COVID-19 outbreak on the Diamond Princess cruise ship: estimating the epidemic potential and effectiveness of public health countermeasures

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Abstract:

Background: Cruise ships carry a large number of people in confined spaces with relative homogeneous mixing. On 3 February, 2020, an outbreak of COVID-19 on cruise ship Diamond Princess was reported with 10 initial cases, following an index case on board around 21-25 January. By 4 February, public health measures such as removal and isolation of ill passengers and quarantine of non-ill passengers were implemented. By 20 February, 619 of 3,700 passengers and crew (17%) were tested positive.
Methods: We estimated the basic reproduction number from the initial period of the outbreak using (SEIR) models. We calibrated the models with transient functions of countermeasures to incidence data. We additionally estimated a counterfactual scenario in absence of countermeasures, and established a model stratified by crew and guests to study the impact of differential contact rates among the groups. We also compared scenarios of an earlier versus later evacuation of the ship.
Results: The basic reproduction rate was initially 4 times higher on-board compared to the R_0 in the epicentre in Wuhan, but the countermeasures lowered it substantially. Based on the modeled initial R_0 of 14.8, we estimated that without any interventions within the time period of 21 January to 19 February, 2920 out of the 3700 (79%) would have been infected. Isolation and quarantine therefore prevented 2307 cases, and lowered the R_0 to 1.78. We showed that an early evacuation of all passengers on 3 February would have been associated with 76 infected persons in their incubation time.
Conclusions: The cruise ship conditions clearly amplified an already highly transmissible disease. The public health measures prevented more than 2000 additional cases compared to no interventions.

However, evacuating all passengers and crew early on in the outbreak would have prevented many more passengers and crew from infection.

Introduction

Cruise ships carry a large number of people in confined spaces with relative homogeneous mixing over a period of time that is longer than for any other mode of transportation.[1] Thus, cruise ships present a unique environment for transmission of human-to-human transmitted infections. The association of acute respiratory infections (ARI) incidence in passengers is statistically significant with season, destination and duration of travel.[2] In February 2012, an outbreak of respiratory illness occurred on the cruise ship off Brazil, resulting in 16 hospitalizations due to severe ARI and one death.[3] In May 2020, a dual outbreak of pandemic (H1N1) 2009 and influenza A (H3N2) on a cruise ship occurred: of 1,970 passengers and 734 crew members, 82 (3.0%) were infected with pandemic (H1N1) 2009 virus, and 98 (3.6%) with influenza A (H3N2) virus.[4] Four subsequent cases were epidemiologically linked to passengers but no evidence of sustained transmission to the community or passengers on the next cruise was reported.[4] In September 2000 an outbreak of influenza-like illness was reported on a cruise ship sailing off the Australian coast with over 1,100 passengers and 400 crew on board, coinciding with the peak influenza period in Sydney.[5] The cruise morbidity was high with 40 passengers hospitalized, two of whom died. A total of 310 passengers (37%) reported suffering from an influenza-like illness.

In December 2019, a novel coronavirus emerged in Wuhan, China, now named SARS-CoV-2, and rapidly spread to all provinces in China and then to various global cities with high interconnectivity with China.[6,7] The resulting ARI due to this coronavirus, a disease now coined COVID-19, is thought to be mainly transmitted by respiratory droplets from infected people. The mean serial interval of COVID-19 is 7.5 days (95% CI, 5.3 to 19) and the initial estimate for the basic reproductive number R_0 was 2.2 (95% CI, 1.4 to 3.9),[8] although higher R_0 have since been reported with a mean now of more than 3.[9] On 18 February 2020, China`s CDC published their data of the first 72,314 cases including 44,672 confirmed cases.[10] About 80% of the confirmed cases were reported to be mild disease or less severe forms of pneumonia, 13.8% severe and 4.7% critically ill. Risk factors for severe disease outcomes are older age and co-morbidities. The progression to acute respiratory distress syndrome occurs approximately 8-20 days after onset of first symptoms, with lung abnormalities on chest CT showing greatest severity approximately 10 days after initial onset of symptoms. [11-13,14] Increasingly, evidence is mounting that also mildly symptomatic or asymptomatic cases can transmit the disease.[15,16]

