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Evaluation of Intervention Measures for Respiratory Disease Transmission on Cruise Ships

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Abstract

Respiratory diseases are common infectious illnesses on cruise ships. This study integrated an individual-to-individual probability model, a susceptible-exposed-infected-recovered (SEIR) epidemic model at the individual scale, and an onboard indoor social contact network model for evaluating the infection risk on a typical cruise ship voyage. The integrated model was validated by data from a previous influenza outbreak and was able to simulate the infection spreading. The model was used to assess the effects of various intervention measures on controlling influenza on a cruise ship with one index passenger. The results show that individuals in crew cabins and restaurants faced the highest infection risk. Increasing the air change rate in some or all locations could reduce the infection risk to some extent. High-efficiency particulate air (HEPA) filters and ultraviolet germicidal irradiation (UVGI) devices in ventilation systems were the most effective measures. Surgical masks worn by crew members or a quarantine of the index passenger and his/her roommate could reduce the attack rate only to a moderate extent.

Key Words: Cruise ship; Airborne disease transmission; Indoor social contact network; Intervention measures; Simulations

Introduction

The cruise industry is the fastest-growing category in the leisure travel market [1], and it has been estimated that a record of 21.3 million passengers cruised globally in 2013 [2]. Cruise ships are becoming larger, and some have a capacity of more than 3000 people, including passengers and crew. A cruise ship can be thought of as a floating island or a city on the sea. People from diverse geographical locations gather on cruise ships and spend an average of seven days together [3]. Most cruise ship packages include a land-based tour component. A cruise ship may stop at multiple ports, where travellers can disembark and spend hours or days visiting the local population and environment [3].

Despite their attractions, cruises pose an important public health challenge [4]. Although a cruise voyage may suggest an outdoor experience, passengers and crew members spend most of their time in various indoor environments such as dining rooms, theatres, dancing halls, and cabins [3, 5]. Crew members and passengers from many parts of the world share sanitation facilities, common supplies of food and drinking water, and air conditioning systems [6]. Such confined environments facilitate person-to-person transmission of airborne pathogens [7] and may increase the risk to passengers and crew of infection by pathogens [8]. Extended stays at ports of call, where passengers disembark for sightseeing tours and other land-based activities, may negatively affect the health of the local port communities. In addition, approximately one third of cruise passengers are elderly people, who may be more susceptible to infectious diseases than the general population [9].

Among passengers and crew members seeking care in a ship's infirmary, respiratory tract infections are the most common diagnosis, accounting for 29.1% of all visits [8, 10, 11]. Influenza is the most frequently occurring respiratory disease [8]. From 1984 to 2012, more than 20 confirmed outbreaks of influenza linked to cruise ships were reported in the literature, for example, in the investigations of Minooee et al. [10], Kak [11], and Kornylo et al. [12]., the attack rate, which is defined as the number of new cases in the population at risk divided by the number of persons at risk in the population, ranged from 0.5% to 37% [13]. Some influenza outbreaks have been very severe. For example, after a cruise from Sydney to Noumea in September 2000, approximately 310 of the 1,100 passengers reported influenza-like symptoms and 40 required hospitalization, with two deaths [14].

The particular vulnerabilities of cruise ships to influenza outbreaks include: (1) large numbers of people in close social contact; (2) cruise durations that are long enough to encompass from two to four generations, while the incubation period typically ranges from one to three days [15] with an average of 1.9 days [16]; (3) mixing of people from the northern and southern hemispheres, where a vaccination may not be available during the off-season for influenza; and (4) crew members can be a source and reservoir of continuing infection for new passenger cohorts, as infections may remain on board from one cruise to the next [17, 18]. The influenza virus can be easily spread from person to person by inhalation of air that contains aerosols or droplets from infected people who cough or sneeze [5]. Among all the possible influenza transmission routes on a cruise ship, airborne transmission plays an important role.

The Centers for Disease Control and Prevention (CDC) have recommended various intervention measures, such as isolating/cohorting ill passengers and crew members, influenza vaccination, and antiviral prophylaxis [19]. Wearing of face masks (respiratory protection devices) and encouragement of respiratory hygiene and cough etiquette can also reduce the transmission of influenza [20]. Increasing ventilation [13] and installing high-efficiency particulate air (HEPA) filters [21] and ultraviolet germicidal irradiation (UVGI) devices [22] in the ship's ventilation systems can also reduce the possibility of air contamination.

However, our literature search found little quantitative risk assessment of respiratory disease transmission on cruise ships. This paper reports our quantitative assessment of various intervention measures for reducing the risk of infection during an influenza outbreak on a cruise ship, where influenza was used as an example of the respiratory diseases that may be transmitted.

Materials and Methods

Quantitative risk assessment requires a reliable model. This paper integrates an individual-to-individual probability model, a susceptible-exposed-infected-recovered (SEIR) epidemic model at the individual scale, and an onboard indoor social contact network model for evaluating infection risk on a typical cruise ship voyage. The following subsections describe these models.

