Analysis of efficacy of intervention strategies for COVID-19 transmission: A case study of Hong Kong

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ABSTRACT

By the end of February 2021, COVID-19 had spread to over 230 countries, with more than 100 million confirmed cases and 2.5 million deaths. To control infection spread with the least disruption to economic and societal activities, it is crucial to implement the various interventions effectively. In this study, we developed an agent-based SEIR model, using real demographic and geographic data from Hong Kong, to analyse the efficiency of various intervention strategies in preventing infection by the SARS-CoV-2 virus. Close contact route including short-range airborne is considered as the main transmission routes for COVID-19 spread. Contact tracing is not that useful if all other interventions have been fully deployed. The number of infected individuals could be halved if people reduced their close contact rate by 25%. For reducing transmission, students should be prioritized for vaccination rather than retired older people and preschool aged children. Home isolation, and taking the nucleic acid test (NAT) as soon as possible after symptom onset, are much more effective interventions than wearing masks in public places. Temperature screening in public places only disrupted the infection spread by a small amount when other interventions have been fully implemented. Our results may be useful for other highly populated cities, when choosing their intervention strategies to prevent outbreaks of COVID-19 and similar diseases.

1. Introduction

Coronavirus disease 2019 (COVID-19) has been threatening human life. Hong Kong has a high risk for infection spread because of its high population density. In 2003, 1,755 out of a total of 8,096 (21.7%) confirmed SARS cases, were from Hong Kong (WHO, 2002). Other respiratory infections such as influenza (e.g. H1N1, H5N1, and H7N9) have also been widely spread in Hong Kong (Tam, 2002; Wu et al., 2014; Wu et al., 2010). Since the first confirmed COVID-19 case on 23 Jan 2020, Hong Kong confirmed 1,197 cases up to 30 June (HKCHP, 2020).

SARS-CoV-2 possibly transmits via close contact, long-range airborne, and fomite routes. Many outbreaks showed that close contact including short-range airborne is the predominant route for SARS-CoV-2 transmission (Chirizzi et al., 2021; Zhang et al, 2020b).

Although some outbreaks such as a restaurant in Guangzhou (Li et al., 2021) and a choir in Washington State, USA (Hamner et al., 2020) showed the possibility of long-range airborne route, there is no solid evidence for its predominance. In this study, we assume that the short-range airborne transmission due to close contact predominates. For fomite transmission, it has become increasingly clear that the fomite route is less important (Goldman, 2020; US CDC, 2021). Therefore, we only considered close contact as the main transmission route in the study.

An agent-based SEIR model is frequently used for simulating infection spread because it has a high reliability, can consider more influencing factors, involves the spatial relationship of a population, and links both social and environmental processes (Nishi et al., 2020; Du et al., 2021; Zhang et al., 2018; Zhang et al., 2020a). However, due to

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the difficulties of data collection, almost all studies focused on simulation are based on a series of hypothetical datasets rather than a comprehensive real dataset. These hypothetical datasets may result in estimation errors and unrealistic conclusions, and may therefore be unreliable in guiding the formulation of intervention plans.

After it was recognized that there was human-to-human transmission of the SARS-CoV-2 virus, both pharmaceutical and non-pharmaceutical interventions, such as contact tracing (Cheng et al., 2020), social distancing (Morawska and Cao, 2020), vaccination (Curtis et al., 2020), mask wearing (Tang et al., 2020a), self-isolation (MacIntyre, 2020), temperature screening (Vilke et al., 2020), and mandatory quarantine (Tang et al., 2020b), have been implemented for infection prevention and control. The efficacy of interventions aimed at blocking transmission vary, due to different implementation strategies used by local governments, as well as variation in compliance. Excessive prevention may also result in unnecessary economic losses (Ye et al., 2020). Optimizing interventions is critical for preventing COVID-19 transmission, and preventing potential future pandemics.

In this study, we used an improved agent-based SEIR model and simulated the COVID-19 spread in Hong Kong, using actual data. We analyzed the efficiency of several main non-pharmaceutical interventions, such as school/workplace closure, contact tracing, health screening at all borders, reducing the rate of close contact, and reducing restaurant dine-in capacity. The results based on this real data strongly support non-pharmaceutical interventions in the future.

2. Methods

2.1. Data sources

An improved agent-based SEIR model was used to simulate the spread of infection in Hong Kong between 23 Jan and 31 Apr 2020. The data for COVID-19 cases were obtained from case reports issued by the Centre for Health Protection of Hong Kong (HKCHP, 2020). Based on the

data log from HKCHP (2020), the imported date and whether or not quarantined of each imported infected case were recorded. All demographic data were obtained from the Hong Kong Census and Statistics Department (HKCSD, 2020). All locations were simplified into seven groups: residence (D: households in residential communities); workplaces (W: offices in companies); schools (S: classes in schools); restaurants (R); markets (K); shopping malls (M); and hospitals (H) (Zhang et al., 2018; Liu et al., 2020). Information and location of all residential buildings, hospitals, schools and kindergartens, universities, restaurants, and shopping malls were obtained from the Hospital Authority, Hong Kong government, population census, the Education Bureau of Hong Kong, and Midland Housing Agency.

2.2. Data processing

Based on characteristics of COVID-19, we divided all patients into three categories: local case; imported case; and possible local case (Appendix A). The population of Hong Kong was 7,500,700 at the end of 2019. By projection from the 2016 by-census, 1,154,246 were students and 4,005,916 were workers. We assigned all Hong Kong residents to different residential buildings for all 431 district council constituency areas (DCCAs) and the 511 major housing estates reported in the 2016 Hong Kong population by-census (Appendix B). There were more than 28,000 residential buildings, 16 hospitals (that can receive COVID-19 patients), 130 big shopping centres, 30 university districts, 2179 schools (primary, middle, and high school) and kindergartens, and over 16,000 registered restaurants (Fig. 1). As there is no known database for the location of markets and office buildings, we randomly distributed them by population density. All people were assigned to a residential building, school, and workplace according to the real distribution of age, gender, and school location. Detailed data for each type of building is given in Appendix C.

Hong Kong has high departure and arrival populations to and from other countries and territories. Zhang et al. (2021) shows the arriving
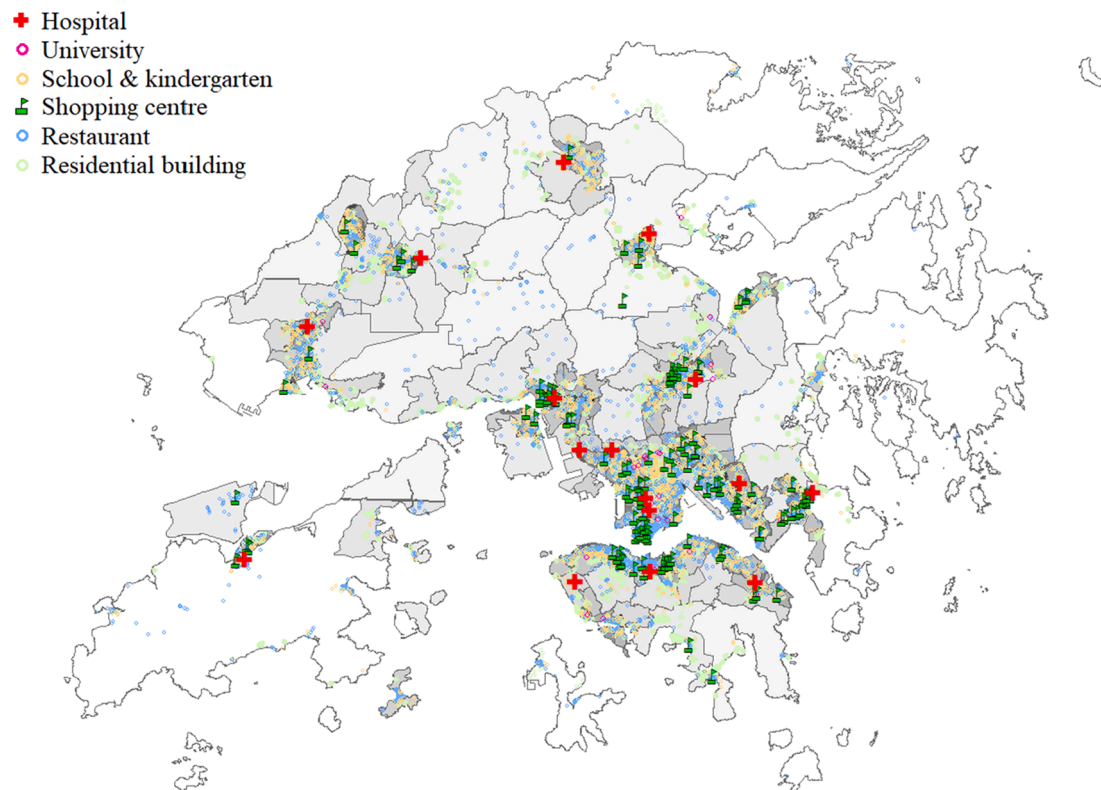

Fig. 1. Building and 431 district council constituency area distribution in Hong Kong.

and departing populations between 1 January and 30 April 2020. Hong Kong implemented strict travel restrictions starting on 30 January 2020. The total arriving and departing populations gradually decreased after the Chinese New Year (CNY) holiday. Following the 14-day mandatory quarantine order for individuals arriving from mainland China, the number of arrivals decreased by 94% compared to the levels during the period of 1–20 January. After travel restrictions were extended to all countries and territories on 26 March, the daily arriving population has not exceeded 5,000 (including local residents and foreign visitors).