On 3 February, 2020, an outbreak of COVID-19 was reported on Cruise Ship Princess Diamond off the Japanese coast, with initially 10 persons confirmed to be infected with the virus. The number has since ballooned into the largest coronavirus outbreak outside of mainland China. By 19 February, 619 of 3,700 passengers and crew (17%) were tested positive. By 24 February, two persons had died. The outbreak was traced to a Hong Kong passenger who disembarked on 25 January, and found to have carried the virus. After docking near New Taipei City, on January 31, the ship arrived in Yokohoma, Japan. By the following day, the Japanese health ministry ordered a 14-day quarantine for everyone on board and rushed to close its ports to all other cruise ships. The public health measures taken according to news reports and the media were removal of all PCR positive passengers and crew from the ship and their isolation in Japanese hospitals. The remaining test-negative passengers and crew remained on board. Passengers were quarantined in their cruise ship cabins, and only allowed out of the cabin for one hour per day. By 20 February, the decision was made to evacuate and more than 3000 passengers left the ship, mostly air-evacuated by their respective countries.[10]

The cruise ship with a COVID-19 index case onboard between the 21-25 January serves as a good model to study its potential to spread in a population that is more homogenously mixed, compared to the more spatially variable situation in Wuhan.

We set out to study the empirical data of COVID-19 confirmed infections on the Cruise ship Diamond Princess, to estimate the basic reproduction number (R_0) under cruise ship conditions, the response effectiveness of the quarantine and removal interventions, and compare scenarios of an earlier and later evacuation of the ship.

Methods:

We used data on confirmed cases on the cruise ship as published on a daily basis by public sources[17,18] to calibrate a model and estimate the basic reproduction number R_0 from the time sequence and amplitude of the case rates observed. COVID-19 is thought to have been introduced by an index case from Hong Kong visiting the ship between the 21 to 25th of January, 2020. We thus used the date of 21 January 2020 as the first time point, *t=0*, assuming the index case was infectious from the first day on the ship. The estimates of R_0 and the associated Covid-19 incidence on the cruise ship was derived using a compartmental model estimating the dynamics of the number of susceptible (S), exposed (E), infected (I), and recovered (R) individuals, adapted but modified from a published COVID-19 study.[19] We analyzed two instances of the model assuming respectively: (1) a homogenous population (3700 individuals), and (2) a stratified population of crew (1000 individuals) and guests (2700 individuals). The model used a relationship between the daily reproductive number, β, and R_0 to infer the transmissibility and contact rate across the whole cruise ship population by the relationship:

$$\beta = transmissibility * contact\ rate = R_0/i$$

where the infectious period equals to one over the recovery rate (γ), $i = 1/\gamma$

In the homogeneous model, the infectious period, i, of COVID-19 was set to be 10 days based on previous findings.[8] In the situation of no removal (ill persons taken off the ship to be isolated in a Japanese hospital), the incubation period (or, the latent period), l was estimated to be approximately 5 days (ranging 2 to 14 days).[20] In order to model the removal/isolation and quarantine interventions, we implemented time dependent removal and contact rates as are described in Table 1. We run an additional sensitivity analysis reducing the R_0 to 3.7, as this was estimated the average value across mainland China studies of COVID-19.[9].

We further estimated a counterfactual scenario of the infections dynamics assuming no interventions were implemented, assuming no removal and subsequent isolation of ill persons and assuming an infectious period of 10 days, with a contact rate remaining the same as in the initial phase of the outbreak. Additionally, in the stratified model of crew and guests, the contact rate was assumed to be different due to the assumption that crew could not be easily quarantined as they had to continue their services on board for all the passengers and possibly had more homogeneous mixing with all the passengers, whereas passengers may be mixing more within their preferred circles and areas. We kept the transient change in the contact rate and the removal of ill PCR confirmed patients starting from the 3rd and the 5th of February respectively as in the first model. Parameters are described in Table 1.

The model describing a homogeneous population onboard is given by:

$$\frac{dS}{dt} = -\beta I \frac{S}{N}$$

$$\frac{dE}{dt} = \beta I \frac{S}{N} - E/l$$

$$\frac{dI}{dt} = E/l - \gamma I$$

$$\frac{dR}{dt} = \gamma I$$

where S denote all susceptible people on the cruise ship, E all exposed, I all infected and R all recovered or removed, and where $N = S + E + I + R$ denotes the whole population.