Individual-to-individual Probability Model

Riley et al. [23] developed the Wells-Riley mathematical model, Eq (1), to estimate the probability of airborne transmission of an infectious agent indoors;

$$P = \frac{C}{S} = 1 - \exp\left(-\frac{Iqpt}{Q}\right) \tag{1}$$

where P is the probability of infection for susceptibles; C is the number of infection cases; S is the number of susceptibles; I is the number of source infectors; q is the quantum generation rate by an infected person (quanta h^{-1}), which represents the generation rate of an infectious dose and the average infectious source strength of an infected person; p is the pulmonary breathing rate of each susceptible (m^3h^{-1}); t is the exposure duration (h); and Q is the air change rate with fresh air (m^3h^{-1}).

Brookmeyer et al. [24] developed the competing-risks model, Eq (2), for calculating the generation probability of an infectious agent within t hours;

$$\int_0^t \lambda e^{-\lambda\tau} e^{-C\tau} d\tau = \frac{\lambda}{\lambda + C}\left[1 - \exp(-(\lambda + C)t)\right] \tag{2}$$

where λ is the generation rate of infectious agents and C is the clearance rate combined with the air change rate.

Liao et al. [25] linked the Wells-Riley mathematical model and competing-risks model to account for the impact of both enhanced engineering control measures and protection against respiratory infections. As given by Eq (3), the probability of susceptible individual i being infected by one infector j in location choice l, $P_{i,j,l}$, is

$$P_{i,j,l} = 1 - \exp\left\{\left[-\left(\frac{q(1-\eta_i)t_l p(1-\eta_s)}{Q_l + Q_{lr}\eta_r + h_u V_l}\right)\left(1 - \exp(-(h_l + h_{lr}\eta_r + h_u)t_l)\right)\right]\right\} \tag{3}$$

where η_i = 58% is the particle filtration efficiency of a surgical mask used by an infector [26]; t_l is the exposure duration in location choice l (h); p = 0.48m^3h^{-1} [27]; η_s=58% is the efficiency of a surgical mask used by a susceptible person [26]; $Q_l = h_l V_l$ is the fresh air supply rate that removes the infectious droplet nuclei in location choice l (m^3h^{-1}); $Q_{lr} = h_{lr} V_l$ is the airflow rate through a recirculated HEPA filter in location choice l (m^3h^{-1}); η_r = 92.5% is the single-pass removal efficiency for infectious droplet nuclei passing through a recirculated HPEA [25]; h_u= 12h^{-1} is the inactivation rate of infectious droplet nuclei due to UVGI [28]; V_l is the volume of the ventilated space in location choice l (m^3); h_l is the fresh air change rate in location choice l (h^{-1}); and h_{lr} is the air change rate through a recirculated HEPA filter in location choice l (h^{-1}).

The quantum generation rate q is a much more difficult parameter to quantify. Generally q is backward calculated epidemiologically using the Wells-Riley mathematical model from previous outbreaks, on the basis of an often incomplete knowledge of ventilation parameters and averaged infection rates. Table 1 shows the quantum generation rates reported in the literature for influenza outbreaks. A value of q = 66.91 quanta h^{-1} has commonly been used [27, 29, 30]. The present study used both q = 66.91 quanta h^{-1} and the lowest value shown in Table 1, q = 15 quanta h^{-1}.

Table 1. Quantum generation rates for influenza

Case	q (quanta h^{-1})	Reported by
Outbreak in an elementary school in Taiwan, 2003-2004	66.91 (log normal)	Liao et al. [27]
Outbreak on a grounded commercial airliner [31]	15-128	Rudnick et al. [32]
	28	Gao et al. [33, 34]
Outbreak during an airplane flight in Australia [35]	515	SzeTo et al. [36]

Susceptible-exposed-infected-recovered Model at the Individual Scale

The classic SEIR compartmental epidemic model [37, 38] calculates the transition rates for people in four states: susceptible, exposed, infected and recovered. This model assumes that each individual in the homogeneously mixed population has an equal chance of coming into contact with another person. The model also assumes that the probability of contact with a given person in the population is independent of whether or not there has been previous contact with that person [39]. In practice, each individual on a cruise ship has a finite set of contacts to whom they could pass an infectious disease, and the ensemble of all such contacts forms a "mixing network" [40]. Thus, the classic SEIR epidemic model is not suitable for evaluating a respiratory disease outbreak on a cruise ship. Instead, this study adopted a SEIR model at the individual scale that had been used by Gao [33] to simulate a respiratory disease outbreak in Hong Kong urban communities. The model can calculate the probability of an individual's being susceptible, exposed, infected, or recovered, and quantitatively explain the transition rates between the four states for each individual.

The SEIR epidemic model at the individual scale can be represented by Eq (4):

$$\frac{dS_i}{dt} = -\left(1-\prod_{g=1}^{G}\left(1-\sum_{l=1}^{L_g}\eta_{i,l}\left(1-\prod_{j=1}^{N_l}\left(1-P_{i,j,l}\eta_{j,l}I_j\right)\right)\right)\right)S_i \tag{4}$$

$$\frac{dE_i}{dt} = \left(1-\prod_{g=1}^{G}\left(1-\sum_{l=1}^{L_g}\eta_{i,l}\left(1-\prod_{j=1}^{N_l}\left(1-P_{i,j,l}\eta_{j,l}I_j\right)\right)\right)\right)S_i - \alpha E_i \tag{5}$$

