China in December 2019. [9, 10] The first major SARS-CoV-2 outbreak on a naval ship was onboard the Theodore Roosevelt aircraft carrier in March 2020. After these, at least 50 outbreaks occurred during cruise ship voyages, yielding more than 1100 confirmed cases, and over 20 naval ships, resulting in 2500 confirmed cases as of March 2021. [11, 12] Based on these reports, we decided to conduct a systematic review and meta-analysis to elucidate whether the transmissibility of SARS-CoV-2 is heterogeneous across these outbreaks.

Around 30 million people were transported worldwide on cruise ships in 2019,
up 6% from 28.2 million in 2018. [13] Unfortunately, many cruise lines around the world have been suspended with cruise ships unable to operate during the pandemic for fear of fostering large outbreaks of disease. It is therefore imperative to provide guidance for forestalling suspicious COVID-19 outbreaks on cruise ships, and indeed warships, once suspected COVID-19 cases are identified. [14] It is worthy of investigating whether isolation of suspected cases on board is sufficient to control an outbreak, or if a return to port followed by quarantine on land is necessary, and how these containment measures are potentially affected by vaccination.

Hence, the aims of our study are two-fold. One is to estimate relevant parameters related to the transmissibility of SARS-CoV-2 and examine whether the transmissibility of SARS-CoV-2 on cruise ships and warships was consistent across ship-based outbreaks by pooling multiple data from all outbreaks occurring onboard on the basis of meta-analysis. The other is to assess the effectiveness of NPIs (non-pharmaceutical interventions) given different coverage rates of vaccination.
Materials and Methods

The data of COVID-19 outbreaks on cruise ships and warships obtained from public messages [15-18] and the literature [19-25] was used to estimate the parameters of a compartmental model. The characteristics of COVID-19 outbreaks on cruise ships and warships were listed in Table 1. Detailed information about these outbreaks in the six ships enrolled in this study is described in the appendix (Table A1).

The Bayesian DAG of Meta-analysis with a SEIR model underpinning

To model the dynamics of COVID-19 evolution on each ship, a four-compartment model of susceptible-exposed-infectious-removed (SEIR) was applied. The compartmental model based on the characteristics of COVID-19 was shown in Figure A1 of the Appendix with detailed relationships and notations. In brief, the subjects on board were divided into four compartments namely, individuals susceptible to SARS-CoV-2 (S(t)), those exposed and infected but not yet infectious (E(t)), those infectious (I(t)), and those who have been removed from the infectious compartment (R(t)). The S(t), E(t), I(t), and R(t) denote the number of cases at time t. Importantly, we assume that infectious individuals can enter the removal (R) state either because they recover from infection in the traditional sense and become immune, or because they are fully and perfectly isolated from the rest of the onboard
subjects. Given an effective exposure, the SEIR model assumes that all subjects of the exposed state (E) progress to the infectious state (I). The model was used to evaluate the propagation of SARS-CoV-2 causing COVID-19 from the outbreaks of warships and cruise ships. Following a previous application of an SEIR model for COVID-19 clustered events on board [24], the propagation of COVID-19 outbreaks on each ship was driven by the transmission coefficient (β), the reciprocal of the infectious period (α), and the recovery rate (σ). Important assumptions in our SEIR model are as follows. (1) All cases in the E state will move into the infectious state by definition because we want to model the undetectable cases for evaluating the effect of NPIs. Therefore, all cases of the E state became detectable cases (I+R compartment) later. (2) The E state referred to cases that were initially infected but undetectable (unobserved). If these cases are identified by test or the presence of symptoms they are then considered to be in an infectious state. A detectable case is defined as an individual who can be identified by a test or the presence of symptoms during an outbreak. The ratio of symptomatic and pre-symptomatic cases is dependent on the testing strategy used. For example, both were included in the outbreak on Greg Mortimer; whereas only the symptomatic case was included in outbreaks on the voyage of the Charles de Gaulle aircraft carrier and Theodore Roosevelt aircraft carrier. Therefore, the number of predicted observed cases (detectable cases) was the
total number of persons in the I and R compartment. The number of total predicted
cases, including undetectable and detectable cases, was the total number of persons in
the E, I, and R compartment in this model. (3) We assumed similar transmission
probability between symptomatic and asymptomatic cases. (4) Although some crews
and passengers left the board in batches without contacting other people after landing,
a close population was still considered during the period to stay on board. Therefore,
their status still needed to be followed by their testing results. By solving the
nonlinear ordinary differential equations of the SEIR model, the expected number of
subjects at each component can be derived as a function of the three parameters. In
addition, we define the time at which containment measures are successful as the time
beyond which no member of the S class progresses to the E class. Therefore, the
estimated shortest time of successful containment measures (no member of the S class
progresses to the E class), was at the moment of the number of final observed cases
inside the CI of predicted total cases (E+I+R) in our model.

