Epidemiological characteristics and the effectiveness of countermeasures to control coronavirus disease 2019 in Ningbo City, China

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Abstract

Background: A novel coronavirus (SARS-CoV-2) has spread widely and led to high disease burden around the world. This study aimed to explore key parameters of SARS-CoV-2 infection and to assess the effectiveness of interventions to control the coronavirus disease 2019 (COVID-19).

Methods: A susceptible – exposed – infectious – asymptomatic – recovered (SEIAR) model was developed for the assessment. Data of symptomatic and asymptomatic infection of SARS-CoV-2 were collected to calculate the key parameters of the model in Ningbo City, China.

Results: A total of 157 confirmed COVID-19 cases (including 51 imported cases and 106 secondary cases) and 30 asymptomatic infections were reported in Ningbo City. The proportion of asymptomatic has an increasing trend. The proportion of asymptomatic of elder people was lower than younger people, and the difference was statistical significant (Fisher's Exact Test, P = 0.034). There were 22 clusters associated with 167 SARS-CoV-2 infections, among which 29 cases were asymptomatic, with a proportion of 17.37%. We found that the secondary attack rate of asymptomatic was almost the same as that of symptomatic cases, and no significance was observed (χ^2 = 1.350, P = 0.245) by Kruskal-Wallis test. The effective reproduction number (R_{eff}) was 1.43 which revealed that the transmissibility of SARS-CoV-2 was moderate. If the interventions were not strengthened, the duration of the outbreak would last about 16 months with a simulated attack rate of 44.15%. The total attack rate and duration of the outbreak would increase along with the increasing delay of intervention.

Conclusions: SARS-CoV-2 had moderate transmissibility in Ningbo City, China. Asymptomatic infection has the same transmissibility as symptomatic. The integrated interventions were implemented at different stages during the outbreak, which found to be exceedingly effective in China.

Key words: SARS-CoV-2; COVID-19; Transmissibility; Effectiveness; Forecasting

Background

The coronavirus disease 2019 (COVID-19), with the pathogen of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), has spread widely and led to high disease burden around the world, especially in China, South Korea, Japan, Iran, Italy, and the United States of America[1-6]. As of March 23, the number of confirmed COVID-19 cases surpassed 300 000 globally and 81 601 in China[7]. The rapid increase in the number of confirmed cases, the wide range of countries affected, and the enormous impact on people's health and national economies emphasized the importance of understanding the epidemiological characteristics and the transmission mechanism of COVID-19.

As the most affected country in first wave of the transmission, it is important to assess the effectiveness of the interventions implemented in China during the outbreak and to share the experience of controlling the disease for other potential countries of the following wave of the outbreak. As the commonly employed tool to assess the effectiveness of the interventions, mathematical models and have been used to explore the epidemiological characteristics and the transmission mechanism of COVID-19, to perform the forecasting of the transmission and assess the effectiveness of interventions such as social distance and wearing masks[1,8-12]. However, certain key parameters of the COVID-19 remain unclear, such as the proportion of asymptomatic infection and the transmissibility of the asymptomatic, which might lead to some uncertainty of the modelling results.

In this study, a susceptible – exposed – infectious – asymptomatic – recovered (SEIAR) model was developed based on our previous studies[9,13,14]. The data of symptomatic and asymptomatic infection of SARS-CoV-2 were collected to calculate the key parameters (including the proportion of asymptomatic infection and the transmissibility of the asymptomatic) in Ningbo City, China. The SEIAR model was employed to fit the collected data in the city, to calculate the transmissibility of the disease, and to further assess the effectiveness of the implemented interventions.

Methods

Data collection

Ningbo City is a large city in Zhejiang Province, China, with a population of 8.2 million. In this study, we collected the information of all the reported COVID-19 cases and asymptomatic infections in Ningbo City as of March 14, 2020, including sex, age, occupation, exposed date, onset date, and diagnosed date. Contact tracing of each case was performed to investigate the number of close contacts, as well as the contact modes and time. The information of each confirmed case and asymptomatic infection was collected from Ningbo Center for Disease Control and Prevention (CDC). A case investigation was conducted according to the National Novel Coronavirus Pneumonia Prevention and Control Program announced by National Health Commission of the People's Republic of China.