The report of confirmed cases of COVID-19 was obtained from the Hong Kong Centre for Health Protection (CHP). After data processing (Appendix A), there were 623 imported cases, 322 local cases, and 93 possible local/imported cases.

2.3. Improved Agent-based SEIR model

The SEIR model is widely used in simulations of infection spread, and especially in simulations of COVID-19 transmission (Annas et al., 2020; Yang et al., 2020). We improved the SEIR model with an agent-based approach, and considered both symptomatic and asymptomatic transmission (Fig. 2a). All individuals were categorised into 5 groups: the susceptible (S); the exposed without symptoms (E; non-infectious); the infected without symptoms (asymptomatic) (I_A; infectious); the non-hospitalized infected with symptoms (symptomatic) (I_S); and the removed (R), namely the infected who have recovered or who died. Since SARS-CoV-2 virus is mainly transmitted via the indoor close contact route (Zhang et al., 2020b; Chirizzi et al., 2021), we only considered this route of virus transmission in our model. Therefore, in this simulation, the susceptible who were in close contact with the infected for longer periods, were more likely to be infected.

In the agent-based model, all individuals were divided into 4 groups: students (S_{td}); workers (W_{rk}); people without mobility (P_{nm}, termed 'immobile individuals'); and people with mobility with no formal occupation (P_m, termed 'mobile individuals'). The total number of workers and students were obtained from the Hong Kong by-census. Anyone younger than 3 or older than 85 years was considered to be an immobile individual, while all residents between 3 and 85 were considered to be mobile individuals with the exception of students and workers.

The time step was set to 1 h in the simulation. The assumptions concerning individuals' daily routines are shown in Fig. 2b. These assumptions include: immobile individuals stay at home the entire day;
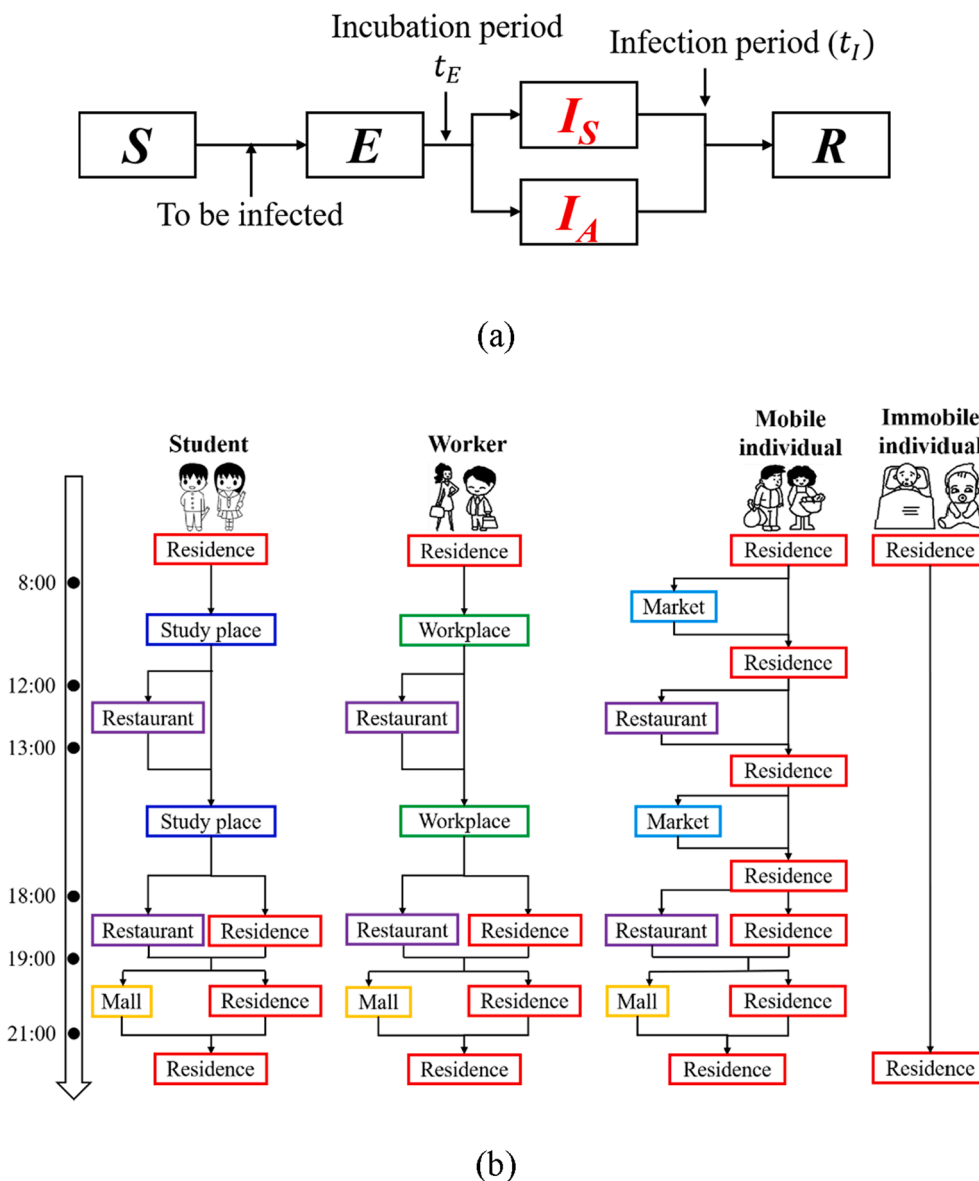
Fig. 2. Model introduction. (a) An improved SEIR model; (b) daily commutes in the agent-based model (the ratio of workers/students going to companies/schools, and of P_1 to P_4, are time-variant parameters); (c) construction of the agent-based SEIIR model (Y: yes; N: no; NAT: nucleic acid testing; Q: policy for mandatory quarantine for arriving population; P: precision of nucleic acid testing for exposed and asymptomatic cases; P_{TD}: probability of fever detection when entering public areas; P_{TS}: precision of fever detection for symptomatic individuals; β_l: the transmission rate during close contact per hour; E_M: mask efficiency for infection risk reduction; t_E: incubation period; t_I: infectious period).

Personal parameter setting

Fixed parameter

COVID-19 related factors
Symptomatic/asymptomatic,
superspreader/normal spreader,
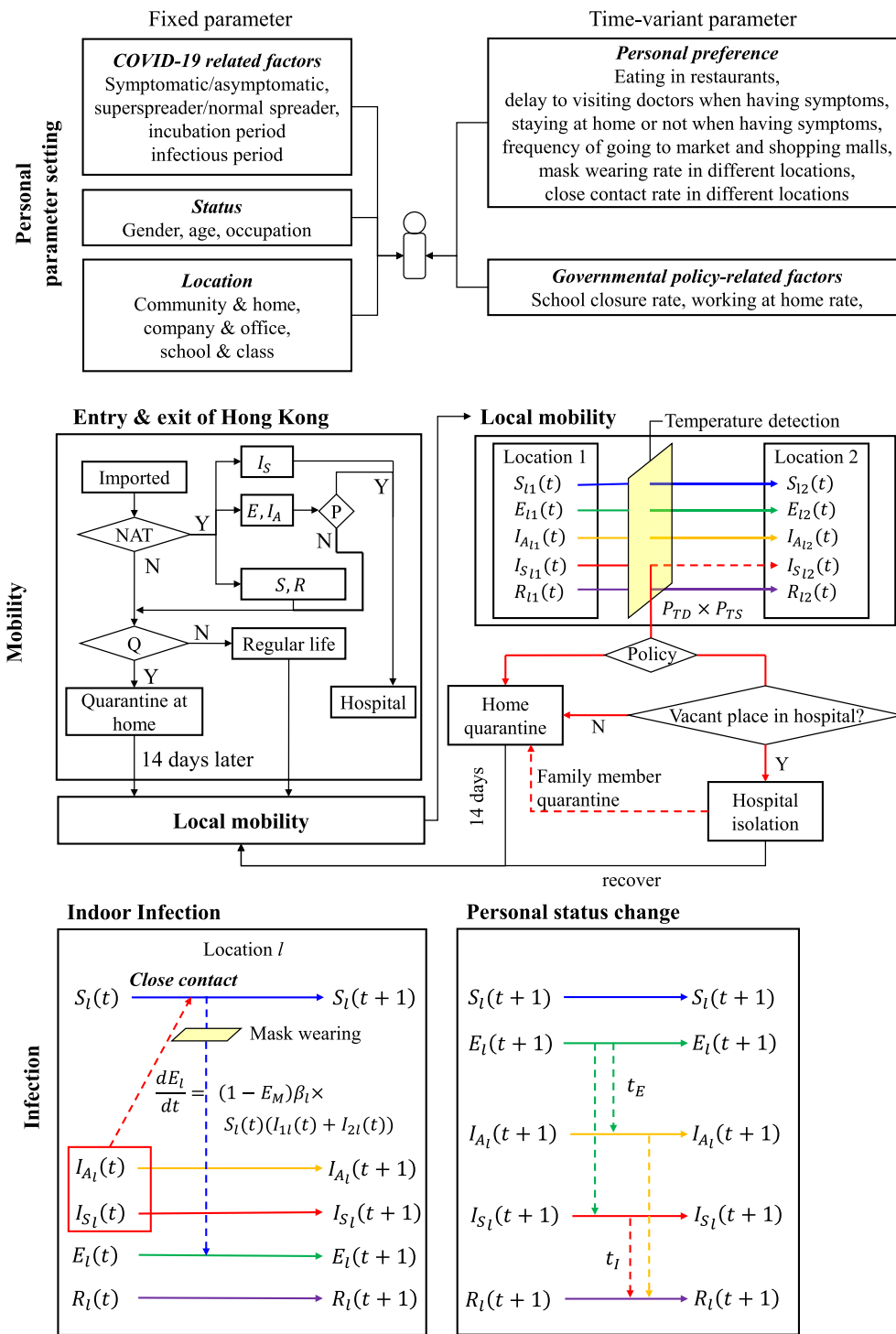incubation period
infectious period