$$\frac{dI_i}{dt} = \alpha E_i - \gamma I_i \tag{6}$$

$$\frac{dR_i}{dt} = \gamma I_i \tag{7}$$

$$S_i + E_i + I_i + R_i = 1 \quad (8)$$

where S_i, E_i, I_i, and R_i are the probabilities of individual i being susceptible, exposed, infected and recovered, respectively, in an onboard indoor social contact network model; I_j is the probability that individual j will be infected; α and γ are the average infection rate and recovery rate, respectively; $1/\alpha$ and $1/\gamma$ are the average incubation period and infectious period, respectively, where $1/\alpha$ =1.9 days and $1/\gamma$=4.1 days [16]; G represents the collection of locations; g represents each location, g=1, 2, …, G; L_g represents the collection of possible choices for an individual visiting location g; l represents one of the location choices in location g, l=1, 2, …, L_g; $\eta_{i,l}$, $\eta_{j,l}$ are the probabilities of individual i or j, respectively, visiting location choice l; $\eta_{i,l}$=0 or 1, $\eta_{j,l}$=0 or 1; N_l is the number of possible visitors to location choice l, with the exception of individual I him- or herself; and $P_{i,j,l}\eta_{j,l}I_j$ is the probability that individual i will be infected by individual j in location choice l of location g. The onboard indoor social contact network model, including the parameters G, g, L_g, and l, will be described in the following subsection.

The SEIR epidemic model at the individual scale was solved by the 4th-order Runge-Kutta method using MATLAB 13.0. The time step was one simulation day (24 hours), starting from the time at which each individual woke up in the morning. The total number of susceptible, exposed, infected, and recovered people was the expectation sum of the probabilities of each individual's being susceptible, exposed, infected and recovered, as given by Eq (9), (10), (11) and (12), respectively:

Total number of susceptible people at simulation day

$$t = \sum_{i=1}^{N} S_i^t \quad (9)$$

Total number of exposed people at simulation day

$$t = \sum_{i=1}^{N} E_i^t \quad (10)$$

Total number of infected people at simulation day

$$t = \sum_{i=1}^{N} I_i^t \quad (11)$$

Total number of recovered people at simulation day

$$t = \sum_{i=1}^{N} R_i^t \quad (12)$$

where N is the total number of people onboard the cruise ship; and S_i^t, E_i^t, I_i^t, and R_i^t are the probabilities of individual i being susceptible, exposed, infected and recovered, respectively, at simulation day t. Furthermore,

The attack rate of infection at simulation day is given by Eq (13):

$$t = \sum_{i=1}^{N} \left(I_i^t + R_i^t \right) / N \tag{13}$$

The infection risk in location g at simulation day is given by Eq (14):

$$t = \sum_{i=1}^{N_g} \sum_{l=1}^{L_g} \eta_{i,l} \left(1 - \prod_{j=1}^{N_l} \left(1 - P_{i,j,l} \eta_{j,l} I_j^t \right) \right) / N_g \tag{14}$$

where N_g is the maximum number of visitors to location g per simulation day.

Onboard Indoor Social Contact Network Model

To effectively assess the infection risk of influenza, it is essential to understand that the structure of a contact network can profoundly affect the dynamics of infectious disease transmission [41]. For the indoor social contact network model on cruise ships, this investigation used a method similar to that of Gao (Gao [33]; Gao et al. [42]), who simulated a respiratory disease outbreak in urban communities in Hong Kong.

According to the deck plans of major cruise ships, indoor spaces include staterooms, crew cabins, restaurants, theatres, bars, lounges, small public places and public rooms for crew members. Small public places include shops, fitness centres, galleries, internet cafes and game rooms, etc. An individual may visit some of the indoor spaces several times a day, for example, going to restaurants for breakfast, lunch and dinner. Therefore, as shown in Table 2, onboard indoor spaces can be classified into 11 groups of locations: staterooms, crew cabins, restaurants at breakfast time, restaurants at lunch time, restaurants at dinner time, theatres, bars, lounges, small public places in the evening, small public places at night and public rooms for crew members. Some locations, such as restaurants or theatres, have a limited number of seats, and therefore it is impossible for all the passengers to go to these places together at the same time. Therefore, these locations can be divided into several location choices according to visiting time. Each location choice represents a location at one fixed duration that people may visit.

Furthermore, people onboard can be divided into three groups according to their functions: Group 1 for passengers; Group 2 for crew members who share breathing air with the passengers and serve them directly in restaurants, theatres, bars, lounges and small public places; and Group 3 for crew members who do not share breathing air with the passengers, such as stewards, engineers, captain, officers, etc. Thus, only Group 2 has an airborne transmission route contact with Groups 1 and 3, who shares crew cabins and public rooms for crew members with Group 2. There is no direct contact between Groups 1 and 3.

Table 2. Locations of onboard indoor spaces

Location g	Function	Total number of each location g	Number of possible location choices L_g
Staterooms	Passenger accommodation	1000	1000
Crew cabins	Crew accommodation	200	200
Restaurants at breakfast time	Breakfast (each restaurant can be divided into two location choices: one for 7:00-8:00 and the other for 8:00-9:00)	3[a]	6
Restaurants at lunch time	Lunch	3[a]	3
Restaurants at dinner time	Dinner (each restaurant can be divided into two location choices: one for 17:30-19:30 and the other for 19:30-21:30)	3[a]	6
Theatres	Shows (each theatre can be divided into two location choices: one for 17:30-19:30 and the other for19:30-21:30)	1	2
Bars	Drinks	2	2
Lounges	Resting	1	1
Small public places in the evening	Visiting in the evening, including shops, fitness centres, galleries, internet cafes, game rooms, etc. (each small public place can be divided into two location choices: one for 17:30-19:30 and the other for 19:30-21:30)	20	40
Small public places at night	Visiting at night, including shops, fitness centres, galleries, internet cafes, game rooms, etc.	20	20
Public rooms for crew members	Recreation (the room can be divided into four location choices according to visiting duration per day)	1	4

[a] There are usually three large restaurants on a typical cruise ship, including a buffet restaurant.