Stemming from the SEIR model mentioned above, we developed a Bayesian
meta-analysis model depicting the COVID-19 outbreak for the six ships enrolled in
this study. Figure 1 shows the Bayesian directed acyclic graphic (DAG) of our meta-
analysis model. The observed number of COVID-19 cases on ship \( k \) on day \( j \) provides
information on the expected numbers of infectious and removed subjects. This
information, together with the fixed number of total onboard subjects for ship k, was used for the estimation of the three parameters, $\beta_k$, $\alpha_k$, and $\sigma_k$, embedded in the SEIR model. For ships that implemented NPIs, the impact on COVID-19 transmission was captured by the transmission coefficient $\beta'_k$. The daily number of COVID-19 cases provides information on the evolution of the four compartments. A normal distribution was applied to capture the expected count of compartments S and E. Regarding the daily count of I and R, one of the distributions of normal, binomial, or Poisson was selected depending on the convergence status by using the trace plot of sampling history. [24]

Using the Bayesian meta-analysis model, the information on COVID-19 propagation on each type of ship was integrated to derive the posterior information on the distribution of the three main parameters and the effectiveness of NPIs on containing COVID-19 outbreaks on ships. In addition, meta-analyses were also conducted on these outbreaks on cruise ships and warships, respectively. We used random effects on the log scale to capture the heterogeneity across ships for each parameter.

While informative priors for the two disease progression parameters $\sigma_k$ and $\alpha_k$ were used to fit the mean duration from exposure to infectious and from infectious to recovered for 5.25 (95% CI: 4-7) and 7 (95% CI: 5-12) days in the COVID-19
outbreak of Diamond Princess Cruise Ship, respectively [10, 24, 26], non-informative priors were used for transmission coefficient with (β_k') and without (β_k) NPI.

To cope with the uncertainty of full joint parameters related to these outbreaks, the Bayesian Markov Chain Monte Carlo (MCMC) was applied to estimate the transmission coefficients, recovery, and incubation rates, and their 95% credible intervals (CI) of COVID-19 outbreaks on each ship. The posterior distributions of the common transmission coefficient with (β_c') and without (β_c) NPIs, and the two disease progression parameters (α_c, and σ_c) were also derived from the Bayesian meta-analysis model.

With this integrated information on COVID-19 propagation, future outbreaks on cruise ships under different scenarios including the implementation of NPIs and levels of vaccine protection for onboard subjects can be predicted (right plate, Figure 1). Specifically, we envisaged a cruise ship of the size of Diamond Princess with a total of 3711 crews and passengers on board heading for a 14-day voyage, with a single person in the infectious state (I) on initiation of the voyage (day 0), who was then discovered on the 7th day of the voyage. We then considered how the imposition of NPIs at that point would affect the subsequent size of the outbreak, and additionally assessed the impact of 0%, 10%, 30%, 50%, 70%, and 90% of the ship’s population having been previously successfully vaccinated against SARS-CoV-2, where the
influence of vaccine protection was captured by a reduction in transmission coefficient written by $\beta_c^* = \beta_c \times (1 - \text{Vaccine protection})$ and $\beta_c' = \beta_c' \times (1 - \text{Vaccine protection})$ for the scenario without and with NPIs, respectively. In each case, we used Bayesian Markov Chain Monte Carlo (MCMC) methods to estimate the final outbreak size and the total number of detectable cases during the voyage if there were 1 or 5 infectious cases boarding ships initially.

Results

Descriptive characteristics of COVID-19 outbreaks on each of the ships used in this study are listed in Table 1. Table 2 shows the results of both parameters, transmission coefficient $\beta$ (per day) and $R_0$, which were estimated by the Bayesian SEIR model with and without NPIs.

Note that the total number of COVID-19 detectable and final cases were predicted by the Bayesian SEIR model (Figure 2(b)-(d) and Figure 3; appendix Table C4-C5). The reported cases and predicted cases by the model in these outbreaks are shown in Figure 2-3. The time of disembarking quarantine, such as on the Panshi fast combat support ship, the Charles de Gaulle aircraft carrier, and the Diamond Princess Cruise Ship, was highly associated with stopping the spread of COVID-19 on ships in our models because the potential cases in the E state and confirmed cases (I state + R state) at that time were very close to the final size of outbreaks in our model (Table 2).
In addition, the date of successful containment measures was later than the date of disembarking quarantine in the others. So, on-board quarantine alone seemed not to stop the spread of COVID-19.