The model describing a stratified population onboard is given by:

$$\frac{dS_g}{dt} = -\beta_{gg} I_g \frac{S_g}{N_g} - \beta_c I_c \frac{S_g}{N_g}$$

$$\frac{dE_g}{dt} = \beta_{gg} I_g \frac{S_g}{N_g} + \beta_c I_c \frac{S_g}{N_g} - E_g/l$$

$$\frac{dI_g}{dt} = E_g/l - \gamma I_g$$

$$\frac{dR_g}{dt} = \gamma I_g$$

$$\frac{dS_c}{dt} = -\beta_c I_c \frac{S_c}{N_c} - \beta_{gc} I_g \frac{S_c}{N_c}$$

$$\frac{dE_c}{dt} = \beta_c I_c \frac{S_c}{N_c} + \beta_{gc} I_g \frac{S_c}{N_c} - E_c/l$$

$$\frac{dI}{dt} = E_c/l - \gamma I_c$$

$$\frac{dR}{dt} = \gamma I_c$$

where S denotes susceptible, E exposed, I infected and R recovered or removed, $N = S + E + I + R$, and the subscript g and c are indicating guest and crew respectively. Overall, we assume mortality is negligible.

Models with interventions were calibrated to reports of total infection occurrence, while models simulating the counterfactual scenarios where left with the naïve parameter settings. Net effects of countermeasures where estimated as the difference between the counterfactual scenario and the model with the interventions calibrated to data. Model parameters are described in Table 1.

We here also present estimations of plausible consequences of a hypothetical third intervention strategy, whereby all individuals onboard would have been evacuated either on 3rd of February or 19th of February. We estimated the number of latent cases on 3rd February evacuation and on 19 February, 2020.

Results:

Using the SEIR model assuming relatively homogenous mixing of all people onboard, we estimated R_0 to 14.8 based on calibrating the predicted cumulative number of infections to the observed cumulative number of infections among all people onboard. This resulted in an estimate of β (the daily reproduction rate) to 1.48. To derive this estimate we calibrated function describing transient change in the β as a result of changes in contact rate and the removal of symptomatic infections. The parameter values of contact rate, quarantine interventions and removal presented in Table 1 are the results of the calibration to the cumulative incidence data. The contact rate between persons on the cruise ship was calibrated to give the best fit to data with a reduction of 70% by the quarantine countermeasure with onset 3 February, 2020. The transient function of isolation of infected cases with an onset on 5 February, 2020, reduced the infectious period from 10 to 4 days, and substantially reduced the number of infections on the ship. In Figure 1 we present the change in R_0 based on the relationship between R_0 and β and how it is affected by the transient countermeasures of quarantine and removal of ill patients in the model. Here R_0 should be interpreted as the basic reproductive rate in a totally naïve population on the Diamond Princess (i.e. same contact rate), and not the actual basic reproductive number over time on the cruise ship. The R_0 was 14.8 initially and then R_t declined to a stable 1.78 after the quarantine and removal interventions were initiated (Figure 1).

The predicted cumulative number of cases over time from this model described the observed cases well, but overestimated the cumulative case incidence rate initially (Figure 2). This allowed to compensate for reporting bias in the initial phase, given that the proportion of testing of all passengers was patchy while at the end of the study (19 February, 2020) the testing of passengers had a higher coverage and was more complete. The modelled cumulative number of cases on 19 February, 2020, is 613 out of the 3700 people at risk, while the observed reported number of cases is 619. The counterfactual scenario assuming homogenous rates among crew and guests without any interventions (no removal off the ship or isolation of ill persons nor any quarantine measures for the remaining passengers on boat), estimated the number of cumulative cases to be 2920 out of the 3700 after 30 days, that is by 19th of February (Figure 2). The net effect of the combined interventions was estimated to prevent a total number of 2307 cases by 19 February, 2020 (Figure 2).

In a sensitivity analysis we modified the R_0 to 3.7 (and consequently $\beta\ to\ 0.37$) as this has been reported the average basic reproduction number from studies of COVID-19 in China.[9] However, from our simulation, even in the absence of any intervention, such a low R_0 cannot explain the rapid growth of incident cases on the cruise ship (Figure 3). This sensitivity scenarios excluded countermeasures from the model making it unrealistic that the low R_0 assumed would actually be the true value in the cruise ship situation with confined spaces and high homogeneous mixing of the same persons, and also omitting the strong interventions put into place.

We additionally modeled a scenario stratified by crew and guests whereby we assumed the parameter values of transmission risk to be for crew to guest than for guest to crew (Table 1). The predicted cumulative number of infected crew and guests by 19th of February from this model was 168 out of 1000 (16.8%) respectively 464 out of 2700 (17.2%) (Figure 4). The total number of cumulative cases by 19th of February predicted from this model was 632, close to the observed number of cases of 619. The model predicted cumulative incidence rates was overestimated for crew while underestimated for guests based on available tests results at the time of writing (Figure 4). These data still need to be validated against the empiric data of test results in all crew and passengers which should soon become available.