The indoor social contact network model assumes that all individuals in Group 1 follow the schedule shown in Table 3 for one simulation day. Because of the uncertainty in the daily routes of the individuals, this study adopted an individual-location probability network from Gao [33] to connect individuals with locations that they might visit. In this probability network, both the individuals and the locations are represented by nodes. An edge between an individual node and a location node denotes a connection between the individual and the location (location visits). The weight of the edge represents the probability that the individual will visit the location in a simulation day. The simulation first randomly assigned individuals to staterooms or crew cabins. Connections were then built between the individuals and the rest of the locations to represent contacts between individuals in different locations. All visitors were assumed to visit one location choice l, entering and leaving at the same time.

Table 3. Schedule for the passengers in a simulation day

Choice	Time period	Activity	Location *g*
1	7:00-8:00	Breakfast	Restaurants at breakfast time
2	8:00-9:00		
	8:00/9:00-12:00	Sightseeing	Onshore
	12:00-13:00	Lunch (50% of passengers return to the ship for lunch)	Restaurants at lunch time
	13:00-17:30	Sightseeing	Onshore
1	17:30-19:30	Dinner	Restaurants at dinner time
2	19:30-21:30		
1	17:30-19:30	Watching shows	Theatres
2	19:30-21:30		
1	17:30-19:30	Shopping, exercising, etc.	Small public places in the evening
2	19:30-21:30		
1	21:30-23:00	Drinking/dancing/resting/ shopping	Bars
2	21:30-23:00		Lounges
3	21:30-23:00		Small public places at night
4	21:30-23:00	Sightseeing/recreation	Outdoor decks
	23:00-7:00	Sleeping	Staterooms

Case Setup

The baseline case in this study assumed a seven-day cruise with 2,000 passengers and 800 crew members, which are the typical numbers on cruise ships [12]. Furthermore, each simulation day was assumed to be a “port day”, on which the ship docked at a port early in the morning and departed in the afternoon. Group 1 was made up of 2,000 individuals accommodated in 1,000 two-person staterooms. Groups 2 and 3 consisted of 320 and 480 crew members, respectively, who slept in 200 four-person cabins. The total number and number of possible choices for each location *g* are shown in Table 2.

Table 4 lists the key parameters in each location during a simulation day, and Table 5 shows the estimated exposure duration in these locations. According to ISO regulation [43], the quantity of outdoor air should not be less than 40% of the total air supply. Therefore, the air change rate through a recirculated HEPA filter in location choice l, h_{lr}, is $9h^{-1}$ in staterooms and crew cabins and $12h^{-1}$ in other locations [25].

Table 4. Location parameters

Location g		Number	h_l[a]	Area (m^2/person)	Height (m)	Max. # of passengers	# of crew members	Crew ID No.
Staterooms	—	1000	6	8.5 m^2	2.4	2	0	—
Crew cabins	—	200	6	4.25 m^2	2.4	0	4	2001-2800
Restaurants at breakfast/ lunch/dinner time	Restaurant 1	1	12	1.5[b]	2.4	400	40	2001-2040
	Restaurant 2	1	12	1.5[b]	2.4	400	40	2041-2080
	Restaurant 3	1	12	1.5[b]	2.4	200	20	2081-2100
Theatres	Theatre	1	12	2[b]	4.8[c]	500	50	2101-2150
Bars	Bar 1	1	12	2[b]	2.4	300	30	2151-2180
	Bar 2	1	12	2[b]	2.4	300	30	2181-2210
Lounges	—	1	12	2[b]	2.4	300	30	2211-2240
Small public places in evening/at night	—	20	12	2[b]	2.4	20[d]	4[d]	2241-2320
Public rooms for crew members	—	1	12	2[b]	2.4	0	200[e]	Randomly from 2001 to 2800[e]

[a] Adopted from Germanischer Lloyd [44].
[b] Adopted from EN ISO 7547 [43].
[c] The theatre occupies a two-deck space.
[d] Numbers are for each small public place.
[e] 200 crew members were selected randomly from Groups 2 and 3.

Table 5. Estimation of indoor exposure duration in one simulation day

Location g	Exposure duration for Group 1 (h)	Exposure duration for Group 2 (h)	Exposure duration for Group 3 (h)
Staterooms	8	—	—
Crew cabins	—	12	12
Restaurants at breakfast time	1	2	—
Restaurants at lunch time	1	1	—
Restaurants at dinner time	2	4	—
Theatres	2	4	—
Bars	1.5	1.5	—
Lounges	1.5	1.5	—
Small public places in the evening	2	4	—
Small public places at night	1.5	1.5	—
Public rooms for crew members	—	2	2

Model Validation

The case of an influenza outbreak on a cruise from New York City to Montreal during the period of August 31 to September 10, 1997 [45], was selected to validate the model used in this study. In this case, the cruise ship carried 1,445 passengers and 631 crew members. A total of 42 individuals presented to the ship's infirmary with influenza symptoms. A group of Australian passengers may have harboured influenza before boarding the ship, and the illness was spread by one of them [9].