Case definitions and case finding

COVID-19 was classified as suspected case, confirmed case, and asymptomatic infection as follows:

a) Suspected case: A suspected case could be diagnosed if there is an epidemiological history and any 2 of the clinical features or no clear epidemiological history and 3 of the following clinical features: fever and / or respiratory symptoms; having specific imaging features of COVID-19; In the early stage of the disease, the total number of leukocytes was normal or decreased, and the lymphocyte count was decreased.

b) Confirmed case: The case should be suspected case and has any one of the following evidence: SARS-CoV-2 was detected by real-time fluorescence reverse transcription – polymerase chain reaction

(RT-PCR); the genome of the virus was sequenced and highly homologous to the known new coronavirus.

c) Asymptomatic infection: No symptom but SARS-CoV-2 was tested positive from respiratory tract specimens.

Close contacts are defined as: During the period from two days before the symptoms onset to the isolation of a confirmed case, people who have close contact (within 1 meter) with the confirmed case and without effective protection, such as people who live, study, work together with the patients; medical staff, family members or other people who have close contact during the diagnosis, treatment, nursing and visiting of the patients; passengers who share the same vehicle and have close contact during the trip with the cases.

Specimen collection and the virus testing

Sample collection: the respiratory tract specimens (such as throat swab, nose swab, deep expectoration fluid, respiratory tract aspirate, bronchial lavage fluid, alveolar lavage fluid, etc.) were collected at the early stage of the infection. The specimens were then repacked in the biosafety cabinet of the biosafety secondary laboratory. All specimens were placed in a suitable size sample collection tube with a spiral cover and a gasket. The information of the collected samples were recorded, including the sample number, type, patient's name, and sampling date, before sending to the testing laboratory within 24 hours for detection. The collection, transportation and detection of specimens were conducted according to the second category of highly pathogenic microorganisms to ensure the biological safety.

The nucleic acid of the COVID-19 virus was detected by real-time fluorescence RT-PCR. Two pairs of novel coronavirus gene primers and probes were selected for ORFlab and N gene (ORFlab: Forward primer 5'-CCCTGTGGGTTTTACACTTAA-3', Reverse primer 5'-ACGATTGTGCATCAGCTGA-3', Fluorescence probe 5'-FAM-CCGTCTGCGGTATGTGGAAAGGTTATGG—BHQl-3'; N: Forward primer

5’-GGGGAACTTCTCCTGCTAGAAT-3’, Reverse primer 5’-CAGACATTTTGCTCTCAAGCTG-3’, Fluorescence probe 5’-FAM-TTGCTGCTGCTTGACAGATT-TAMRA-3’).. Nucleic acid was extracted by using virus RNA/DNA nucleic acid extraction reagent of Tianlong biology. Real-time fluorescent RT-PCR was conducted by using novel coronavirus SAR-CoV-2 nucleic acid reagents of Shanghai Berger. The reaction system was referred to the instructions of relevant manufacturers. Result judgement: negative: no CT value or CT value > 40; positive: CT value < 37; suspicious: CT value is between 37 and 40, and it is recommended to repeat the experiment.