Both estimates were relatively high with consistent figures ranging from 0.66 (95% CI:0.44-0.91) to 0.92 (95% CI:0.90-0.94) for the transmission coefficient, \( \beta \) (per day), and \( R_0 \) ranging from 4.62 (95% CI:3.06-6.32) to 6.45 (95% CI:6.24-6.68) without NPIs (Figure 4). The forest plots of the overall effective size of \( R_0 \) with or without NPIs are shown in Figure 4. The pooled estimates after meta-analysis were 0.79 (95% CI:0.72-0.87) and 5.67 (95% CI:4.74-6.88).

Transmission coefficients and effective reproductive numbers (\( R_t \)) including cruise ships and warships were reduced after the application of NPIs with a range from 0.17 (95% CI:0.16-0.19) to 0.69 (95% CI:0.54-0.84) for \( \beta \) and 1.21 (95% CI:1.12-1.30) to 4.87 (95% CI:3.81-5.95) for \( R_0 \). The pooled estimate for \( R_t \) was 1.99 (95% CI:1.09-3.01), which was smaller than that of \( R_0 \) (Figure 4b).

**Effectiveness of NPIs and Vaccination**

Strict infection control measures could reduce COVID-19 transmission by 57.9% for the Taiwan Panshi fast combat support ship, and 81.9% for the Theodore Roosevelt aircraft carrier, respectively. Meanwhile, according to the transmission
coefficients estimated from the meta-analysis NPIs could reduce COVID-19 transmission by 49.5%.

Figure 5 shows the number of COVID-19 detectable cases and predicted total cases under 0%, 10%, 30%, 50%, 70%, and 90% vaccine protection during the voyage of the cruise ship based on 300 simulations from the model posterior. According to the results of the Bayesian hierarchical model (Figure 4a-4b), the prior distributions of $\sigma$, $\alpha$, and the logarithm of $R_0$ without or with the control of NPIs were assigned as gamma distribution (shape: 641.5, inverse-scale: 3409), gamma distribution (shape: 649, inverse-scale: 4557), normal distribution (mean: 1.7298, SD:0.0893), and normal distribution (mean: 0.6522, SD: 0.2453), respectively (Figure 5). In the simulation of Bayesian SEIR models with above-mentioned parameters, there would be 45 (95% CI:25-71), 33 (95% CI:20-52), 18 (95% CI:11-26), 9 (95% CI:6-12), 4 (95% CI:3-5), and 2 (95% CI:2-2) final cases under 0%, 10%, 30%, 50%, 70%, and 90% vaccines protection without NPIs during two weeks of the voyage, respectively. (Table C6-C11 in the Appendix). On a 14-day voyage where the first case is only discovered on the 7th day of the voyage, the final size of outbreaks under different vaccine protection scenarios with or without NPIs is shown in Figure 6 (Table C12). There would be 17 (95% CI:11-25), 14 (95% CI:9-19), 9 (95% CI:6-11), 5 (95% CI:4-6), 3 (95% CI:2-3), and 2 (95% CI:1-2) final cases under 0%, 10%, 30%,
50%, 70%, and 90% vaccines protection, and NPIs was performed immediately when symptomatic cases were found on day 7, respectively. If all passengers and crews are under at least 70% protection from vaccination then we predicted the total size of a COVID-19 outbreak in a scenario like this to be below 5 cases, regardless of whether NPIs are implemented or not on day 7. But the limited spreading of COVID-19 (below 5 cases) can be expected under higher levels of vaccine protection even if there is more than 1 infectious case on board at the start of the voyage; for example, our simulated results show how the final size of COVID-19 cases would have been reduced to 3 (95% CI:2-3) had 70% of the passengers and crew been covered by vaccine compared with the corresponding 17 (95% CI:11-25) COVID-19 cases under the real scenario in the era without the vaccine.

Discussion

To our knowledge, this is the first comparison of COVID-19 outbreaks on different ships. The R$_0$ of COVID-19 was estimated using data from a series of outbreaks on cruise ships and warships in the Bayesian SEIR model. On-board quarantine alone seemed not to stop the spread of COVID-19. Across individual ships, we observed a range of reductions in COVID-19 transmission under strict infection-control measures from 57.9 – 81.9%. Subject to the assumptions of our meta-analysis, we found that R$_0$ was lowered to around 73% of its original value by the introduction
of NPIs on ships.