Instead of keeping all passengers on board, another option would have been to evacuate all individuals onboard the cruise ship earlier, and allow them to go home for a potential quarantine in their respective home countries. We modeled that an evacuation by 3 February, 2020, would have resulted in 76 latent cases (cases during the incubation time), while an evacuation by 19 February would have resulted in 246 latent cases.

Discussion:

Modelling the COVID-19 on-board outbreak reveals important insights into the epidemic risk and effectiveness of public health measures. We found that the reproductive number of COVID-19 in the cruise ship situation of 3,700 persons confined to a limited space was around 4 times higher than in the epicenter in Wuhan, where R_0 was estimated to have a mean of 3.7.[9] Interestingly, a rough estimation of the population per square km on this 18-deck ship of 286 by 62 meters (0.32 km^2) assuming only 50% of decks are used by most people onboard and thus approximately 24,400 persons per km^2 compared to urban Wuhan estimate approximately 6000 persons per km^2 (9,000,000/1528) indicates a difference in the approximately same range (4), suggesting R_0 and contact rate as dependent on population density building which is also supported by previous research.[21] In population-based models on observational data the population per square km is often substantially different, affecting the R_0 and β coefficient implicitly by changes in the contact rate expressed as:

$$\frac{R_0}{i} = Transmissibility * contact\ rate$$

The local estimate of R_0 can be divided into a localized contact rate and a multiplier that is necessary for moving from one population to another:

$contact\ rate = contact\ rate_{localized} * pd$, where pd is the population density multiplier. In our case it was approximated to 4. Here the contact rate is relating to a contact rate in a defined population in a certain area and the population density multiplier modifies the contact rate when moving across different local population and geographical areas representing heterogeneity in population density. In the case of the cruise ship, the potential relationship of R_0 to population density appear thus mainly be attributed to the contact rate and mixing effects. This information is also important for other settings characterized by high population densities.

With such a high R_0, we estimated that without any interventions within the time period of 21 January to 19 February, 2920 out of the 3700 (79%) would have been infected, assuming relatively homogenous mixing between all people on board.

The quarantine and removal interventions launched when the outbreak was confirmed (3 February vs. 5th of February) substantially lowered the contact rate and reduced the cumulative case burden by an estimated 2307 cases by 19 February. We note, however, that the longer time span of simulation beyond 19th February, assuming people would stay on the boat, would reduce the net effect of the intervention substantially. We further note that an earlier evacuation would have corresponded to disembarking a substantially lower number of latent undetectable infections (76 vs. 246), likely giving rise to some further transmission outside the ship.

We also found that contact rate of guest to guest and crew to crew appeared higher than the contact rate from guest to crew, perhaps driven by high guest attack rates within cabins. However, testing of crew was delayed, and there was a testing bias towards testing more passengers than crew. Hence our access to empiric data may have and this analysis need to be revisited when all data is available.

The limitations of our study include our lack of data on the lag time between onset of symptoms, testing and potential delay to the availability of test results. Due to the large number of people, not everyone was tested, and we suspect that the PCR results do not totally tally with real-time data. We had no access to data on incident cases in crew versus passengers, nor any data on whether there was clustering of cases around certain nationalities. Furthermore, although the Hong Kong passenger was assumed to be the index case, it could well have been possible that there was more than one index case on board who could have contributed to transmission, and this would have lowered our estimated R0. Lastly, our models are based on human-to-human transmission and do not take into account the possibility that fomites, or water systems with infected feces, or air conditioning contributed to the outbreak.

The interventions that included the removal of all persons with confirmed COVID-19 disease combined with the quarantine of all passengers substantially reduced the anticipated number of new COVID-19 cases compared to a scenario without any interventions (17% attack rate with intervention versus 79% without intervention) and thus prevented a total number of 2307 additional cases by 19t February. However, the main conclusion from our modelling is that evacuating all passengers and crew early on in the outbreak would have prevented many more passengers and crew members from getting infected. A scenario of early evacuation at the time of first detection of the outbreak (3 February) would have resulted in only 76 latent infected persons during the incubation time (with potentially still negative tests). A late evacuation by 19 February would have resulted in about 246 infected persons during their incubation time. These data need to be confirmed by empiric data of testing all evacuated persons after 19 February.