Transmission model

Based on our previous study[9], we developed a SEIAR model to simulate the transmission of COVID-19 in Ningbo City. In the model, individuals were divided into five compartments: susceptible (S), exposed (E), infectious (I), asymptomatic (A), recovered (R). The model based on the following assumptions and facts:

a) During the outbreak period, the natural birth rate and death rate in the population was in a relative low level and therefore were not considered in the model.

b) Importation of COVID-19 was resulted from people mobility. However, we have collected data of imported cases. The importation was simulated by a function as follows:

   $Importation = n_t$

   In the function, n_t refers to imported COVID-19 cases at time t.

c) The incubation period and latent period of human infection was defined as $1/\omega$ and $1/\omega'$. Based on our previous study[9], we set $\omega = \omega'$.

d) The infectious period of I and A was defined as $1/\gamma$ and $1/\gamma'$. By analyzing the reported data, we found that I and A were both isolated when they were diagnosed in Ningbo City. Therefore, we set $\gamma = \gamma'$.

e) By analyzing the reported data, we found that no death case was reported in Ningbo City. Therefore, case fatality rate was no considered in our study.

f) The proportion of asymptomatic infection was defined as p.

g) The S will be infected through sufficient contact with I, and the transmission rate was defined as β. We also assumed that the transmissibility of A was κ times that of I, where $0 \leq \kappa \leq 1$.

Therefore, the SEIAR model is shown as follows:

$$\begin{cases} \frac{dS}{dt} = -\beta S(I + \kappa A) \\ \frac{dE}{dt} = \beta S(I + \kappa A) - \omega E \\ \frac{dI}{dt} = (1-p)\omega E - \gamma I \\ \frac{dA}{dt} = p\omega E - \gamma A \\ \frac{dR}{dt} = \gamma I + \gamma A \end{cases}$$

The transmissibility of the COVID-19 based on the SEIAR model

In this study, we used the R_0 to assess the transmissibility of COVID-19. Commonly, R_0 was defined as the expected number of secondary infections that result from introducing a single infected individual into an otherwise susceptible population[15-17]. If $R_0 > 1$, the outbreak will occur. If $R_0 < 1$, the outbreak will toward an end. Therefore, $R_0 = 1$ is the threshold of the transmission. However, if intervention was implemented, R_0 should be replaced as R_{eff} which could be calculated by the following equation:

$$R_{eff} = \frac{\beta S(1 - p + \kappa p)}{\gamma}$$

Parameter estimation

The parameters of the SEIAR model were shown in Table 1. In our previous study, we found that the epidemic curve would be heterogeneous before and after the interventions were implemented[16,17]. Therefore, the values of β should be different in different stages during the transmission. In our study, we estimated the values of β by curve fitting of the SEIAR model with the reported data.

Since there was no evidence on the relative transmissibility of A compared to that of I, we calculated the secondary attack rate (SAR) of A and I from clustered cases in our collected data. And the difference between SAR of A and I was test to define the value of κ.

Although there were some literatures reported the asymptomatic infection[18-20], the value of p remained unclear. In this study, we calculated the value of p from clustered cases in Ningbo City. We also collected the date of exposure, date of symptom onset, and date of isolated of the cases. Therefore, the values of ω, ω', γ, and γ' were estimated by the collected data.

Simulation methods and statistical analysis

The imported cases were simulated as transmission sources and the secondary cases were employed for the curve fitting. The procedures of the simulation and curve fitting were performed by Berkeley Madonna 8.3.18 (developed by Robert Macey and George Oster of the University of California at Berkeley. Copyright ©1993-2001 Robert I. Macey & George F. Oster, CA, USA) was employed to perform the curve fitting and the simulation. The simulation methods (Runge-Kutta method of order four with tolerance set at 0.001) were the same as the previously published researches[15-17,21-23]. The goodness of fit was judged by Chi-square (χ^2) value calculated by SPSS 21.0 (IBM Corp, Armonk, NY, USA).

Results

Epidemiological characteristics

As of February 25, 2020, a total of 157 confirmed COVID-19 cases (including 51 imported cases and 106 secondary cases) and 30 asymptomatic infections were reported in Ningbo City. The peak of reported cases based on onset date and reported date was on January 22, and February 3, 2020, respectively (Figure 1). The peak of imported cases, secondary cases, and asymptomatic infection occurred on January 26, January 22, and

February 5, 2020, respectively (Figure 1). The proportion of asymptomatic had an increasing trend and fitted well with a logistic differential equation model (Figure 2).