Unfortunately, the itinerary of this voyage was not available. We modified Tables 2 and 4 according to the passenger and crew numbers. Groups 1, 2 and 3 had 1,445, 251, and 380 people, respectively. The initial computing conditions were $I_1^0 = 1$, $S_1^0 = E_1^0 = R_1^0 = 0$, $S_i^0 = 1$, and $E_i^0 = I_i^0 = R_i^0 = 0$ (i = 2, …, 2076), which meant that only one passenger had developed influenza before embarking on the cruise. A quantum generation rate of 15 quanta h^{-1} was used to obtain the results shown in Figures 1 and 2.

Figure 1 shows the simulated transmission process of this influenza outbreak. The rates of change in the numbers of both susceptible individuals and infectors were very low, and a peak in the infection did not occur because the cruise was short. On the last day, the number of total infectors was 27. Figure 2 shows the cumulative number of infectors in this outbreak, which was different from the number of infectors on the last day because some of the infectors reporting cases of influenza had already recovered. The cumulative number of infectors was 44, which is close to the 42 that were recorded for this influenza outbreak [45]. Because the calculated result agrees well with the outbreak record, the model used in the simulation has been validated.

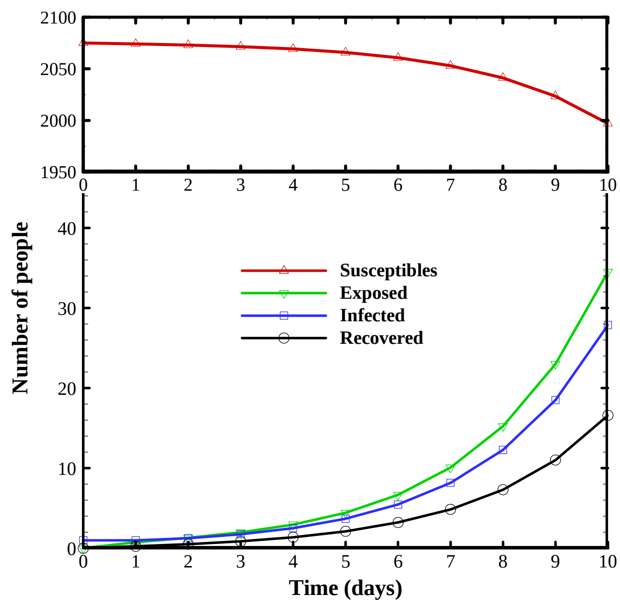


Fig. 1. The calculated susceptible, exposed, infected, and recovered individuals in the influenza outbreak on the ship.

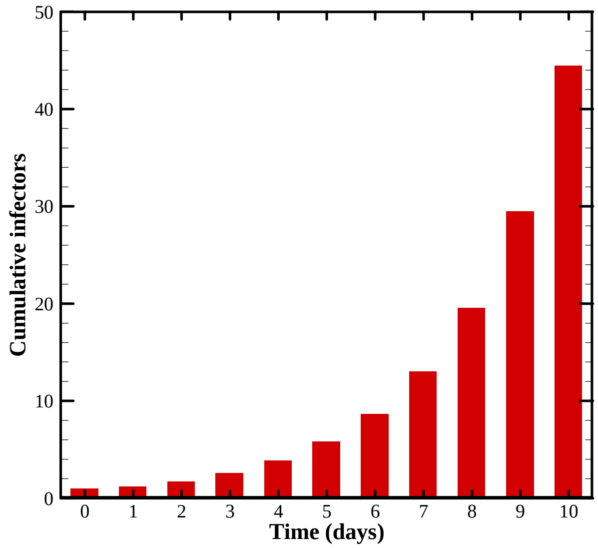
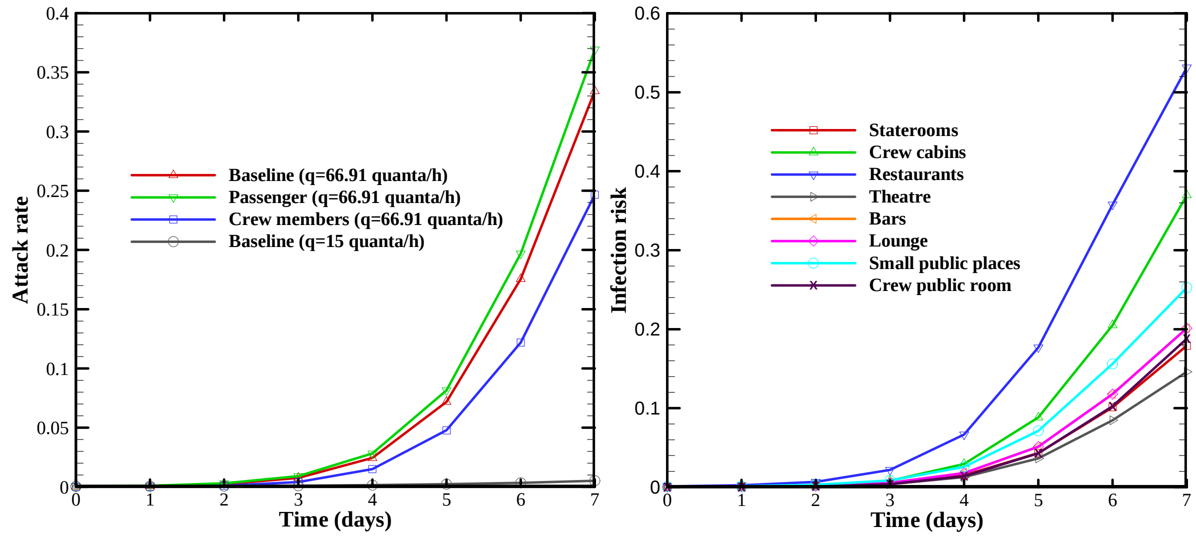