$R_0$ was estimated as 5.73 for the COVID-19 outbreak on the Diamond Princess cruise ship in this study. This result was similar to previous reports [27-29] and consistent with other outbreaks on the Grand Princess and Polar expedition cruise ships in our study. We note the high transmissibility of SARS-CoV-2 on cruise ships and warships found in our study and the fact that it may be spread via air, droplets, and fomites. Indeed, the persistence of coronaviruses, such as Severe Acute Respiratory Syndrome (SARS) coronavirus, Middle East Respiratory Syndrome (MERS) coronavirus, or endemic human coronaviruses on inanimate surfaces for up to 9 days has been reported. [30] Diarrhea occurred in about 10% of COVID patients [31] and the finding of 2019-nCoV particles in stool specimens indicates a fecal-oral route for coronavirus, [31, 32] which could account for why it’s caused outbreaks on cruise ships with an intensity often seen in the past with gastro-causing norovirus. The fecal spread could present new challenges to the virus's containment on cruise ships and warships. Environmental decontamination was never mentioned as a precaution taken on any of the ships studied here and perhaps this could therefore explain why on-board quarantine and isolation alone did not appear sufficient to prevent the further spread of COVID-19 on these ships.

Nevertheless, NPIs during the voyage, such as wearing masks, eating at table in
separate sittings, and isolation of flu-like cases appeared to substantially reduce COVID-19 transmission in this study. Furthermore, the effectiveness of quarantine and isolation in reducing the number of infected passengers was 37% during the outbreak of the Diamond Princess cruise ship. [24] Strict NPIs, including wearing an N95 mask, full PPE, and cases isolation, could not however stop transmission of COVID-19 on the Greg Mortimer expedition cruise ship, which may have continued from cross-contamination via crew’s meal services and other asymptomatic cases because rapid antibody COVID-19 testing of patients may be a high false negative rate in the acute phase. In addition, only testing symptomatic cases and the isolation of them with their contacts are insufficient because many patients were asymptomatic.

[23] Furthermore, quarantine aboard the Panshi fast combat support ship for a period of 6 days before disembarkation (9-15 April) seems not to have prevented the spread of COVID-19 onboard the ship.

Asymptomatic cases may be the potential sources of SARS-CoV-2 infection and the key to controlling outbreaks. In addition, asymptomatic SARS-CoV-2 transmission with high viral load has been reported. [33] Under the assumption of the same transmission probability between symptomatic and asymptomatic cases, our SEIR model fitted well to data from different outbreaks on cruise ships and warships. The fraction of pre-symptomatic transmission events out of pre-symptomatic plus
symptomatic transmission events was 37% [95% confidence interval (CI), 27.5 to 45%] in a previous study. [34] High proportions of asymptomatic cases were found in outbreaks on ships, which may result from a higher proportion of latent cases. Therefore, COVID-19 continues to spread during the on-board quarantine period because these asymptomatic cases cannot be easily detected and universal testing of all passengers and crew was rarely performed.

A major COVID-19 outbreak will be potentially triggered while cruise ships are moving. The cruise industry has stopped due to the huge impact of COVID-19. Even if the vaccine coverage rate was 100% among passengers and crew, the effectiveness of 2-dose messenger RNA (mRNA) or adenovirus vectored COVID-19 vaccines will be imperfect and is likely to wane over time and in the face of new variants of SARS-CoV-2. [35, 36] This study introduces some frameworks to allow the resumption of the cruise industry in the post-COVID-19 era. For example, if one asymptomatic COVID-19 person boards the cruise ship for a two-week trip and there is greater than 70% vaccine protection among the passengers and crews, then our simulation results suggest that even without NPIs there will be only limited COVID-19 cases during such a voyage. Furthermore, it appears that it may be possible to readily control the spread of COVID-19 on a cruise ship that has more than 90% vaccine protection among passengers and crew even if 5 infectious cases board the cruise ship. However,
new strains of SARS-CoV2 have been developed and even high vaccine coverage seems to be limited to protection from infection. Hence, it might seem prudent that NPIs should still be performed immediately when any new case emerges arising from new subvariants after re-opening in the post-COVID-19 pandemic era. In addition, full disembarkation and quarantine should be considered because on-board isolation and quarantine alone do not appear to be enough to stop the spread of COVID-19 onboard a ship.