The incidence of female was higher than male, but the proportion of asymptomatic of female was lower than male, but no significance was observed ($\chi^2 = 2.196$, $P = 0.138$). The incidence of elder people was higher than younger people, but the proportion of asymptomatic of elder people was lower than younger people, and the difference was statistical significant (Fisher's Exact Test, $P = 0.034$). The most infected people were farmers, housework and unemployment individuals, retirees, public officials, and students. However, the scatter children, workers, students, individual business people, housework and unemployment individuals, and farmers had the highest proportion of asymptomatic (Table 2).

The median incubation period of the reported cases was 5 days (range: 1 – 15 days) (Figure 3). Therefore, $\omega = \omega' = 0.2$. The median duration from symptoms onset to diagnosed date and from symptoms onset to isolated of the reported cases was 4.0 days (range: 0 – 17 days) and 3 days (range: 0 – 15 days), respectively (Figure 3). Therefore, $\gamma = \gamma' = 0.3333$.

There were 22 clusters associated with 167 SARS-CoV-2 infections reported in Ningbo City. Among the 167 clustered infections, 29 cases were asymptomatic infection, with a proportion of 17.37%, thus $p = 0.1737$. The detailed information of 7 clusters was collected, the infection sources of 2 clusters were found to be asymptomatic (denoted as Cluster A) and the other 5 clusters were symptomatic (denoted as Cluster B). We found that the SAR of asymptomatic was almost the same as that of symptomatic cases, and no significance was observed ($\chi^2 = 1.350$, $P = 0.245$) by Kruskal-Wallis test. Therefore, $\kappa = 1$. We also found higher proportion of asymptomatic in the infected cases in Cluster A than Cluster B, and the age of infection source of Cluster A was lower than that of Cluster B (Table 3).

Transmissibility of COVID-19

The simulated results showed that our model fitted well (χ^2 = 39.798, P = 0.524) with the reported epidemic curve of COVID-19 in Ningbo City (Figure 4). The data were divided into stage 1 (before February 1, 2020) and stage 2 (after February 1, 2020), and the parameter β was divided into β_1 and β_2, the values of them were 5.81 × 10^{-8} and 8.87 × 10^{-10}. Therefore, the values of R_{eff} were 1.43 and 0.02 in the two stages.

Effectiveness of countermeasures

Based on our simulation, if the interventions were not strengthened on February 1, 2020, the SARS-CoV-2 would spread rapidly with a peak on August 19, 2020 and the reported COVID-19 cases would be 43011 on that date. Moreover, the transmission would go to an end on May 25, 2021. The duration of the outbreak would last about 16 months with a simulated attack rate of 44.15% (Figure 5). In Ningbo City, the integrated interventions were implemented at different stages during the outbreak (Figure 1), which found to be exceedingly effective (Table 4).

If January 14, 2020 was set as the initial time (t = 0), we simulated the interventions were strengthened on different delays (t = 0, 30, 60, …) (Table 4). We found that total attack rate (TAR) and duration of the outbreak (DO) would increase when the delay increased. But the two indices increased rapidly when the delay was longer than 180 days. The similar findings were observed when we increased the values of R_{eff} up to 2.20 and 3.58. The TAR would increase up to 69.72% and 80.06%, and the DO would decrease down to 242 days and 154 days, respectively. The two indices increased rapidly when the delay was longer than 90 days and 60 days.

Discussion

In this study, the median incubation period of the reported cases was 5 days, the median duration from symptoms onset to diagnosed date and from symptoms onset to isolation of the reported cases was 4.0 days and 3 day, respectively. The results are similar to another recent estimate[24]. There was also a research showed the median incubation period was 6.7 days, the interval time from between illness onset and diagnosed was 4.5 days [25]. The different period might be related to the different diagnostic capacity and virus transmission range in each region.