Status
Gender, age, occupation

Location
Community & home,
company & office,
school & class

Time-variant parameter

Personal preference
Eating in restaurants,
delay to visiting doctors when having symptoms,
staying at home or not when having symptoms,
frequency of going to market and shopping malls,
mask wearing rate in different locations,
close contact rate in different locations

Governmental policy-related factors
School closure rate, working at home rate,

Mobility

Entry & exit of Hong Kong

Imported → NAT — Y → I_S
NAT — Y → E, I_A → P — N
P — Y →
E, I_A → S, R
NAT — N →
S, R
Q — N → Regular life
Q — Y → Quarantine at home — 14 days later
Hospital

Local mobility

Local mobility

Temperature detection

Location 1		Location 2
$S_{l1}(t)$		$S_{l2}(t)$
$E_{l1}(t)$		$E_{l2}(t)$
$I_{A_{l1}}(t)$		$I_{A_{l2}}(t)$
$I_{S_{l1}}(t)$		$I_{S_{l2}}(t)$
$R_{l1}(t)$		$R_{l2}(t)$

$P_{TD} \times P_{TS}$

Policy

Home quarantine ← N ← Vacant place in hospital? — Y → Hospital isolation

14 days
Family member quarantine

recover

Infection

Indoor Infection

Location l

$S_l(t)$ →(Close contact)→ $S_l(t+1)$

Mask wearing

$$\frac{dE_l}{dt} = (1 - E_M)\beta_l \times S_l(t)(I_{1l}(t) + I_{2l}(t))$$

$I_{A_l}(t)$ → $I_{A_l}(t+1)$
$I_{S_l}(t)$ → $I_{S_l}(t+1)$
$E_l(t)$ → $E_l(t+1)$
$R_l(t)$ → $R_l(t+1)$

Personal status change

$S_l(t+1)$ → $S_l(t+1)$
$E_l(t+1)$ → $E_l(t+1)$
t_E
$I_{A_l}(t+1)$ → $I_{A_l}(t+1)$
$I_{S_l}(t+1)$ → $I_{S_l}(t+1)$
t_I
$R_l(t+1)$ → $R_l(t+1)$

(c)

students/workers stay at their places of study/work between 8 a.m. and 12 noon, and between 1 p.m. and 6 p.m.; they will eat in their classrooms/offices or randomly choose one of the ten restaurants nearby between 12 noon and 1 p.m.; After school/work, they will eat at a restaurant or at home (6 p.m. to 7 p.m.); For mobile individuals (the third column in Fig. 2b), they may go to markets in the morning (8 a.m. to 12 noon) and afternoon (1 p.m. to 6 p.m.). Everyone except immobile individuals may go to shopping malls or stay at home from 7 p.m. to 9 p.m. Different patterns of movement during the week and on weekends

were also considered (Figures S2B and S2C).

We considered three operations in this simulation: *personal parameter setting, mobility,* and *infection* (Fig. 2c). In *personal parameter setting*, all individuals are given a gender, an age, an occupation (e.g. student, worker), a home address, an office address (only for workers), a classroom address (only for students) based on the distribution projected from the latest Hong Kong population by-census. Each individual will be assigned COVID-19-related factors (e.g. symptomatic/asymptomatic and super-spreader/normal-spreader if infected) based on the

distribution from the CHP case report. Personal preferences and government policy-related factors were also included as time-variant parameters (Figure S2). In *mobility*, all residents travel between buildings (lines between locations in Fig. 2b). If there is fever detection at a public place, symptomatic people have a probability of being detected when entering the place, and therefore to be hospitalized. If someone is found to be infected, their family members will be isolated at home for the 14-day mandatory quarantine. In *infection*, all susceptible individuals have a probability of being infected if they are in the same indoor environment as infectious people (I_S and I_A). The infection probability is dependent on any risk reduction brought about by mask wearing and other intervention measures. All agents have a timer in the simulation, and the timer has a resolution of one hour per step. Once infected, the personal status (E, I_S, I_A, or R) (Fig. 2a) would move to the next status when the personal timer reaches the threshold of each period. At the start, imported cases are the only infection source until the first local case is infected. At this point, both imported and local cases spread the infection in Hong Kong.

2.4. Parameter setting in the simulation

Infection spread between 14 January (date of symptom onset of the first confirmed case) and 30 April 2020. The following data was obtained from the HKCHP (2020) reports: the date of entering Hong Kong (only for imported cases); whether the case had been mandatorily quarantined at home (only for imported cases); the date of symptom onset; and the date of hospital admission of each confirmed case. The data for all imported cases were used for the input setting of the simulation. Individual status (S, E, I) upon entering Hong Kong was deduced from the case report and the time distribution of incubation and infectious periods. We randomized the exact timing within the day of arrival for the imported population. In the simulation, we used the effective reproduction number per day, R_t, which was defined as the number of secondary infection(s) generated by an infected index case in the presence of control interventions (Cowling et al., 2010), to show the extent of the infection spread. The detailed calculation for R_t refers to Appendix D. All fixed and time-variant parameters for the simulation are listed in Table 1 and Figure S2.

The average incubation period of COVID-19 is around 5 days, with the 95th percentile of the distribution at 12.5 days (Li et al., 2020; Linton et al., 2020), and it fits a log-normal distribution (Linton et al., 2020; Lauer et al., 2020). The infectious period was set to 5 days (Kissler et al., 2020). Among all infected patients, the asymptomatic proportion has been estimated to be 17.9% (95% Crl: 15.5–20.2%) (Mizumoto et al., 2020). For viral shedding, some studies showed that onset of symptom is usually 1 day after peak infectiousness (He et al., 2020) and significantly diminish 1–2 days after symptom onset (Goyal et al., 2021). Some researchers concluded that the maximum viral RNA copies appear at day 4 to 8 after symptom onset (Lui et al., 2020; Wölfel et al., 2020; Zheng et al., 2020; Zou et al., 2020). In this study, we hypothesized that patients have no infectivity during the latent period and have a constant infectivity during the infectious period.

In the simulation, all time-varying parameters involved the probability of workers/students eating at restaurants, workers going to workplaces or students going to schools, visiting markets and shopping malls per day, a successful fever detection at a public area, delay from symptom onset to taking a NAT, home isolation after symptom onset, mask wearing rate in workplaces, schools, markets and shopping malls, people who are not in education, employment or training deciding to dine out, and the close contact rate in homes, offices, schools, restaurants, markets and shopping malls. The detailed setting of these parameters can be found in Appendix E.

Table 1
Fixed and time-variant parameters in the simulation.

Parameter	Default Value	Source
Simulation period	Jan. 14 to Apr. 30	First case had the symptom on Jan. 14 (HKCHP, 2020)
Efficiency of mask	50%	Assumed based on Sickbert-Bennett et al.(2020)
Rate of contact tracing	50%	Assumed
Percent of asymptomatic cases	18%	HKCHP, 2020
Incubation period	5.2 days (log-normal distribution)	Li et al., 2020; Linton et al., 2020; Lauer et al., 2020
Infectious period	5 days	Kissler et al., 2020
Total population	7,500,700	Hong Kong government (https://www.censtatd.gov.hk/hkstat/sub/so20.jsp)
Total workers	4,005,916	
Total students	1,154,246	
Distribution of students	–	Based on census data (Appendix C)
Number of residential buildings	28,063	Estimated based on census of major housing estates (https://www.bycensus2016.gov.hk/en/bc-dp.html) and Midland housing agency (https://www.midland.com.hk/). All buildings are accurately located
Number of homes	2,675,849	Estimated based on CSD 2019 (https://www.censtatd.gov.hk/press_release/pressReleaseDetail.jsp?charsetID = 1&pressRID = 4612)
The maximum number of family members	10	Assumed
Number of offices	400,799	Assumed based on the total number of workers and average number of workers per office (Zhang et al., 2020a)
Number of companies	4226	Assumed based on total number of offices and average number of offices per company (Zhang et al., 2020a)
Number of schools	2209	Education Bureau of the Hong Kong Government (https://www.edb.gov.hk)
Number of classes	37,900	Education Bureau of the Hong Kong Government (https://www.edb.gov.hk)
Number of restaurants	15,979	Food and Environment Hygiene Department, HKSAR (https://www.fehd.gov.hk)
Number of markets	1,884	Food and Health Bureau of Hong Kong (http://www.fhb.gov.hk)
Number of major shopping malls	130	Based on the list on Wikipedia, and then manually confirmed by our team https://en.wikipedia.org/wiki/List_of_shopping_centres_in_Hong_Kong
Number of hospitals (only received COVID-19 patients)	16	HKCHP, 2020
Capacity for COVID-19 patients of all hospitals	1000	Assumed
Time to start work/school in the morning	8:00	Zhang et al., 2020c
Time for lunch	12:00	Zhang et al., 2020c
Time for work/school in the afternoon	13:00	Zhang et al., 2020c
Time for dinner	18:00	Zhang et al., 2020c
Time for shopping	19:00	Zhang et al., 2020c
Time for going home at night	21:00 15%	Zhang et al., 2020c