There were some limitations to our modeling and estimates of the $R_0$ of COVID-19, most obviously the assumptions of a close population even with leaving the board in batches, a homogeneous random mixing population, and no difference of transmission probability between symptomatic and asymptomatic cases. The estimated results on the transmission parameters for Grand Princess Cruise Ship may be biased towards underestimation because not everyone on board was tested. [37] In addition, the basic and effective reproductive number may be underestimated because only the finally detectable cases were modeled, which is affected by the different testing strategies. All undetectable cases, such as asymptomatic cases without receiving testing, did not enter the infectious state in this study. However, consistent results were obtained from the different outbreaks under consideration. Most of the outbreaks that took place on cruise ships and warships were reported during the
Wuhan strain and Alpha VOC period. Furthermore, only the aggregate data on the number of cases that evolved through the clustered event without detailed information on the history of previous infections were available. The evaluation of the protective effectiveness derived from the infection by ancestral strains was thus hampered. In addition, potential changes in the reproduction number of SARS-CoV-2 variants [38] are not considered in our model. However, as the omicron variants and subvariants had higher transmissibility and immune escape than the ancestral strain [39], and vaccination protection against emerging variants strains may not be desirable due to weaning immunity. Hence, the results of our simulation will be the best scenarios for the prediction of the future challenge in the post-COVID-19 pandemic era. However, given a body of evidence indicating an enhanced and long-lasting immune response built on hybrid immunity [40], passengers and crews recovered from previous infections with updated vaccination status can further secure the safety on board in terms of the risk of the COVID-19 outbreak.

In conclusion, we find the limited spread of SARS-CoV-2 during two weeks of a voyage under at least over 70% of vaccine protection with NPIs. The crew with masks for any contact with passengers is suggested. Furthermore, testing for symptomatic cases with their contacts disembarked quarantine, and isolation of symptomatic/asymptomatic cases should nevertheless be performed as soon as
possible when COVID-19 cases are found on ships because of the high proportion of asymptomatic/pre-symptomatic cases likely to be present. Of course, a higher rate of updated vaccination protection among the crew and passengers is necessary for stopping the spreading of COVID-19 on cruise ships.

Data availability statement

The data that support the findings of this study are openly available in the public domain and in the literature [15-25]. They are listed in the Appendix.

Acknowledgments

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Contributors

CCL, CYH, JKC, and PSW contributed to the study conception/design. CYH and JKC took the responsibility for drafting the manuscript. CCL, CYH, and JKC took the responsibility for statistical analysis. MFY, LSC, and HHC contributed to the study
conception and the accuracy of the data analysis. CCL, HHC, and PSW reviewed and revised the article.

Conflict of interest

All authors declared no competing interests.

References


Table 1. Characteristics of COVID-19 outbreaks from empiric data on cruise ships and warships

<table>
<thead>
<tr>
<th>Name of ships</th>
<th>Total number of persons on board</th>
<th>Total number of cases (%)</th>
<th>Asymptomatic cases (%)</th>
<th>Testing strategy</th>
<th>NPIs</th>
<th>The period of NPIs</th>
<th>NPIs actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panshi Fast Combat Support Ship</td>
<td>377</td>
<td>44 (11.7)</td>
<td>17 (38.6)</td>
<td>all sailors&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Yes</td>
<td>before 9 April</td>
<td>Wearing masks; At table in batch</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Isolated flu-like cases</td>
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<tr>
<td>Theodore Roosevelt aircraft carrier</td>
<td>4779</td>
<td>1271&lt;sup&gt;*&lt;/sup&gt; (26.6)</td>
<td>572 (43.0)</td>
<td>asymptomatic cases &lt;sup&gt;a&lt;/sup&gt; all crew&lt;sup&gt;b&lt;/sup&gt;</td>
<td>No</td>
<td>before 26 March</td>
<td>Onboard quarantine</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Disembarked quarantine</td>
</tr>
<tr>
<td>Charles de Gaulle Aircraft Carrier</td>
<td>1767</td>
<td>1148 (65.0)</td>
<td>130/1001 (13.0)</td>
<td>asymptomatic cases &lt;sup&gt;b&lt;/sup&gt; all service members&lt;sup&gt;a&lt;/sup&gt;</td>
<td>No</td>
<td>before 7 April</td>
<td>Contacts quarantine</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Onboard quarantine; Disembarked quarantine</td>
</tr>
<tr>
<td>Diamond Princess Cruise Ship</td>
<td>3711</td>
<td>761 (20.5)</td>
<td>410 (53.9)</td>
<td>asymptomatic cases &lt;sup&gt;c&lt;/sup&gt; All passengers&lt;sup&gt;a&lt;/sup&gt; all passengers and crew&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Yes</td>
<td>Before 3 Feb.</td>
<td>Onboard quarantine</td>
</tr>
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<tr>
<td>Greg Mortimer, Polar Expedition Cruise Ship</td>
<td>217</td>
<td>128 (60.0)</td>
<td>104 (81.3)&lt;sup&gt;**&lt;/sup&gt;</td>
<td>All passengers&lt;sup&gt;a&lt;/sup&gt; all passengers and crew&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Yes</td>
<td>After 16 Feb.</td>
<td>Disembarked quarantine Wearing PPE</td>
</tr>
<tr>
<td>Grand Princess Cruise Ship</td>
<td>3571</td>
<td>122 (3.4)</td>
<td>Not available</td>
<td>asymptomatic cases &lt;sup&gt;a&lt;/sup&gt;</td>
<td>No</td>
<td>before 10 March</td>
<td>Onboard isolation; Disembarked quarantine</td>
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R<sub>0</sub>: basic reproductive number; SEIR model: Susceptible-Exposed-Infected-Recovered model.