With the global outbreak of COVID-19, many scientists speculate that some infected people could be highly contagious even when they are mild or asymptomatic, and a growing number of studies have shown that many patients of COVID-19 with no or only mild symptoms could transmit the virus to other people. About 17.9 percent of the 634 infected people on board the Diamond Princess cruise ship never showed symptoms[26]. A research team in Japan reported that 13 of the 565 Japanese citizens evacuated from Wuhan in early February were infected, with four of them asymptomatic infection[27]. The viral load that was detected in the asymptomatic patient was similar to that in the symptomatic patients[28]. In our study, among the 167 clustered infections, 29 cases were asymptomatic, with a proportion of 17.37%. Due to differences between the regions, the proportion of asymptomatic patients was likely to be higher than we thought. We also found that the proportion of asymptomatic had an increasing trend. The reason of the increasing remains unclear, which might be: a) although asymptomatic infections are difficult to detect at the early phase of the outbreak, as specialists exploring the virus more deeply, the ability to detect and diagnose asymptomatic infections was improving; b) with the concern about virus evolution, the pathogenicity of the virus are likely to decrease with the increase of the generations during the transmission, therefore an increasing number of infection would become asymptomatic.

By analyzing the SAR of asymptomatic and symptomatic, we found that the value of κ was 1, which suggest the transmission potential of asymptomatic cases are the same as those of symptomatic. The result is consistent with the findings of Guangdong Provincial CDC [28]. This finding is fire-new in Zhejiang Province and suggests that effective quarantine measures for asymptomatic infectious need to be taken seriously, such measures can greatly reduce the further spread of the virus. If isolation measures are not taken for asymptomatic patients, they would not seek health care or visit hospital and cannot be found in their infectious period, and will spread to the other close contacts[20,29]

In our study, the epidemic curve of COVID-19 in Ningbo City were divided into stage 1 (before February 1, 2020) and stage 2 (after February 1, 2020), the values of R_{eff} were 1.43 and 0.02 in the two stages. Compared with our previous study[30], it can be seen the transmissibility of SARS-CoV-2 in Ningbo City is in a moderate level, of course, R_{eff} rather than basic R_0 was used to estimate the transmissibility. Since the outbreak of SARS-CoV-2 in Ningbo city, government has taken corresponding intervention measures, after February 1, 2020, interventions intensified and the spread of the virus was effectively controlled in Ningbo city. Based on our simulation, if the interventions were not implement, the SARS-CoV-2 would spread rapidly with a peak on August 19, 2020 and the duration of the outbreak would last about 16 months, it can also be seen that the intervention had high effectiveness of countermeasures to control the transmission of the virus and the interventions in the city are worth promoting and attention.

The similar findings were observed when we simulated the values of R_{eff} up to 2.20 and 3.58, the results showed that the TAR and DO would increase along with the increasing delay of intervention or with no inventions, it suggested that effective and timely interventions played an important role in controlling the outbreak, the result was similar to other researches[31,32]. Actually, we simulated the value of R_{eff} not only 1.43, but also 2.30 and 3.58[30]， our model involves many parameters, inventions such as wearing masks, increasing social distance and so on could decrease the effective reproduction number and finally be helpful to contain the outbreak.

Ningbo City was successful in preventing and controlling on the COVID-19 infection. It largely benefited from timely and effective intervention measures. Firstly, Wuhan City was locked down on January 23, 2020, which decreased the imported cases and therefore decreased the infection sources in Ningbo City.

Secondly, social distancing, stopping the subways, highway, and airline, staying at home, and wearing mask were performed timely, which strongly cut off most of the transmission route. In addition, enhancing the surveillance system, case finding, and testing the suspected cases or even close contacts were performed strictly, which made sure that symptomatic and asymptomatic infections were isolated timely, thus greatly reducing the spread range of asymptomatic patients.

Limitations

The current available information in our study may not fully elucidate our findings since the following limitations. Firstly, the data of only limited number of COVID-19 patients were collected due to the uncertainty of certain parameters in the model of many reported cases. Secondly, the effectiveness of interventions is assessed as a combination of interventions, rather than as individual interventions. Therefore, more data are urgently needed to accurately estimate the transmissibility of COVID-19.