Table 1 (*continued*)

Parameter	Default Value	Source
Percent of non-mobile individuals in the population		Calculated based on the Hong Kong 2016 Population By-census
Percent of super-spreaders	19%	Adam et al., 2020
Infectivity of super-spreaders	17 times greater	Adam et al., 2020
Probability of fever[1] during the infectious period	50%	Buckner et al., 2020
Mandatory quarantine for arrivals	Gradually quarantine	Zhang et al., 2021
Percentage of workers/ students eating at restaurants	Time-variant	Figure S2(A)
Percentage of 'work at home'	Time-variant	Figure S2(B)
Percentage of school closure	Time-variant	Figure S2(C)
Probability of residents going to markets and shopping malls per day	Time-variant	Figure S2(D) and S2(E)
Probability of staying at home when having symptoms	Time-variant	Figure S2(F)
Mask wearing rate in workplaces, schools, markets, and shopping malls	Time-variant	Figures S2(G) to S2(I)
Close contact rate[2] in homes, workplaces, schools, restaurants, markets, and shopping malls	Time-variant	Figures S2(K) to S2(P)

[1] Fever is defined as a reported temperature of 38.0 degree or higher.
[2] Close contact rate is the percentage of indoor time spent on close contact. 100% of close contact rate shows a person spent all indoor time on close contact.

3. Results

3.1. Basic results

Up until 30 April 2020, Hong Kong had recorded 1,038 confirmed cases of COVID-19. From the data analysis, the average time from symptom onset to hospital admission in Hong Kong was 4.7 days. The majority of infected patients were male (53.8%), and the average age of these patients was 37.8. As Fig. 3 shows, 60.0% of cases were imported, 31.0% were local, and 9.0% were possible local/imported. Among all the imported and possible local/imported cases, 64.9% were mandatorily quarantined. The number of non-quarantined imported cases peaked around Mar. 22, which led to a peak of local infections between Mar. 26 and Apr. 5.

Based on the developed agent-based model, we did 1,000 simulations of the spread of infections from Jan. 14 to Apr. 30 (Fig. 4a). The peak of the number of exposed and infected appeared around Mar. 24 and Mar. 29, respectively. The results for local cases showed that 69.4% were infected at home, 12.2% in companies/offices, 2.5% in schools/classes, 12.0% in restaurants, 1.4%, in markets, and 2.5% in shopping malls. The effective reproduction number (R_t) was initially 2.1, and then gradually decreased to 0.7 after the first wave (Fig. 4b). R_t returned to 2.1 on Mar. 11, and gradually decreased to 1 after 9 days. R_t was no more
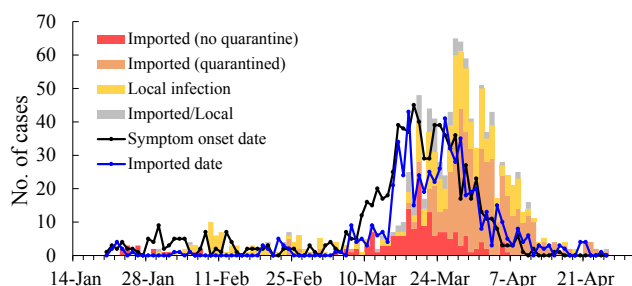

Fig. 3. Cases reported in Hong Kong between Jan. 14 and Apr. 30.

than 0.5 at the end of April.

3.2. Contact tracing

Contact tracing helps isolate potential infection sources. When the contact tracing rate increased from 10% to 50% and from 50% to 90%, the infection risks were respectively reduced by 20.9% and 12.2% (Fig. 5A). The risk reduction efficiency would be higher if earlier contact tracing had been implemented during the outbreak. If the local government had started contact tracing on January 24, infection risk could have been reduced by 14.6% compared with starting contact tracing three weeks later (Fig. 5B).

3.3. Close contact rate

We considered different close contact rates for various indoor environments (Fig. 6). The simulation showed that home was the most sensitive place for infection spread due to the frequency and duration of close contact. The total number of infected individuals would decrease by 32.4% if all co-residents could reduce time in close contact by 50% (Fig. 6A). Offices and restaurants were also sensitive to the close contact rate. The total number of infected individuals would decrease by 16.6% and 19.6% if all workers and diners could reduce their close contact rates by 50%, respectively (Fig. 6B and 6D). Since almost all schools in Hong Kong were closed during this period of the COVID-19 pandemic, the reduction on close contact rate in schools was relatively insignificant. The total number of infected individuals only decreased by 5.7% if all students reduced their close contact rate by 50% (Fig. 6C). Markets and shopping malls had a low sensitivity with regard to the close contact rate. The total number of infected individuals could be reduced by 4.9% and 7.6% if there is no close contact in markets and shopping malls, respectively (Fig. 6E and 6F). In general, if the close contact rate was reduced by 50% in all indoor environments, the infection risk could be reduced by 68.5% (Fig. 6G).

3.4. Vaccination

The percentage of successful vaccinations can be easily estimated by multiplying the vaccine efficacy and the percentage of vaccinated residents. Vaccines have different efficacies, and in order to simplify discussion, we used effective vaccination rate (vaccination rate × vaccine efficacy) in the simulation and did not take the time lag to develop immunity into account. In Hong Kong, if 20%, 40%, 60%, and 80% of residents were successfully vaccinated, the total infection risk could be reduced by 31.5%, 57.4%, 75.4%, and 89.5%, respectively (Fig. 7A). Vaccinating different groups also has various risk reduction outcomes. Students had the longest time on close contacts and also contacted with many people per day. Students had the longest time on close contacts and also contacted with more people per day. If there is no association between the vulnerability to SARS-CoV-2 and age, students are the most vulnerable group for infection, followed by workers, then the mobile, and finally the immobile (Fig. 7B). If 35,000 students were effectively vaccinated, the total number of infected individuals could be reduced by 7.9%. However, there is a negligible effect if 35,000 immobile individuals were vaccinated. Vaccination is much more crucial if there are no strict strategies to prevent and control infectious disease spread. If there had been no preventive measures, approaching 50% of residents would have been infected before the end of April (Fig. 7C). The total number infected could be reduced by 90.0% if 40% of residents are successfully vaccinated. The infection could be naturally controlled if 80% of residents were successfully vaccinated even in the absence of preventive strategies, and in this case, only 159 individuals would get infected.
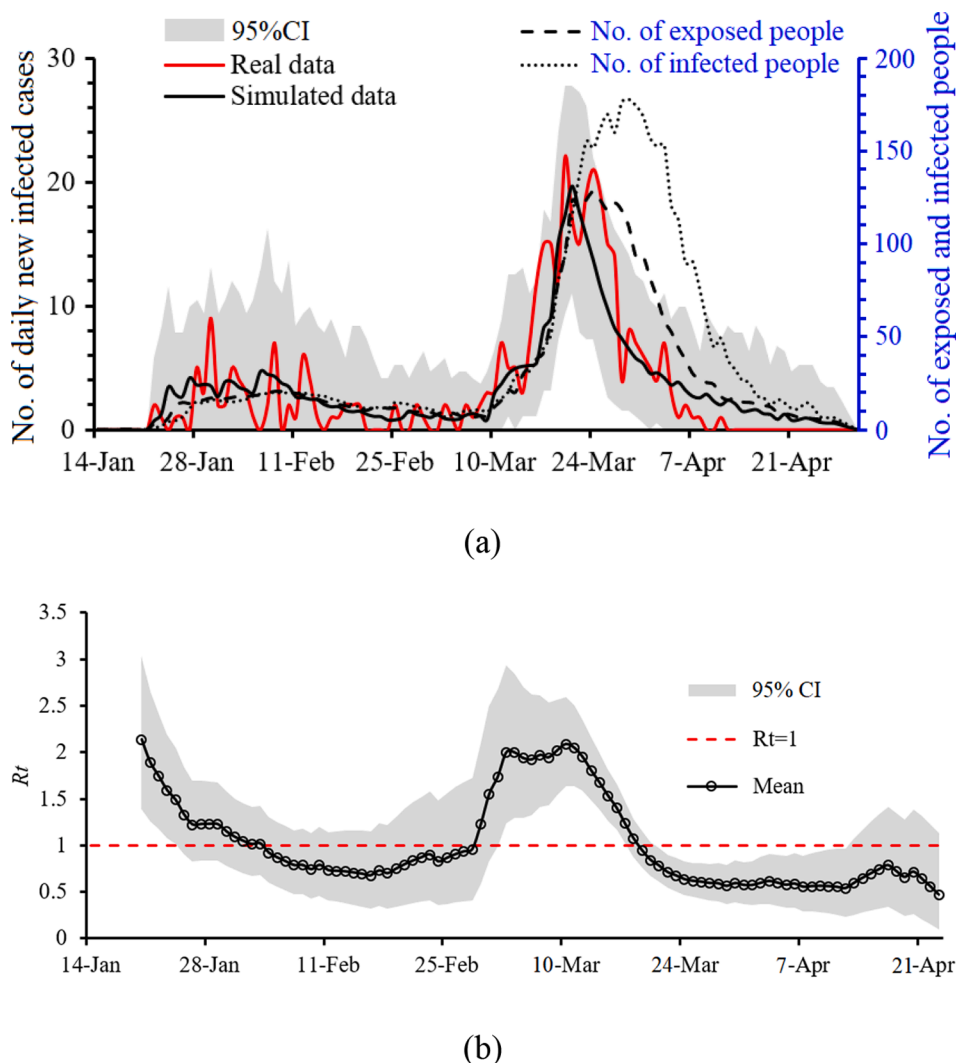
(a)