Fig. 2. Cumulative number of infectors on the ship.

Results

Our study started with a baseline case that used the conditions shown in Tables 2 through 5. Since a quantum generation rate of 15 quanta h^{-1} was satisfactory in the validation case, while 66.91 quanta h^{-1} has been the most commonly used rate in past studies, as shown on Table 1, both values were used for simulating the baseline case in this investigation. The baseline case used one original infected passenger as the initial condition, i.e., $I_1^0 = 1$, $S_1^0 = E_1^0 = R_1^0 = 0$, $S_i^0 = 1$, and $E_i^0 = I_i^0 = R_i^0 = 0$ ($i = 2, \ldots, 2800$).

As shown in Figure 3(a), the attack rates under quantum generation rates of 15 and 66.91 quanta h^{-1} were 0.52% and 33.42%, respectively. This figure also shows the attack rates for passengers and crew members. The attack rate calculated for q = 15 quanta h^{-1} was too small to clearly demonstrate the efficacies of different intervention measures. Therefore, the commonly applied q = 66.91 quanta h^{-1} was used for the other simulations presented in this section. Figure 3(b) shows the infection risks in different locations for the baseline case when q = 66.91 quanta h^{-1}. People in the restaurants and crew cabins had higher infection risks than those in the other locations. The baseline case shows that the influenza outbreak infected one third of the people on the cruise ship.



(a) (b)

Fig. 3. Simulated results for the baseline case: (a) attack rate with q = 15 quanta h^{-1} and Q = 66.91 quanta h^{1} and (b) infection risks in different locations.

Single Intervention Measures

For control of an influenza outbreak, this study considered several single engineering control measures, respiratory protection and public health intervention measures. As shown in Table 6, these measures include (1) increasing the ventilation rate (VR) of HVAC systems; (2) installing HEPA filters in the HVAC systems (HEPA); (3) using UVGI devices in the HVAC systems (UVGI); (4) wearing surgical masks (SM); and (5) quarantining the index person and his/her roommate (QI).

Table 6. Single intervention measures

Abbreviation	Single intervention measure
VR1	Increasing air change rate of HVAC systems for restaurants and crew cabins by 20%
VR2	Increasing air change rate of HVAC systems for restaurants and crew cabins by 50%
VR3	Increasing air change rate of HVAC systems for all locations by 20%
VR4	Increasing air change rate of HVAC systems for all locations by 50%
HEPA	Installing HEPA filters in HVAC systems for all locations
UVGI	Installing UVGI devices in HVAC systems for all locations
SM	Wearing of surgical masks by crew members in restaurants, bars, lounges, and small public places
QI1	Quarantining the index passenger and his/her roommate in their stateroom at Day 2
QI2	Quarantining the index passenger and his/her roommate in their stateroom at Day 3
QI3	Quarantining the index passenger and his/her roommate in their stateroom at Day 4

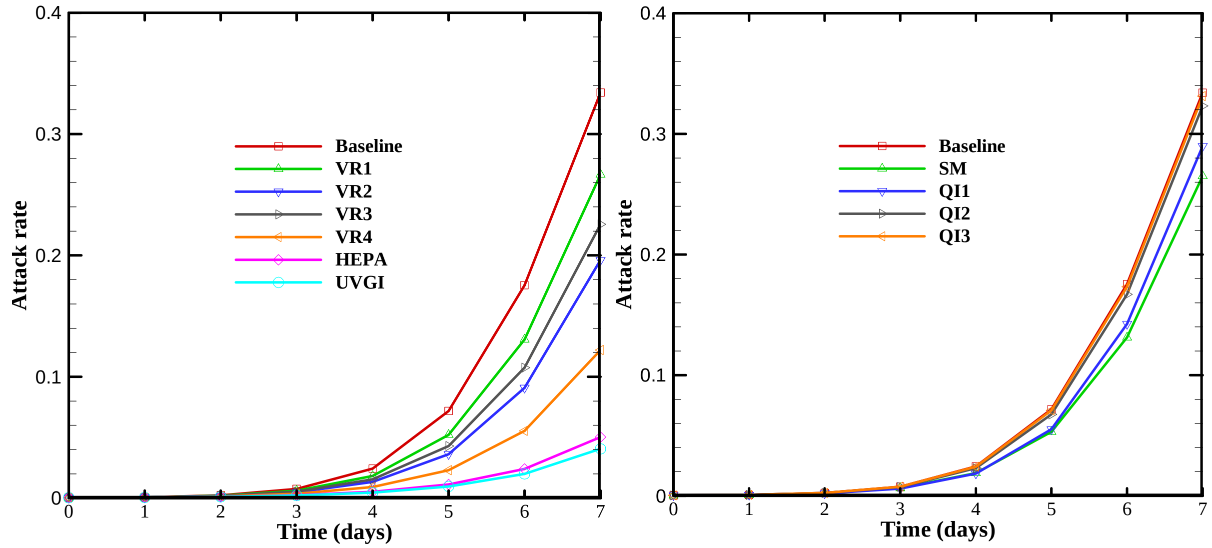
Because the baseline case shows a high infection risk in the restaurants and crew cabins, increasing ventilation was the first measure considered for these locations, as well as a general increase in ventilation in all the spaces. The installation of HEPA filters and UVGI devices in the HVAC systems would eliminate possible infection caused by these systems. The use of surgical masks by crew members serving in restaurants, bars, lounges, or small public places could be enforced during an outbreak. Quarantining patients and their roommates could be difficult in cases of influenza, but it may be necessary for severe infectious diseases such as SARS. This investigation evaluated the effectiveness of each measure.