NPIs: Non-pharmaceutical interventions; <sup>a</sup> Testing after disembarkation; <sup>b</sup> Testing on voyage; <sup>c</sup> Testing during onboard quarantine.
PPE: Personal Protective Equipment. All passengers wearing surgical masks; The crew with N95 masks for any contact with passengers.

*Sixty-six suspected COVID-19 without laboratory-confirmed infection were not included.
† 130 asymptomatic cases were found among 1001RT-PCR confirmed cases.
** Pre-symptomatic plus symptomatic cases were supposed.
Table 2. Estimated results on parameters for COVID-19 propagation on each ship by using the Bayesian SEIR model.

<table>
<thead>
<tr>
<th>Name of ships</th>
<th>The date of disembarking or quarantine</th>
<th>Estimated by Bayesian SEIR model</th>
<th>The estimated shortest time of successful containment measures (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panshi fast combat support</td>
<td>15 April</td>
<td>(\beta = 0.273 \ (0.254-0.293)) (before 9 April)</td>
<td>1.92 (1.80-2.06)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\sigma = 0.189 \ (0.184-0.194)) (10-15 April)</td>
<td>4.62 (3.06-6.32)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\alpha = 0.142 \ (0.136-0.148)) (before 9 April)</td>
<td>38 (16 April)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(R_0 = 0.657 \ (0.439-0.905)) (before 9 April)</td>
<td>6.45 (6.24-6.68)</td>
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<td></td>
<td></td>
<td></td>
<td>(before 31 March)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.21 (1.12-1.30)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(1-11 April)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.29 (3.14-3.44)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(before 16 March)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5.15 (4.90-5.47)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(before 16 March)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5.18 (4.91-5.46)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(17 March to 7 April)</td>
</tr>
<tr>
<td>Theodore Roosevelt aircraft</td>
<td>26 March to 14 April</td>
<td>(\beta = 0.919 \ (0.898-0.939)) (before 31 March)</td>
<td>4.87 (3.81-5.95)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\sigma = 0.189 \ (0.184-0.194)) (1-11 April)</td>
<td>22 (5 April)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\alpha = 0.143 \ (0.137-0.148)) (before 31 March)</td>
<td>23 (14 March)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(before 31 March)</td>
</tr>
<tr>
<td>Charles de Gaulle aircraft</td>
<td>13 April</td>
<td>(\beta = 0.468 \ (0.444-0.488)) (before 16 March)</td>
<td>1.69 (0.61-2.92)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\sigma = 0.191 \ (0.186-0.196)) (before 16 March)</td>
<td>48 (15 April)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\alpha = 0.142 \ (0.137-0.149)) (before 16 March)</td>
<td>(8-13 April)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Diamond Princess Cruise Ship</td>
<td>16 February</td>
<td>(\beta = 0.796 \ (0.610-0.972)) (before 8 March)</td>
<td>5.73 (4.21-7.32)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\sigma = 0.187 \ (0.134-0.238)) (8-13 March)</td>
<td>28 (16 February)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\alpha = 0.143 \ (0.090-0.196)) (8-13 March)</td>
<td>(before 16 February)</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Greg Mortimer, polar</td>
<td>Cases quarantine onboard</td>
<td>(\beta = 0.693 \ (0.535-0.839)) (before 5 March)</td>
<td>4.87 (3.81-5.95)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\sigma = 0.189 \ (0.184-0.194)) (8-13 March)</td>
<td>22 (5 April)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\alpha = 0.142 \ (0.136-0.148)) (before 5 March)</td>
<td>(5 April)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(before 5 March)</td>
</tr>
<tr>
<td>Grand Princess Cruise Ship</td>
<td>10 March</td>
<td>(\beta = 0.735 \ (0.700-0.768)) (before 8 March)</td>
<td>5.18 (4.91-5.46)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\sigma = 0.189 \ (0.184-0.194)) (8-13 March)</td>
<td>23 (14 March)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\alpha = 0.142 \ (0.136-0.148)) (before 8 March)</td>
<td>(14 March)</td>
</tr>
</tbody>
</table>