(b)

Fig. 4. Simulation results. (a) Spread of local infections with time (officially reported and simulated data show the daily number of newly infected cases; the grey area denotes the 95% confidence interval); (b) daily effective reproduction number R_t.
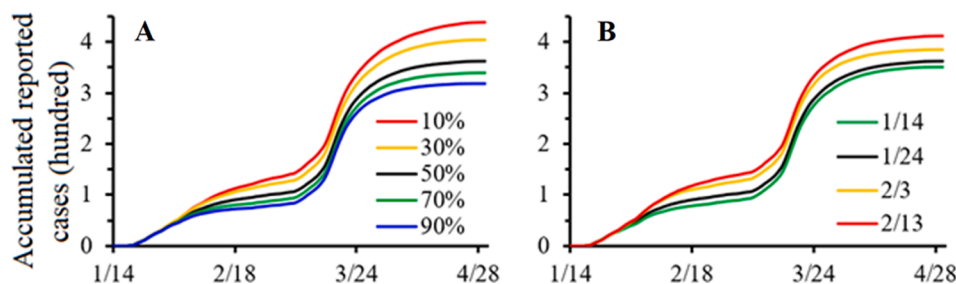

Fig. 5. Efficiency of risk reduction using close contact tracing. (A) percent of traced individuals; (B) the date of implementing close contact tracing at the actual level (with a 10-day interval).

3.5. Other intervention strategies for infection control and prevention

The infection risk would be much lower if patients had a NAT immediately after symptom onset. The average delay from symptom onset to hospital admission during the COVID-19 pandemic in Hong Kong was 4.7 days. If the delay in seeking care was reduced from 5 days to 2 days (Fig. 8A), 41.1% of infections could be avoided. If symptomatic patients could seek help within half a day, 63.5% of the infections could be prevented. Instead of visiting a doctor, home isolation after symptom onset is also effective. If all patients could isolate themselves at home

after symptom onset with their family members, the total number of infections would be only one fifth of what they would be if there were totally free movement (Fig. 8B). Wearing a mask in public places can reduce the infection risk via the close contact route. If all people could wear masks in all public indoor environments, the total infection risk could be reduced by 32.5% (Fig. 8C). Fever detection can help filter those patients who have fever. Comparing 100% fever detection rate with no fever detection in public places finds that 30.8% of the number of infections could be eliminated (Fig. 8D). If the severity of the disease doubles (e.g., due to mutations or a weak immune system), the total
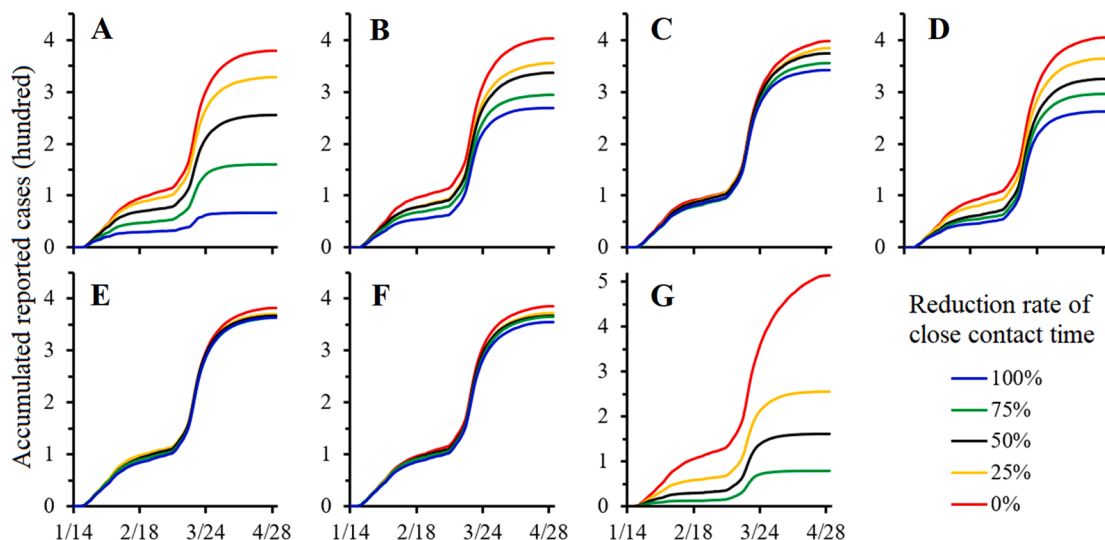
Fig. 6. Efficiency of risk reduction due to close contact rate in (A) home; (B) workplace; (C) school; (D) restaurant; (E) market; (F) shopping mall; (G) all indoor environments. (100% reduction in close contact rate means that there is no close contact in a specific indoor environment).
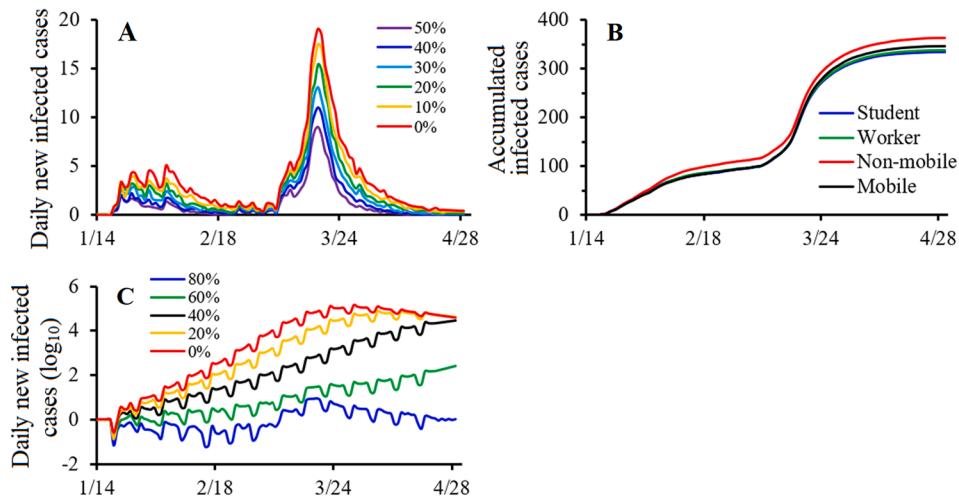

Fig. 7. Vaccination. (A) different effective vaccination rates combining with strategies which have been implemented; (B) only 35,000 used in each group; (C) different effective vaccination rates under uncontrolled condition.
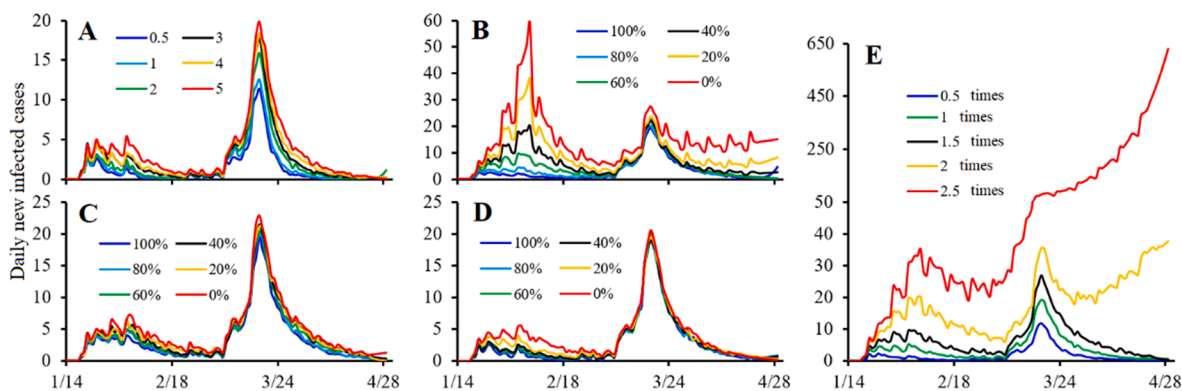

Fig. 8. Other intervention effects on infection control and prevention. (A) Delay in receiving a NAT after symptom onset (days); (B) probability of home isolation after symptomatic onset; (C) rate of mask wearing; (D) fever detection rate in public places; (E) initial R_0.

number of infected individuals would increase four folds (Fig. 8E), and the disease would be hardly controlled by the current intervention levels in Hong Kong.