With the exception of the intervention measure used in each particular case, the rest of the conditions in the VR, HEPA, and UVGI cases were exactly the same as in the baseline case. For the SM case, this study made an assumption that crew members of Group 2 wear surgical masks only in restaurants, bars, lounges and small public places. And adjustments were made in the model of individual-to-individual infection probability $P_{i,j,l}$ on the basis of whether or not the efficiencies η_i and η_s were used between Groups 1 and 2 and within Group 2 in the restaurants, bars, lounges and small public places. For the QI cases, the indoor social contact network model was revised correspondingly. For example, the index passenger and his/her roommate in their stateroom did not go to other locations for activities except their stateroom at Day 2 and succeeding voyage days for QI1 case.

Figure 4 shows the effectiveness of the intervention measures. As illustrated in Figure 4(a), increasing the air change rate in some or all locations decreased the attack rate. The reduction rates in cases VR1, VR2, VR3 and VR4 were 20.2%, 41.2%, 32.5% and 63.5%, respectively. Increasing the ventilation rate is an effective measure. The higher the ventilation rate, the lower the attack rate would be. Of course, this measure would require a large ventilation system and greater energy use. A comparison of VR2 with VR3 suggests that it would be more effective to focus on areas where the infection risk is high, such as restaurants and crew cabins.

As shown in Figure 4(b), the attack rate was reduced by 84.9%, 87.8% and 20.7%, respectively, in the HEPA, UVGI and SM cases compared with that in the baseline case. The HEPA filters and UVGI devices were particularly effective. Surgical masks worn by crew members can reduce the speed of transmission, but to a lesser extent than the other measures.

Figure 4(c) also shows that quarantining the index passenger and his/her roommate in their stateroom at Days 2, 3 and 4 reduced the attack rate by 13.3%, 3.3%, and 0.9%, respectively. Compared with other measures, quarantining did not seem very effective. Because only the index passenger and his/her roommate were quarantined in the QI cases, other people who had been infected by the index passenger would have continued to spread the diseases. Nevertheless, the earlier the quarantine, the better the reduction in the attack rate would be.



(a) (b)

Fig. 4. Impact of intervention measures on the attack rate of the baseline case: (a) different ventilation rates and the use of HEPA and UVGI, and (b) use of SM and quarantining of the index passenger. Refer to Table 6 for an explanation of abbreviations.

Discussion

At times, a cruise ship will continue from one voyage to the next without a break. In such cases, crew members may serve as reservoirs and carry an infection from cruise to cruise on the same ship, prolonging the transmission of respiratory diseases. In order to investigate the reservoir effect and the efficacy of intervention measures, this study considered an infected crew member in Group 2 working in a restaurant, with $I_{2001}^{0} = 1$, $S_{2001}^{0} = E_{2001}^{0} = R_{2001}^{0} = 0$, $S_i^0 = 1$, and $E_i^0 = I_i^0 = R_i^0 = 0$ (i = 1, …, 2000, 2002,…, 2800). Figure 5 shows that without intervention, the attack rate was 44.2%, which was higher than that of the baseline case with an index passenger. It can be concluded that the risk of infection spreading from one infected crew member is higher than that from an index passenger. The reason for this difference is that crew members working in restaurants have frequent contact with passengers and fellow workers.