In conclusion, the cruise ship conditions clearly amplified an already highly transmissible disease. R_0 is related to population density, and is particularly driven by contact rate and mixing effects, and this explains the high R_0 in the first weeks before countermeasures were initiated. Population densities and mixing need to be taken into account in future modeling of the COVID-19 outbreak in different settings. Early evacuation of all passengers on a cruise ship- a situation with confined spaces and high intermixing- is recommended as soon as an outbreak of COVID-19 is confirmed.

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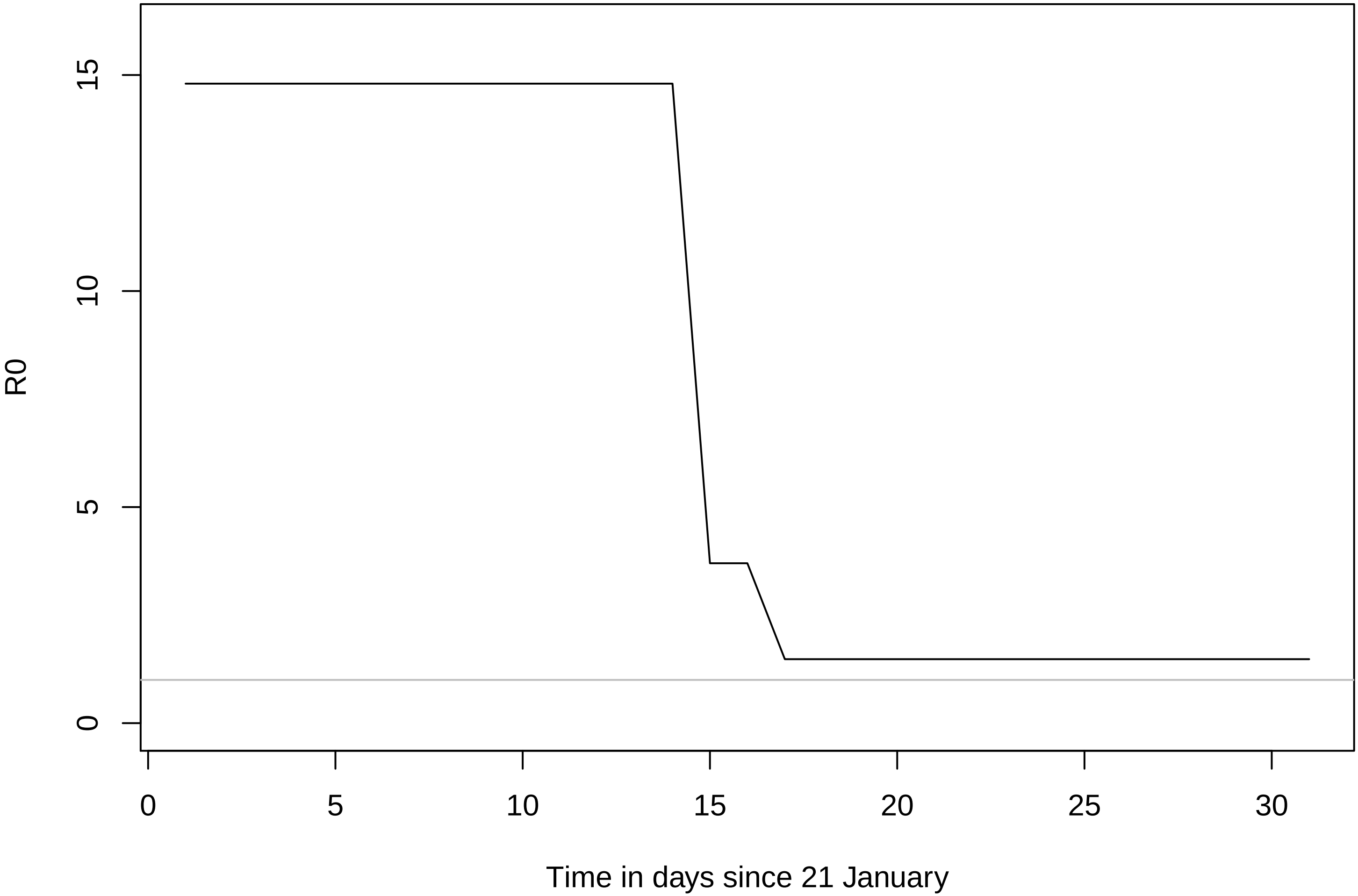
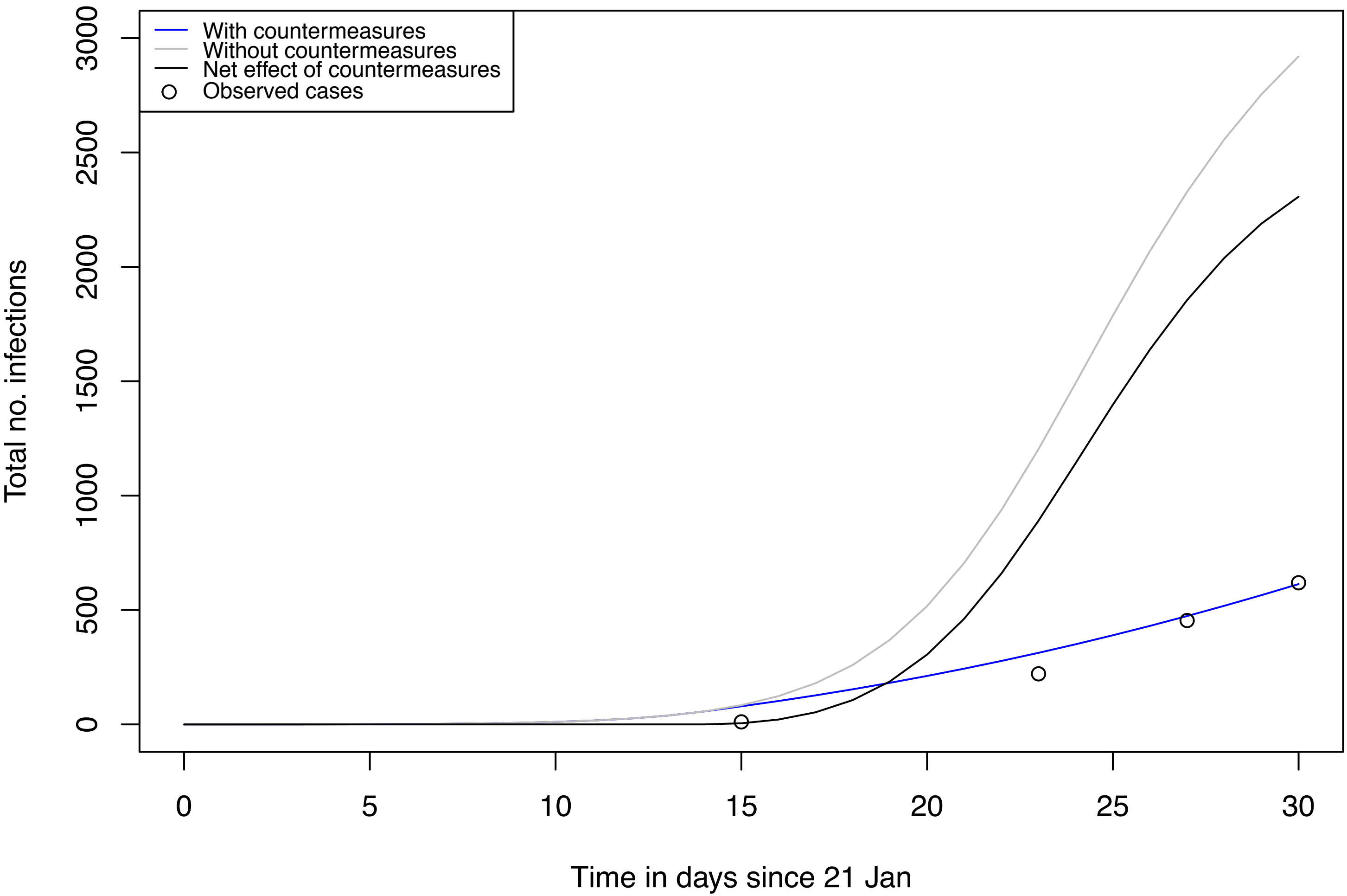
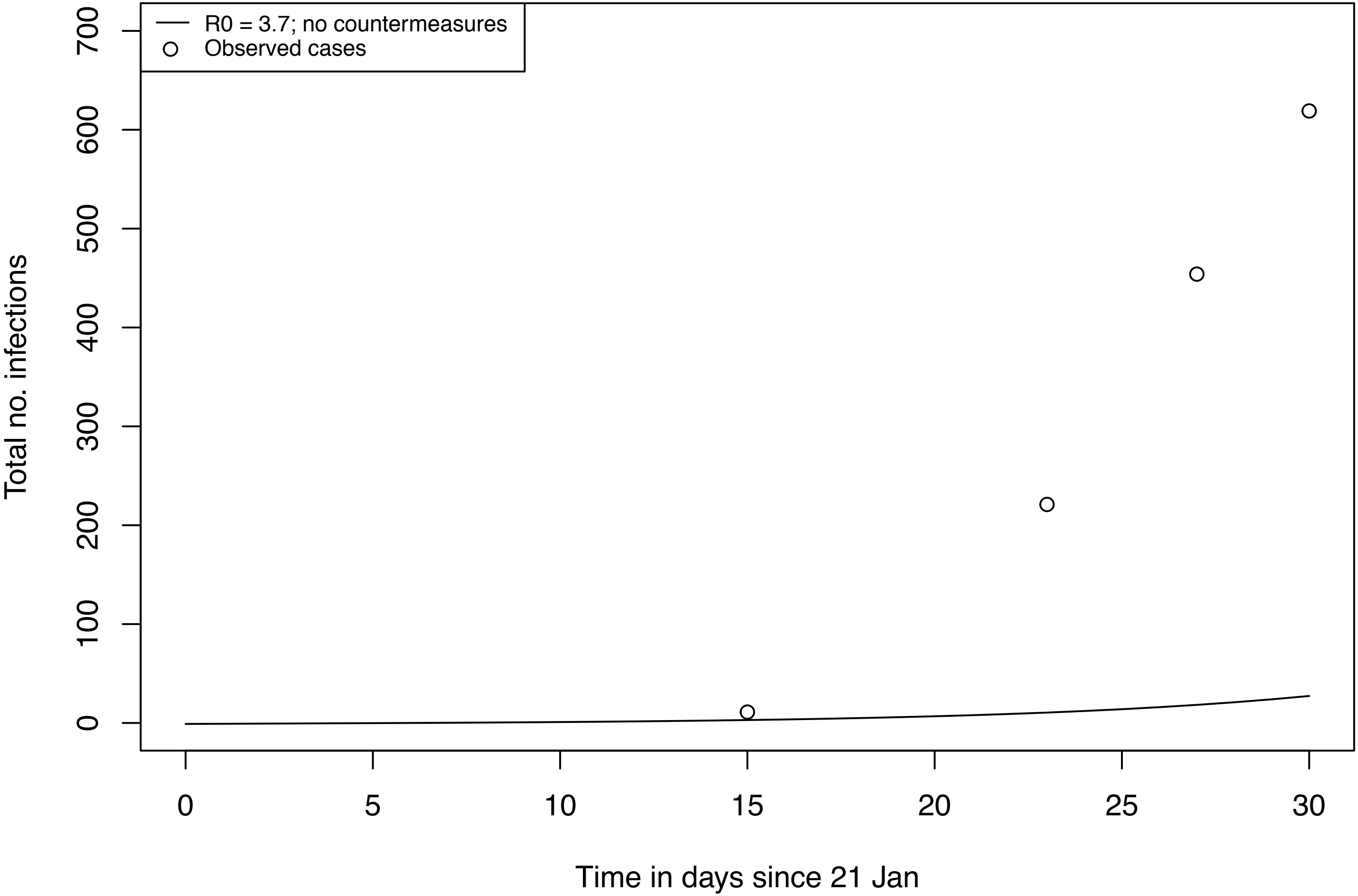