4. Discussion

Pandemics are strongly associated with human behaviour (Zhang

et al., 2021). The effective reproduction number (R_t) decreases when human behaviour is controlled, and vice versa. Before the end of April 2020, Hong Kong experienced two waves of COVID-19 transmission. The local government imposed restrictions on Hong Kong residents for a 15 day period (January 20 to February 3) followed by a 19 day period (March 1 to March 19), to get R_t below 1 during the two waves. The R_t remained around 0.71 after the first wave, and around 0.57 after the second wave. Strict interventions lead to a lower R_t, but can be disadvantageous by causing economic loss, and potentially resulting in mental crises in the community. Less strict interventions will lead to a higher R_t but are more convenient for residents. The goal is therefore to deploy different interventions to control R_t to an optimal value (i.e., less than one) while balancing all factors that are important.

4.1. Contact tracing

After recognizing that human-to-human transmission of the SARS-CoV-2 virus was occurring, many interventions were implemented for infection prevention and control of this transmission route. Contact tracing is an efficient and necessary strategy to disrupt the transmission chain (Cheng et al., 2020), but it requires enormous resources to be effective. To reduce the associated workload while protecting privacy, public digital contact tracing systems were developed in many countries (Bengio et al., 2020). The Exposure Notifications System, a privacy-preserving contact tracing framework developed by Apple and Google, was also deployed in several regions to notify users if they had spent time near a diagnosed person during the past 14 days. The effective reproduction number can be reduced by 33% if contact tracing is implemented (Kretzschmar et al., 2020). For all contact-traced individuals, the infection risk for household contacts is 5.2 times higher than that for non-household contacts (Park et al., 2020). Contact tracing is much more useful in the early stages of an outbreak, when specific treatments are limited (Keeling et al., 2020). In Hong Kong, we also found that if 70% of contacts were traced, the infection risk would be reduced by only 22.9% when compared to less-than-10% of contacts being traced. This relatively low improvement was mainly due to a series of other interventions. If contact tracing is combined with self-isolation, transmission can be reduced by 47%-64% (MacIntyre, 2020). Therefore, governments should make use of other strategies in tandem with contact tracing to effectively block transmission.

4.2. Common health interventions in the community

Many other interventions were implemented during the pandemic. Temperature screening at public areas were popular in many countries and territories. However, this temperature screening has been found to have negligible efficacy for COVID-19 control because a limited percentage of COVID-19 patients experience a fever during the infectious period (Buckner et al., 2020), temperature detection devices are frequently inaccurate, and there is increased personal awareness of prevention and control during a pandemic, (Vilke et al., 2020; Zhang et al., 2020a). In this study, we observed that temperature screening yielded a more noticeable effect at the beginning of the outbreak when other interventions had not been fully implemented. This agrees with other studies that also found that temperature screening tends to be outshone by other mitigation measures taken during this pandemic (Moghadas et al., 2020; Quilty et al., 2020). When compared to no temperature screening being done in any public space, only a 25% reduction in infection risk could be achieved, even when 80% of symptomatic people could be identified at public areas.

Comparing the imaginary situations where mask-wearing is 0% or 100%, we found that infections would be reduced by 47.1% outside the home, by requiring all residents to wear face masks. In contrast to many other regions, the Hong Kong community has been advocating the use of face masks from the start of this pandemic, largely due to the experience of the 2013 SARS epidemic. The rate of face mask wearing increased

from 74.5% in Jan 20–23 to 97.5% in Feb 11–14 (Cowling et al., 2020). Because the mask wearing percentage was already high, raising this number to 100% at the beginning of this simulation did not have a significant impact on the total infection risk. The total infection risk was reduced by only 7.6% when everyone wears a mask in public. This finding is similar to that for Shenzhen (7.8%) where mask usage in public spaces was also recommended (Zhang et al., 2020a). Note that the trend of mask wearing did not apply to familiar locations (e.g. home) (Zhai, 2020; Zhang et al., 2020c), resulting in a much lower percentage of mask usage in private areas and workspaces comparing with public areas. Compared to the actual situation, infection risk could be reduced by 40% if all people wore a mask at all times in all indoor environments, including their homes and offices. A legal requirement to wear a face mask in all public areas does not yield an observable effect in regions where mask wearing is already common, thus the implementation of other government-led interventions may be more time- and cost-effective.

The reduction of close contact rate also played a part in mitigating the speed of infection spread. During the pandemic, the daily number of close contacts in Hong Kong, Wuhan, and Shanghai declined from 17.6 to 7.1 (60%), 14.6 to 2.0 (86%), and 18.8 to 2.3 (88%), respectively. (Zhang et al., 2020c; Zhang et al., 2020d). The close contact rate reduced by 66% at schools, 48.6% at shopping malls, 38.5% at restaurants, 31.0% at markets, 30.8% at offices, and 10.0% at home (Zhang et al., 2020c). Half of infections could be avoided if the indoor close contact rate was reduced by 25%.

4.3. Infection spread within households

After analysing the use of these intervention methods and the effect of changing the close contact rate, we noticed that there was a very high in-household infection risk – virtually 70% of local infections were found to occur at home. The use of different interventions did not yield any improvement in such cases. There was a mere 10% reduction in close contact rate in homes. Although wearing a mask is efficient in blocking transmission via the close contact route, people did not consistently wear a mask at their familiar places (e.g. home, office), even when they presented COVID-19 related symptoms (Zhai, 2020; Zhang et al., 2020c). People spent, on average, 32.6% more time indoors because of the pandemic, and almost 75% of residents spent this indoor time at home during the pandemic (Zhang et al., 2020c). In mainland China, the infection risk for household contacts is 10 times higher than the rest (Lei et al., 2020). In Shenzhen, roughly two-thirds of local patients were infected in their homes (Zhang et al., 2020a). Unfortunately, we have not noticed any feasible means to prevent infection spread in a household other than herd immunity, meaning the health department should not overestimate health intervention methods when making policy. To prepare for the next pandemic, we believe that there is a need to develop a system to reduce the risk of infection spread between co-residents.

4.4. Priority for vaccination

Vaccinations help to decrease the infection risk although the efficacy may be not very high (Hitchings et al., 2021). Because demand is likely to outstrip supply during a pandemic, an optimal strategy for maximum public health and societal benefits should be formulated (Hassan-Smith et al., 2020). High-risk and indispensable workers in occupations such as healthcare, essential services, and the food and transportation sectors should be prioritized for vaccination (Yang et al., 2021). In addition to these people, the Joint Committee on Vaccination and Immunization suggests that the population aged 65 and older should be prioritized for vaccination (DHSC, 2020). The latest COVID-19 Vaccination Programme of Hong Kong, also defined "persons aged 60 years or above" and "residents and staff of residential care homes for the elderly/persons with disabilities" as two of the five priority groups (GHKSAR, 2021).

However, our study showed that students should be prioritized for vaccination after those in the high-risk and indispensable occupation categories, closely followed by workers, and mobile people. Although older people are more vulnerable to COVID-19 (Mueller et al., 2020), they had the lowest number of contacts during the pandemic (Zhang et al., 2020d). As a result, vaccinating this age group is unlikely to effectively utilize the herd effect and control the number of infected cases. The priority for vaccination maybe changed if mortality of people with different age is considered. The health department should also consider the potential adverse reactions to which elderlies and people with chronic diseases are more prone (Torjesen, 2021) when deciding who should have a higher priority. Retired people and preschool aged children should not be prioritized for vaccination, unless there is evidence that vulnerability to SARS-CoV-2 is strongly associated with age.

4.5. Delay in taking NAT and home isolation

The average infectious period of COVID-19 is around 5 days, and therefore if all symptomatic patients could self-isolate at home after symptom onset, the cross-infection risk could be drastically reduced. Infection risk could be reduced by almost 50% if the probability of self isolation increased from 40% to 80%. Self isolation results in a more significant risk reduction than either mask wearing or thermal screening, and its effectiveness would be even more dramatic if all co-residents isolated at the same time. Seeking medical help as soon as possible after symptom onset is also a good way to reduce the chance of a susceptible person approaching an infected person during the infectious period, thus mitigating the overall infection risk. In Hong Kong, the delay in seeking medical care during the COVID-19 pandemic was 4.7 days after symptom onset, which is longer than in Shenzhen (3.9 days) and other Chinese cities (2.7 days) (Zhang et al., 2020a). Comparing the days people delay before seeking medical care for infections that cause flu-like symptoms in different countries and cities, the lengthy delay in Hong Kong was notable. In Belgium, the median delay was estimated to be 1 for people younger than 20 and 3.8 days for those aged 20–60 for suspected COVID-19 infection (except from nursing home) (Faes et al., 2020). Globally, there was an average of a 4-day (2–6 days) delay for H5N1 infections between 1997 and 2013 (Patel et al., 2014). Patients infected by MERS-CoV (mainly from Saudi Arabia and South Korea) in 2012–2015 delayed by 4.91 days from symptom onset to seeking medical care (Rivers et al., 2016). This delay value reflects the level, convenience, and cost of a local health care system. When taking the economic situation (i.e., GDP per capita) into account, the delay to seeking medical care in Hong Kong was unexpectedly high. By requiring all Hong Kong residents to seek medical care (e.g., undergo a swab test) and isolate themselves at home if they develop COVID-19 symptoms, we anticipated that the number of infected cases would be effectively reduced, based on our study.