Conclusions

SARS-CoV-2 had moderate transmissibility in Ningbo City, China. Asymptomatic infection has the same transmissibility as symptomatic. The integrated interventions were implemented at different stages during the outbreak, which found to be exceedingly effective in China. If intervention were not strengthened, the transmission would last for 16 months and more than 44% people would be infected.

List of abbreviations

COVID-19: coronavirus disease 2019; SARS-CoV-2: severe acute respiratory syndrome coronavirus 2; SEIAR: susceptible – exposed – infectious – asymptomatic – recovered; CDC: Center for Disease Control and Prevention; RT-PCR: reverse transcription – polymerase chain reaction; SAR: secondary attack rate; TAR: total attack rate; DO: duration of the outbreak.

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Availability of data and materials

Extra data is available by emailing to Bo Yi (yibonb@163.com) on reasonable request.

Authors' contributions

TC designed research and performed the modelling; BY, XL, TF, YC, YL, KD, DZ, and RW collected the data; TC, LL, BY, JX, ZL, ZZ, JR, YZ, YW, and MY analyzed the data; TC and LL wrote the manuscript. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

Consent for publication

Not applicable.

Ethics approval and consent to participate

Tis study was designed and performed according to the Helsinki declaration and was approved by the Ethical Review Committee of Ningbo Municipal Center for Disease Control and Prevention (No. 202001). Informed consent was obtained from all individuals. If the participants are less than 18 years then consents were obtained from their parents or legal guardians. All data analyzed were anonymized.

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Figure legends

Figure 1. Epidemic curve of reported cases of COVID-19 in Ningbo City, China.

Figure 2. The temporal distribution of the proportion of asymptomatic infection of COVID-19 in Ningbo City, China.

Figure 3. Key time-to-event distributions. The estimated short incubation period distribution (i.e., the time from latest exposure to illness onset) is shown in Panel A. The estimated long incubation period distribution (i.e., the time from earliest exposure to illness onset) is shown in Panel B. The estimated distribution of times from illness onset to diagnosed date is shown in Panel C. The estimated distribution of times from illness onset to isolated date is shown in Panel D.

Figure 4. Results of curve fitting of the SEIAR model with the reported data. A: curve fitting with imported and secondary cases; B: curve fitting with secondary cases.

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Table 1. Description and values of parameters in SEIARW model

Parameter	Description	Unit	Value	Range	Methods
β_1	Transmission rate at stage 1	Individuals^{-1}·days^{-1}	5.81×10^{-8}	> 0	Curve fitting
β_2	Transmission rate at stage 2	Individuals^{-1}·days^{-1}	8.87×10^{-10}	> 0	Curve fitting
κ	Relative transmissibility rate of A to I	1	1	0 – 1	Reported data
p	Proportion of A	1	0.1737	0 – 1	Reported data
ω	Incubation relative rate	days^{-1}	0.2	0.0667 – 1	Reported data
ω'	Latent relative rate	days^{-1}	0.2	0.0667 – 1	Reported data
γ	Removed rate of the infectious	days^{-1}	0.3333	0.0667 – 1	Reported data
γ'	Removed rate of the asymptomatic	days^{-1}	0.3333	0.0667 – 1	Reported data

Table 2. Epidemiological characteristics of reported COVID-19 cases in Ningbo City, China

Characteristics	Number of symptomatic	Number of asymptomatic	*p* (%)	*IR* (per 100 000)
Sex				
Male	56	15	21.13	1.71
Female	101	15	12.93	2.86
Age (years)				
0 – 9	1	3	75.00	0.59
10 – 19	4	2	33.33	1.00
20 – 29	13	3	18.75	1.44
30 – 39	27	4	12.90	2.16
40 – 49	20	5	20.00	1.69
50 – 59	47	9	16.07	4.24
60 – 69	29	1	3.33	3.14
70 – 79	11	3	21.43	3.52
>= 80	5	0	0.00	2.30
Occupation				
Scattered children	1	1	50.00	NA
Workers	8	4	33.33	NA