R0
0
5
10
15
0
5
10
15
20
25
30
Time in days since 21 January


With countermeasures
Without countermeasures
Net effect of countermeasures
Observed cases
Total no. infections
0
500
1000
1500
2000
2500
3000
Time in days since 21 Jan
0
5
10
15
20
25
30


R0 = 3.7; no countermeasures
Observed cases
Total no. infections
0
100
200
300
400
500
600
700
0
5
10
15
20
25
30
Time in days since 21 Jan

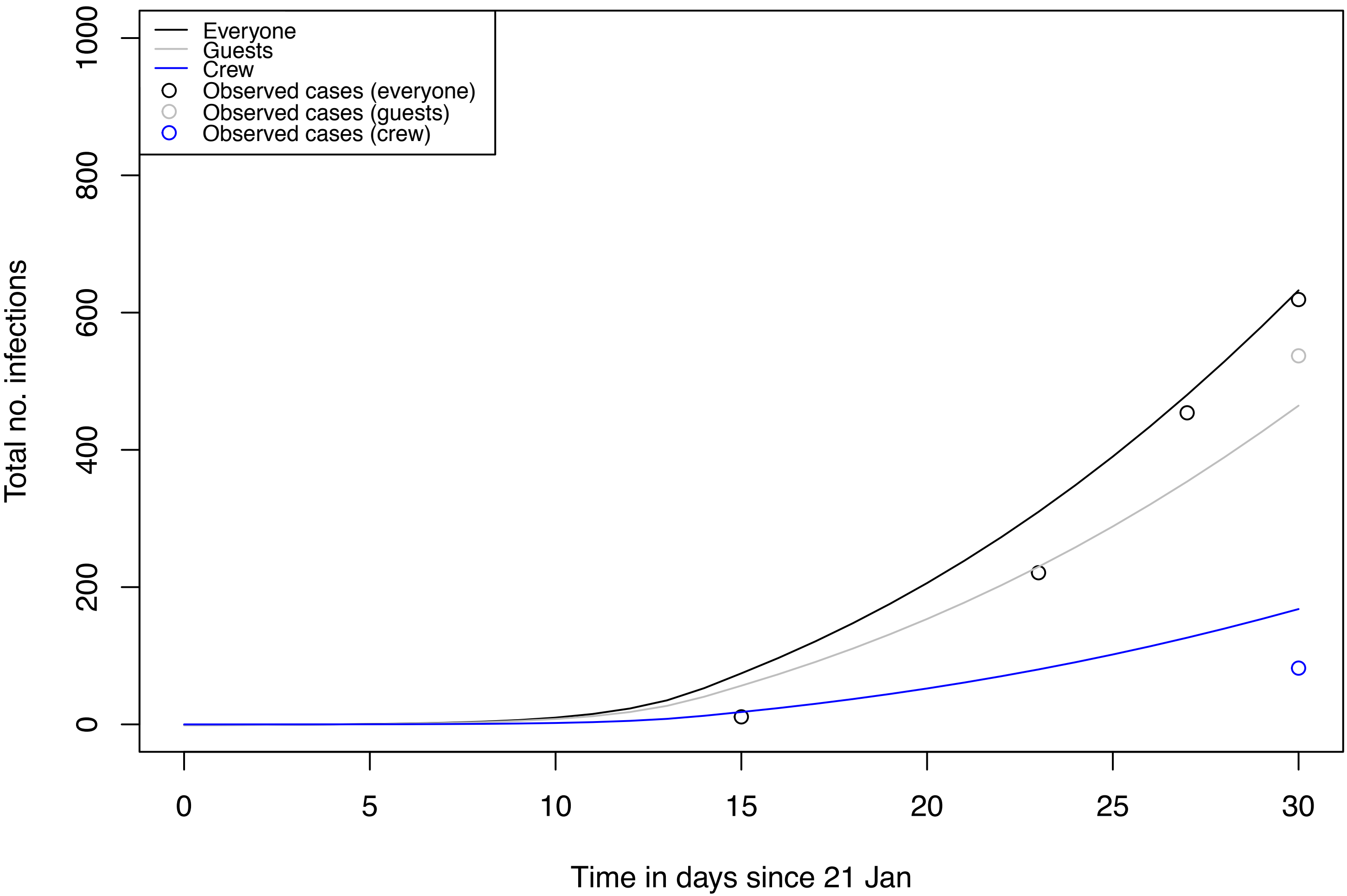

Everyone
Guests
Crew
Observed cases (everyone)
Observed cases (guests)
Observed cases (crew)
Total no. infections
0
200
400
600
800
1000
0
5
10
15
20
25
30
Time in days since 21 Jan

Table 1. Model parameter description and values. Start time (*t = 0)* the 20th of January.

Parameters	Explanation (unit)	Estimated to
β	Overall transmissibility and contact rate (1/day)	$1.48\ if\ t < 14$ $0.44\ if\ t \geq 14$
l	Incubation period (days)	*5 days*
i	Infectious period or time to removal (days)	$10\ if\ t < 16$ $4\ if\ t \geq 16$
N	Total number of people onboard (persons)	*3700*
β_c	Transmissibility and contact rate crew (1/day)	$1.15\ if\ t < 14$ $0.35\ if\ t \geq 14$
β_{gg}	Transmissibility and contact rate guests to guests (1/day)	$1.15\ if\ t < 14$ $0.35\ if\ t \geq 14$
β_{gc}	Transmissibility and contact rate guests to crew (1/day)	$0.17\ if\ t < 14$ $0.05\ if\ t \geq 14$
N_g	Total number of guests onboard (persons)	*2700*
N_c	Total number of crew onboard (persons)	*1000*