4.6. Implementation of interventions

Many interventions should be implemented together to control the COVID-19 infection spread. Self-isolation and taking NAT immediately after symptom onset are only effective for symptomatic patients. It is likely that the pre-symptomatic and asymptomatic patients would continue to spread the disease such that non-symptom-based measures must be implemented alongside to control the infection spread (Moghadas et al., 2020). Measures like mask wearing, contact tracing and the implementation of social distancing policies play a crucial role.

Although the economic cost of not containing the virus would be unimaginably high, especially when the chance of mutation is taken into account, the costs of these mitigation measures are still a major concern for the government and many stakeholders. For the simple preventive means such as the use of facemask and temperature screening in public areas, they should be very feasible with a relatively low expense for most people (e.g., some autistic people may be unable to wear a face mask).

Cost for contact tracing should also be low with the help of existing systems such as Exposure Notification from Apple and Google. However, there could be a high personal economic expense when a possible case is forced to self-isolate, and the government should consider monetarily compensate the qualified individuals. The cost efficiency of delay to hospitalization and percentage of quarantine may depend on geographical factors like the sporadicity of an area (Wang et al., 2020). Study has also shown that social distancing lowers the GDP losses by slowing the pace of COVID-19 infection (Thunström et al., 2020). For more complicated macroeconomic concerns when stricter measures like lockdown or a mix of measurements is to be implemented, "flattening the recession curve" may be the primary goal (Brodeur et al., 2020), but this is generally a mix of policies of infection control and fiscal and monetary policy and thus will not be discussed further. Nonetheless, it is clear that a mix of symptom-based and non-symptom-based measures is essential to thoroughly control the disease.

4.7. Limitations

There are some limitations in this study. We assumed that transmission of infection was only via the close contact route, which means that long-range airborne, and distant fomite routes do not play any part. Other assumptions on individual pattern of daily routines and spatial distribution of some buildings (e.g. workplace, market) would also bring some small errors. Although vertical and horizontal infection spread in a few local high-rise residential buildings was suspected (Kang et al., 2020), this was ignored in our simulation. In addition, some geographic data such as office distribution was not extracted from the actual distribution. Exposure on public transport was assumed to be negligible, since previous literature had shown that the infection risk on local public transport is very small (Zhang et al., 2018). These limitations will inject some error into the simulation result. Similar models could be constructed to examine contact-borne, food/water-borne, and vector-borne disease in future research to improve the accuracy and reliability of the simulation.

CRediT authorship contribution statement

Nan Zhang: Conceptualization, Methodology, Software, Validation, Formal analysis, Data curation, Writing - original draft, Visualization. **Pak-To Jack Chan:** Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing - original draft. **Wei Jia:** Software, Validation, Formal analysis, Data curation. **Chung-Hin Dung:** Investigation, Resources. **Pengcheng Zhao:** Methodology, Formal analysis. **Hao Lei:** Methodology, Writing - review & editing. **Boni Su:** Software. **Peng Xue:** Writing - review & editing, Supervision. **Weirong Zhang:** Writing - review & editing, Supervision. **Jingchao Xie:** Writing - review & editing, Supervision. **Yuguo Li:** Conceptualization, Writing - review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2021.106723.

References

Adam, D.C., et al., 2020. Clustering and superspreading potential of SARS-CoV-2 infections in Hong Kong. Nat. Med. 26, 1714.

Annas, S., Pratama, M.I., Rifandi, M., Sanusi, W., Side, S., 2020. Stability analysis and numerical simulation of SEIR model for pandemic COVID-19 spread in Indonesia. Chaos Solitons Fract. 139, 110072.

Bengio, Y., et al., 2020. The need for privacy with public digital contact tracing during the COVID-19 pandemic. Lancet Digit. Health 2, e342–e344.

Brodeur, A., Gray, D.M., Islam, A., Bhuiyan, S., 2020. A literature review of the economics of COVID-19. J. Econ. Surv. https://doi.org/10.1111/joes.12423.

Buckner, F.S., et al., 2020. Clinical features and outcomes of 105 hospitalized patients with COVID-19 in Seattle. Washington. Clin. Infect. Dis. 71, 2167–2173.

Centre for Health Protection of Hong Kong (HKCHP). COVID-19 case report. Available from, https://chp-dashboard.geodata.gov.hk/covid-19/zh.html (2 Jun 2020b) Accessed date: 2 June 2020.

Census and Statistics Department of Hong Kong (HKCSD). Population. Available from, https://www.censtatd.gov.hk/hkstat/sub/so20.jsp (Accessed date: 2 June 2020).

Census and Statistics Department of Hong Kong (HKCSD). Year.

Cheng, H.Y., Jian, S.W., Liu, D.P., Ng, T.C., Huang, W.T., Lin, H.H., 2020. Contact tracing assessment of COVID-19 transmission dynamics in Taiwan and risk at different exposure periods before and after symptom onset. JAMA Intern. Med. 180, 1156–1163.

Chirizzi, D., et al., 2021. SARS-CoV-2 concentrations and virus-laden aerosol size distributions in outdoor air in north and south of Italy. Environ. Int. 146, 106255.

Curtis, N., Sparrow, A., Ghebreyesus, T.A., Netea, M.G., 2020. Considering BCG vaccination to reduce the impact of COVID-19. Lancet 395 (10236), 1545–1546.

Cowling, B.J., et al., 2010. The effective reproduction number of pandemic influenza: prospective estimation. Epidemiol. 21, 842–846.

Cowling, B.J., Ali, S.T., Ng, T.W.Y., Tsang, T.K., Li, J.C.M., Fong, M.W., Liao, Q., Kwan, M.YW., Lee, S.L., Chiu, S.S., Wu, J.T., Wu, P., Leung, G.M., 2020. Impact assessment of non-pharmaceutical interventions against coronavirus disease 2019 and influenza in Hong Kong: an observational study. Lancet Public Health 5 (5), e279–e288.

Department of Health and Social Care (DHSC). Joint Committee on Vaccination and Immunisation: interim advice on priority groups for COVID-19 vaccination. Sept 25, 2020. https://www.gov. uk/government/publications/priority-groupsfor-coronavirus-covid-19-vaccination-advicefrom-the-jcvi-25-september-2020 (accessed Sept 25, 2020).

Du, E., Chen, E., Liu, J., Zheng, C., 2021. How do social media and individual behaviors affect epidemic transmission and control? Sci. Total Environ. 761, 144114.

Faes, C., Abrams, S., Van Beckhoven, D., Meyfroidt, G., Vlieghe, E., Hens, N., 2020. Time between symptom onset, hospitalisation and recovery or death: statistical analysis of Belgian COVID-19 patients. Int. J. Environ. Res. Public Health 17 (20), 7560. https://doi.org/10.3390/ijerph17207560.

Goldman, E., 2020. Exaggerated risk of transmission of COVID-19 by fomites. Lancet Infect. Dis. 20 (8), 892–893.

Government of the Hong Kong Special Administrative Region (GHKSAR). Protect yourself and others get vaccinated. https://www.covidvaccine.gov.hk/en/programme (Accessed date: Feb 20 2021).

Goyal, A., Reeves, D.B., Cardozo-Ojeda, E.F., Schiffer, J.T., Mayer, B.T., 2021. Viral load and contact heterogeneity predict SARS-CoV-2 transmission and super-spreading events. Elife 10, e63537.

Hamner, L., Dubbel, P., Capron, I., Ross, A., Jordan, A., Lee, J., Lynn, J., Ball, A., Narwal, S., Russell, S., Patrick, D., Leibrand, H., 2020. High SARS-CoV-2 attack rate following exposure at a choir practice—Skagit County, Washington, March 2020. MMWR-Morb. Mortal Wkly. Rep. 69 (19), 606–610.

Hassan-Smith, Z., Hanif, W., Khunti, K., 2020. Who should be prioritised for COVID-19 vaccines? Lancet 396, 1732–1733.

He, X., et al., 2020. Temporal dynamics in viral shedding and transmissibility of COVID-19. Nat. Med. 26, 672–675.

Hitchings, M. D. T. et al. Effectiveness of CoronaVac in the setting of high SARS-CoV-2 P.1 variant transmission in Brazil: A test-negative case-control study. medRxiv (2021) doi:10.1101/2021.04.07.21255081.

Kang, M., et al., 2020. Probable evidence of fecal aerosol transmission of SARS-CoV-2 in a high-rise building. Ann. Intern. Med. 173, 974–980.

Keeling, M.J., Hollingsworth, T.D., Read, J.M., 2020. Efficacy of contact tracing for the containment of the 2019 novel coronavirus (COVID-19). J. Epidemiol. Community Health 74, 861–866.

Kissler, S.M., Tedijanto, C., Goldstein, E., Grad, Y.H., Lipsitch, M., 2020. Projecting the transmission dynamics of SARS-CoV-2 through the postpandemic period. Sci. 368, 860–868.