Students	10	4	28.57	NA
Individual business people	3	1	25.00	NA
Housework and unemployment individuals	36	7	16.28	NA
Farmers	36	7	16.28	NA
Business services	17	3	15.00	NA
Retirees	22	3	12.00	NA
Public officials	11	0	0.00	NA
Teachers	6	0	0.00	NA
Migrant workers	1	0	0.00	NA
Security staffs	1	0	0.00	NA
Lawyers	1	0	0.00	NA
Business owners	1	0	0.00	NA
Medical staffs	1	0	0.00	NA
Unknown	2	0	0.00	NA

_p_: proportion of asymptomatic; _IR_: infection rate; NA: not available.

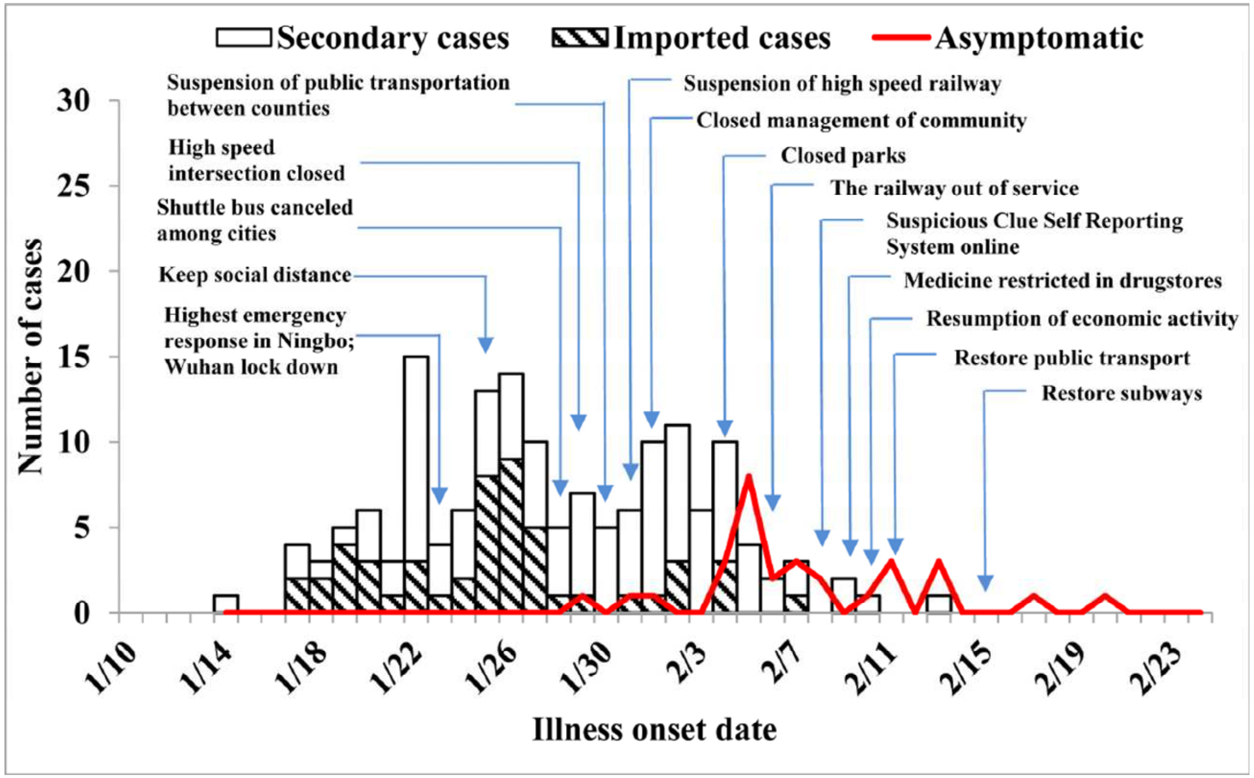
Table 3. The secondary attack rates in nine clusters of COVID-19 in Ningbo City, China.