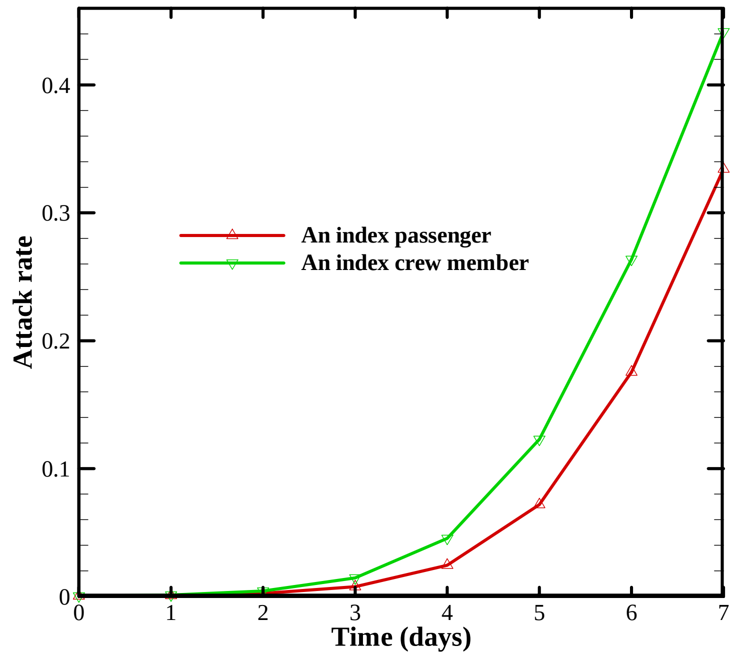


Fig. 5. Comparison of the attack rate with an index passenger and the rate with an index crew member

Cruise ships can be thought of as floating incubators of diseases. Because of the ships' short voyages, the peak in a respiratory disease outbreak rarely occurs. Passengers who have developed respiratory diseases will transmit infectious organisms to new hosts after reaching their destinations; however, such cases are often not reported.

It is also important to note the limitations of this study. The onboard indoor social contact network model made multiple assumptions that may or may not reflect the actual conditions on cruise ships. For instance, there was great uncertainty in the assumption of indoor activities engaged in by the passengers and crew members onboard. In addition, all the days of the voyage were assumed to be "port days". In reality, there are one or more "sea days" in which people could have longer exposure durations indoors. Furthermore, this study did not consider indoor activities that occur while the ship is docked at a port. Some indoor spaces on cruise ships are semi-enclosed, such as staterooms with balconies, and make use of natural ventilation. Passengers and crew members could also spend time on open decks. In addition, because the staterooms and crew cabins are not all of the same size, ventilation conditions differ from space to space.

This study considered only the airborne transmission of disease, neglecting direct person-to-person contact and fomite routes. In the case of influenza, the contribution of each route to the infection rate cannot yet be quantified [46-50].

The Wells-Riley model used in this study assumed well-mixed, steady-state conditions that may or may not be valid on cruise ships. In reality, most indoor spaces onboard are not well mixed and considerably higher concentration of infectious disease viruses would occur closer to the virus source. The risk of disease transmission is therefore likely to be greater for susceptible people in close proximity to the infectors.

The non-uniform distribution of infectious disease viruses can be partially addressed by using computational fluid dynamics (CFD) modelling. CFD is capable to numerically solved Navier-Stoke equations that govern flow and energy and mass conservation equations for air temperature and species concentrations, such as infectious disease viruses. The numerical simulations by CFD can be three-dimensional and transient. Thus, CFD can be used to determine time-dependent, special distributions of infectious disease viruses and the impact of non-uniform virus concentration on occupants [51, 52].

In fact, many studies on infectious disease transmissions have used CFD. For example, Qian et al. [53] integrated the Wells-Riley model into CFD model to predict the spatial distribution of infection risk and showed differences between quanta values determined from mixed and spatially varying CFD models. Ito [54] incorporated the classic SEIR compartmental epidemic model and the Wells-Riley model into CFD model to predict non-uniform distribution of population density of susceptible people, infectors and recovered persons in enclosed spaces. The applications show to be very powerful. Thus, our next study will use CFD to improve the performance of our models used in this paper.

In addition, the simulation results depended greatly on the quantum generation rate, which is a difficult parameter to quantify as it essentially encompasses the concentration of infectious material, virulence of the pathogen, host susceptibility, and ability of the infector to produce an aerosolized pathogen.

Conclusion

This paper integrated an individual-to-individual probability model, a susceptible-exposed-infected-recovered (SEIR) epidemic model at the individual scale, and an onboard indoor social contact network model for evaluating the infection risk on a typical cruise ship voyage. Using influenza as a typical onboard respiratory disease, this study quantitatively assessed various intervention measures for reducing the infection risk onboard. The investigation led to the following conclusions:

The integrated model was validated by using influenza outbreak data from a cruise ship voyage from New York City to Montreal in 1997. The predicted number of infected cases was in good agreement with the actual number of cases.

This study simulated a seven-day cruise with 2,000 passengers and 800 crew members, and each day was assumed to be a port day. When there was an index passenger on the cruise ship, people in restaurants and crew cabins had a higher infection risk than those in other locations. Increasing the ventilation rate of HVAC systems in the restaurants and crew cabins was effective. Installing UVGI devices in all HVAC systems reduced the attack rate by 87.8%. When HEPA filters were installed in the HVAC systems, the efficacy was only slightly lower than that of UVGI devices. The use of surgical masks by crew members serving in restaurants, bars, lounges, or small public places resulted in only a moderate reduction in the attack rate. Quarantining the index passenger and his/her roommate at Day 2 and succeeding days did not greatly reduce the attack rate.

The infection risk from an index crew member was higher than that from an index passenger, because the crew member had potential contact with all the cohorts on the ship.

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Declaration

This work was mainly performed by Mr. Lijie Zheng under the supervision of Dr. Qingyan Chen. Jian Xu and Fangliang Wu contributed to the paper through discussion and by providing useful information to the research.
The authors declare no conflict of interest in relation to the work and preparation of this paper.

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