Kretzschmar, M.E., Rozhnova, G., Bootsma, M.C.J., van Boven, M., van de Wijgert, J.H.H. M., Bonten, M.J.M., 2020. Impact of delays on effectiveness of contact tracing strategies for COVID-19: a modelling study. Lancet Public Health 5 (8), e452–e459.

Lauer, S.A., et al., 2020. The incubation period of coronavirus disease 2019 (COVID-19) from publicly reported confirmed cases: estimation and application. Ann. Intern. Med. 172, 577–582.

Lei, H., Xu, X., Xiao, S., Wu, X., Shu, Y., 2020. Household transmission of COVID-19-a systematic review and meta-analysis. J. Infect. 81, 979.

Li, Q., et al., 2020. Early transmission dynamics in Wuhan, China, of novel coronavirus–infected pneumonia. N. Engl. J. Med. 382, 1199–1207.

Li, Y., et al., 2021. Probable airborne transmission of SARS-CoV-2 in a poorly ventilated restaurant. Build Environ. 196, 107788.

Linton, N.M., et al., 2020. Incubation period and other epidemiological characteristics of 2019 novel coronavirus infections with right truncation: a statistical analysis of publicly available case data. J. Clin. Med. 9, 538.

Liu, Z., Wang, L., Rong, R., Fu, S., Cao, G., Hao, C., 2020. Full-scale experimental and numerical study of bioaerosol characteristics against cross-infection in a two-bed hospital ward. Build. Environ. 186, 107373.

Lui, G., et al., 2020. Viral dynamics of SARS-CoV-2 across a spectrum of disease severity in COVID-19. J. Infect. 81, 318–356.

MacIntyre, C.R., 2020. Case isolation, contact tracing, and physical distancing are pillars of COVID-19 pandemic control, not optional choices. Lancet Infect. Dis. 20 (10), 1105–1106.

Mizumoto, K., Kagaya, K., Zarebski, A., Chowell, G., 2020. Estimating the asymptomatic proportion of coronavirus disease 2019 (COVID-19) cases on board the Diamond Princess cruise ship, Yokohama, Japan, 2020. Eurosurveillance 25, 2000180.

Moghadas, S.M., et al., 2020. The implications of silent transmission for the control of COVID-19 outbreaks. Proc. Natl Acad. Sci. 117, 17513–17515.

Morawska, L., Cao, J., 2020. Airborne transmission of SARS-CoV-2: The world should face the reality. Environ. Int. 139, 105730.

Mueller, A.L., McNamara, M.S., Sinclair, D.A., 2020. Why does COVID-19 disproportionally affect older people? Aging 12 (10), 9959–9981.

Nishi, A., et al., 2020. Network interventions for managing the COVID-19 pandemic and sustaining economy. Proc. Natl. Acad. Sci. 117, 30285–30294.

Park, Y.J., et al., 2020. Contact tracing during coronavirus disease outbreak, South Korea, 2020. Emerg. Infect. Dis. 26 (10), 2465–2468.

Patel, R.B., Mathur, M.B., Gould, M., Uyeki, T.M., Bhattacharya, J., Xiao, Y., Khazeni, N., Chowell, G., 2014. Demographic and clinical predictors of mortality from highly pathogenic avian Influenza A (H5N1) virus infection: CART analysis of international cases. Plos One 9 (3), e91630.

Quilty, B.J., Sam, C., Stefan, F., Rosalind, M.E., 2020. Effectiveness of airport screening at detecting travellers infected with novel coronavirus (2019-nCoV). Eurosurveillance 25, 2000080.

Rivers, C.M., Majumder, M.S., Lofgren, E.T., 2016. Risks of death and severe disease in patients with Middle East Respiratory Syndrome Coronavirus, 2012–2015. Am. J. Epidemiol. 184 (6), 460–464.

Sickbert-Bennett, E.E., et al., 2020. Filtration efficiency of hospital face mask alternatives available for use during the COVID-19 pandemic. JAMA Intern. Med. 180, 1607–1612.

Tam, J.S., 2002. Influenza A (H5N1) in Hong Kong: an overview. Vac. 20, S77–S81.

Tang, B., Xia, F., Tang, S., Bragazzi, N.L., Li, Q., Sun, X., Liang, J., Xiao, Y., Wu, J., 2020a. The effectiveness of quarantine and isolation determine the trend of the COVID-19 epidemics in the final phase of the current outbreak in China. Int. J. Infect. Dis. 95, 288–293.

Tang, S., Mao, Y., Jones, R.M., Tan, Q., Ji, J.S., Li, N.a., Shen, J., Lv, Y., Pan, L., Ding, P., Wang, X., Wang, Y., MacIntyre, C.R., Shi, X., 2020b. Aerosol transmission of SARS-CoV-2? Evidence, prevention and control. Environ. Int. 144, 106039. https://doi.org/10.1016/j.envint.2020.106039.

Thunström, L., Newbold, S.C., Finnoff, D., Ashworth, M., Shogren, J.F., 2020. The benefits and costs of using social distancing to flatten the curve for COVID-19. J Benefit-Cost Anal. 11, 179–195.

Torjesen, I., 2021. Covid-19: Norway investigates 23 deaths in frail elderly patients after vaccination. BMJ. https://doi.org/10.1136/bmj.n149.

US CDC. Science Brief: SARS-CoV-2 and surface (fomite) transmission for indoor community environments. Updated Apr. 5, 2021. Accessed May 8, 2021.

Vilke, G.M., Brennan, J.J., Cronin, A.O., Castillo, E.M., 2020. Clinical features of patients with COVID-19: is temperature screening useful? J. Emerg. Med. 59, 952.

Wang, Q. et al. Effectiveness and cost-effectiveness of public health measures to control COVID-19: a modelling study. medRxiv (2020) doi: 10.1101/2020.03.20.20039644.

Wölfel, R., et al., 2020. Virological assessment of hospitalized patients with COVID-2019. Nat. 581, 465–469.

World Health Organization (WHO). Summary of probable SARS cases with onset of illness from 1 November 2002 to 31 July 2003. Available from, https://covid19. who.int (31 Dec 2003) Accessed date: 1 Jun 2020.

Wu, P., et al., 2014. Responses to threat of influenza A (H7N9) and support for live poultry markets, Hong Kong 2013. Emerg. Infect. Dis. 20, 882–886.

Wu, Z., McGoogan, J.M., 2020. Characteristics of and important lessons from the coronavirus disease 2019 (COVID-19) outbreak in China: summary of a report of 72,314 cases from the Chinese Center for Disease Control and Prevention. JAMA 323 (13), 1239. https://doi.org/10.1001/jama.2020.2648.

Yang, J., et al., 2021. Who should be prioritized for COVID-19 vaccination in China? A descriptive study. BMC Med. 19, 1–13.

Yang, Z., et al., 2020. Modified SEIR and AI prediction of the epidemics trend of COVID-19 in China under public health interventions. J. Thorac. Dis. 12, 165–174.

Ye, Y., Wang, R., Feng, D.a., Wu, R., Li, Z., Long, C., Feng, Z., Tang, S., 2020. The recommended and excessive preventive behaviors during the COVID-19 pandemic: a community-based online survey in China. Int. J. Environ. Res. Public Health 17 (19), 6953. https://doi.org/10.3390/ijerph17196953.

Zhai, J., 2020. Facial mask: A necessity to beat COVID-19. Build. Environ. 175, 106827.

Zhang, H., et al., 2020a. Asymptomatic and symptomatic SARS-CoV-2 infections in close contacts of COVID-19 patients: a seroepidemiological study. Clin. Infect. Dis. https://doi.org/10.1093/cid/ciaa771.

Zhang, J., Litvinova, M., Liang, Y., Wang, Y., Wang, W., Zhao, S., Wu, Q., Merler, S., Viboud, C., Vespignani, A., Ajelli, M., Yu, H., 2020b. Changes in contact patterns shape the dynamics of the COVID-19 outbreak in China. Sci. 368 (6498), 1481–1486.

Zhang, N., Cheng, P., Jia, W., Dung, C.-H., Liu, L.i., Chen, W., Lei, H., Kan, C., Han, X., Su, B., Xiao, S., Qian, H., Lin, B., Li, Y., 2020c. Impact of intervention methods on

COVID-19 transmission in Shenzhen. Build. Environ. 180, 107106. https://doi.org/10.1016/j.buildenv.2020.107106.

Zhang, N., Huang, H., Su, B., Ma, X., Li, Y., 2018. A human behavior integrated hierarchical model of airborne disease transmission in a large city. Build. Environ. 127, 211–220.

Zhang, N., et al., 2020d. Effects of human behaviour changes during the COVID-19 pandemic on influenza spread in Hong Kong. Clin. Infect. Dis. https://doi.org/10.1093/cid/ciaa1818.

Zhang, N., et al., 2021. Changes in local travel behaviour before and during the COVID-19 pandemic in Hong Kong. Cities 112, 103139.

Zheng, S., et al., 2020. Viral load dynamics and disease severity in patients infected with SARS-CoV-2 in Zhejiang province, China, January-March 2020: retrospective cohort study. BMJ 369, m1443.

Zou, L., et al., 2020. SARS-CoV-2 viral load in upper respiratory specimens of infected patients. New Eng. J. Med. 382, 1177–1179.