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The shortest time of successful containment measures (no member of the S class progresses to the E class): the shortest time while the number of final observed cases was inside the CI of predicted total cases (E+I+R). $R_0$: basic reproductive number; SEIR model: *Susceptible-Exposed-Infected-Recovered* model.
CI: credible interval
Figure captions

Figure 1. Bayesian DAG of the meta-analysis model for COVID-19 propagation on ships

- \( N_k \): the total number of persons on the ship \( k \)
- \( \beta_k \): the transmission coefficient on the ship \( k \)
- \( \beta_k^\prime \): the transmission coefficient after NPI has been conducted on the ship \( k \)
- \( \alpha_k \): recovery rate or the reciprocal of time to removal on the ship \( k \)
- \( \epsilon_k \): the reciprocal of the incubation period on the ship \( k \)
- \( I[[]>\text{NPI}] \): a indicator variable for period under NPI measurements on the ship \( k \)

This model used random effect models to describe ship-specific parameter \( \theta_k (\theta_k = \beta_k, \beta_k^\prime, \alpha_k, \epsilon_k) \) which follows normal distribution centered at \( \theta_k \) with precision of \( \tau_k \).
Figure 2. COVID-19 outbreak of warships

[The “predicted detectable cases”, were symptomatic or asymptomatic cases that could be identified as COVID-19 cases following the presentation of classic symptoms or testing and thus include the I and R compartment in our model. The “predicted total infections” include those who have been effectively exposed and infected by SARS-CoV-2 but have yet to be identified as a COVID-19 case by all means, namely the E, I, and R compartment in our model.]

(a) The epidemic curve of COVID-19 outbreak (Note: 13 asymptomatic cases with RT-PCR positive, 4 asymptomatic cases with antibody positive, and one symptomatic case with antibody positive, without exact onset date, recorded by testing date) on the Panshi fast combat support ship

(b) The cumulated COVID-19 observed cases and predicted cases by the Bayesian SEIR model (R: basic reproductive number) on the Panshi Fast Support Ship
(c) The cumulated COVID-19 observed cases and predicted cases by the Bayesian SEIR model (R: basic reproductive number) on the USS Theodore Roosevelt aircraft carrier.

(d) The cumulated COVID-19 observed cases and predicted cases by the Bayesian SEIR model (R: basic reproductive number) on the French Charles de Gaulle aircraft carrier.
Figure 3. The cumulated COVID-19 observed cases and predicted cases by the Bayesian SEIR model on cruise ships. (R: basic reproductive number)

[The “predicted detectable cases” were symptomatic or asymptomatic cases that could be identified as COVID-19 cases following the presentation of classic symptoms or testing and thus include the $I$ and $R$ compartment in our model. The “predicted total infections” include those who have been effectively exposed and infected by SARS-CoV-2 but have yet to be identified as a COVID-19 case by all means, namely the $E$, $I$, and $R$ compartment in our model.]

(a) COVID-19 outbreak on the Diamond Princess Cruise Ship

(b) COVID-19 outbreak on the Grand Princess Ship

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(c) The COVID-19 outbreak on the Greg Mortimer, the polar cruise expedition ship

![Simulated cumulated cases on the polar cruise ship]

- Cumulated observed cases
- Predicted detectable cases by the model
- Predicted total infections by the model
- 95% CI of predicted total infections

Arrived at Montevideo

Testing all passengers and crew

Total 128 cases

Date of onset

The number of reported cases

The number of simulated cases

2020/03/15 2020/03/16 2020/03/17 2020/03/18 2020/03/19 2020/03/20 2020/03/21 2020/03/22 2020/03/23 2020/03/24 2020/03/25 2020/03/26 2020/03/27 2020/03/28 2020/03/29 2020/03/30 2020/03/31 2020/04/01 2020/04/02 2020/04/03 2020/04/04 2020/04/05 2020/04/06 2020/04/07 2020/04/08 2020/04/09 2020/04/10 2020/04/11 2020/04/12 2020/04/13 2020/04/14 2020/04/15
Figure 4. Forest plots for the overall effect of $R_0$ by the Bayesian hierarchical model

(a) The overall effect of $R_0$ for all cruise ships and warships without NPIs

<table>
<thead>
<tr>
<th>Ship Type</th>
<th>$R_0$ (95% CI)</th>
<th>$\beta$ (95% CI)</th>
<th>$\sigma$ (95% CI)</th>
<th>$\alpha$ (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pandu fast combat support ship</td>
<td>4.62 (3.06-6.32)</td>
<td>0.66 (0.44-0.91)</td>
<td>0.19 (0.18-0.20)</td>
<td>0.14 (0.14-0.15)</td>
</tr>
<tr>
<td>Theodore Roosevelt aircraft carrier</td>
<td>6.45 (6.24-6.68)</td>
<td>0.92 (0.90-0.94)</td>
<td>0.19 (0.18-0.19)</td>
<td>0.14 (0.14-0.15)</td>
</tr>
<tr>
<td>Charles de Gaulle aircraft carrier (before 31 March)</td>
<td>5.15 (4.90-5.47)</td>
<td>0.73 (0.70-0.77)</td>
<td>0.19 (0.19-0.20)</td>
<td>0.14 (0.14-0.15)</td>
</tr>
<tr>
<td>Diamond Princess Cruise Ship</td>
<td>5.73 (4.21-7.32)</td>
<td>0.80 (0.61-0.97)</td>
<td>0.19 (0.13-0.24)</td>
<td>0.14 (0.09-0.20)</td>
</tr>
<tr>
<td>Grand Princess Cruise Ship</td>
<td>5.18 (4.91-5.46)</td>
<td>0.74 (0.70-0.77)</td>
<td>0.19 (0.18-0.19)</td>
<td>0.14 (0.14-0.15)</td>
</tr>
<tr>
<td><strong>Effect of summary</strong></td>
<td><strong>5.67 (4.74-6.88)</strong></td>
<td><strong>0.70 (0.72-0.87)</strong></td>
<td><strong>0.19 (0.17-0.20)</strong></td>
<td><strong>0.14 (0.13-0.16)</strong></td>
</tr>
</tbody>
</table>

$R_0$: basic reproductive number; CI: credible interval; NPIs: non-pharmaceutical interventions.

(b) The overall effect of $R_0$ for all cruise ships and warships under the NPIs

<table>
<thead>
<tr>
<th>Ship Type</th>
<th>$R_0$ (95% CI)</th>
<th>$\beta$ (95% CI)</th>
<th>$\sigma$ (95% CI)</th>
<th>$\alpha$ (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pandu fast combat support ship</td>
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<td>0.14 (0.14-0.15)</td>
</tr>
<tr>
<td>Charles de Gaulle aircraft carrier (before 31 March)</td>
<td>5.50 (5.41-5.70)</td>
<td>0.79 (0.76-0.85)</td>
<td>0.19 (0.18-0.19)</td>
<td>0.14 (0.14-0.15)</td>
</tr>
<tr>
<td>Diamond Princess Cruise Ship</td>
<td>5.73 (4.21-7.32)</td>
<td>0.80 (0.61-0.97)</td>
<td>0.19 (0.13-0.24)</td>
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<td>Theodore Roosevelt aircraft carrier</td>
<td>1.21 (1.12-1.39)</td>
<td>0.17 (0.16-0.19)</td>
<td>0.19 (0.15-0.20)</td>
<td>0.14 (0.16-0.15)</td>
</tr>
<tr>
<td>Pandu fast combat support ship</td>
<td>1.92 (1.80-2.06)</td>
<td>0.27 (0.25-0.29)</td>
<td>0.19 (0.18-0.19)</td>
<td>0.14 (0.15-0.15)</td>
</tr>
<tr>
<td><strong>Effect of summary</strong></td>
<td><strong>5.67 (4.74-6.88)</strong></td>
<td><strong>0.70 (0.72-0.87)</strong></td>
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</tr>
</tbody>
</table>

$R_0$: basic reproductive number; CI: credible interval; NPIs: non-pharmaceutical interventions.