Outbreak ID	Classification of infection source	Basic information of the infection source		Number of close contacts	Number of secondary cases		SAR (%)
		Sex	Age (years)		Symptomatic	Asymptomatic	
A	Asymptomatic	Male	24	15	2	1	20.00
B	Asymptomatic	Male	12	9	1	1	22.22
C	Symptomatic	Male	54	21	2	0	9.52
D	Symptomatic	Male	31	38	2	0	5.26
E	Symptomatic	Female	52	12	2	0	16.67
F	Symptomatic	Female	69	11	2	0	18.18
G	Symptomatic	Female	66	9	4	0	44.44

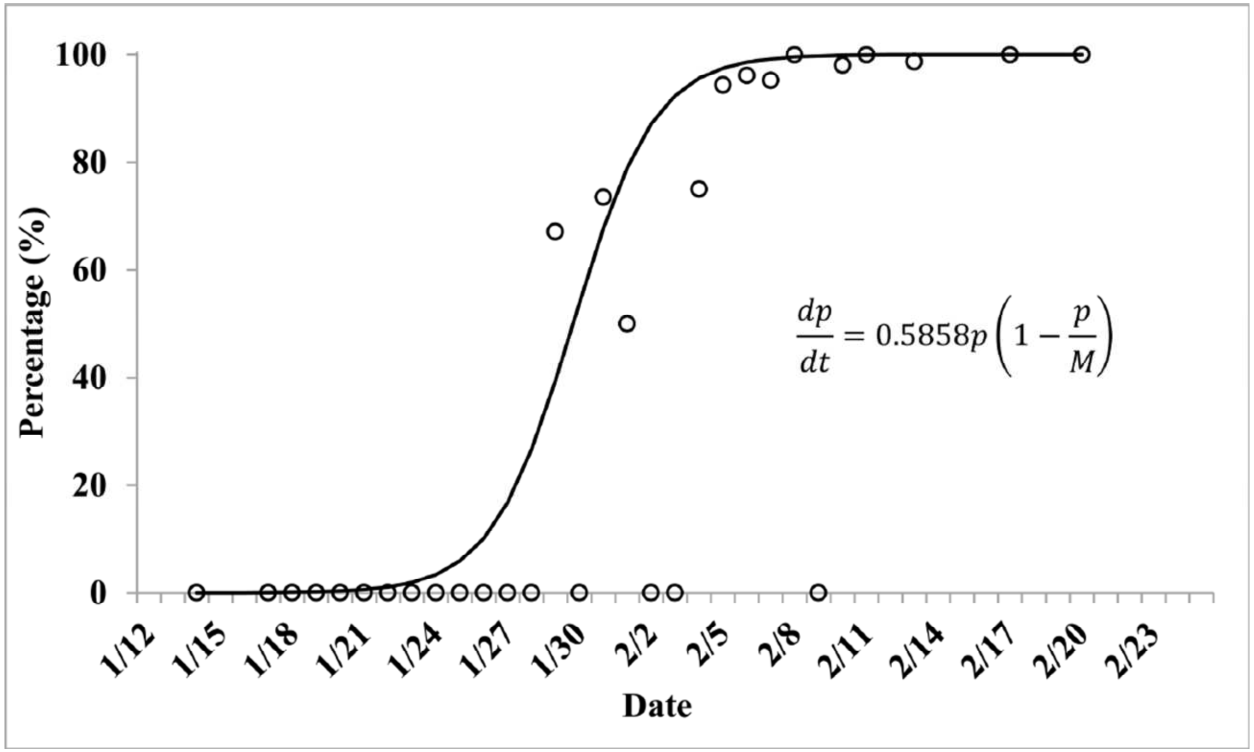
SAR: secondary attack rate.

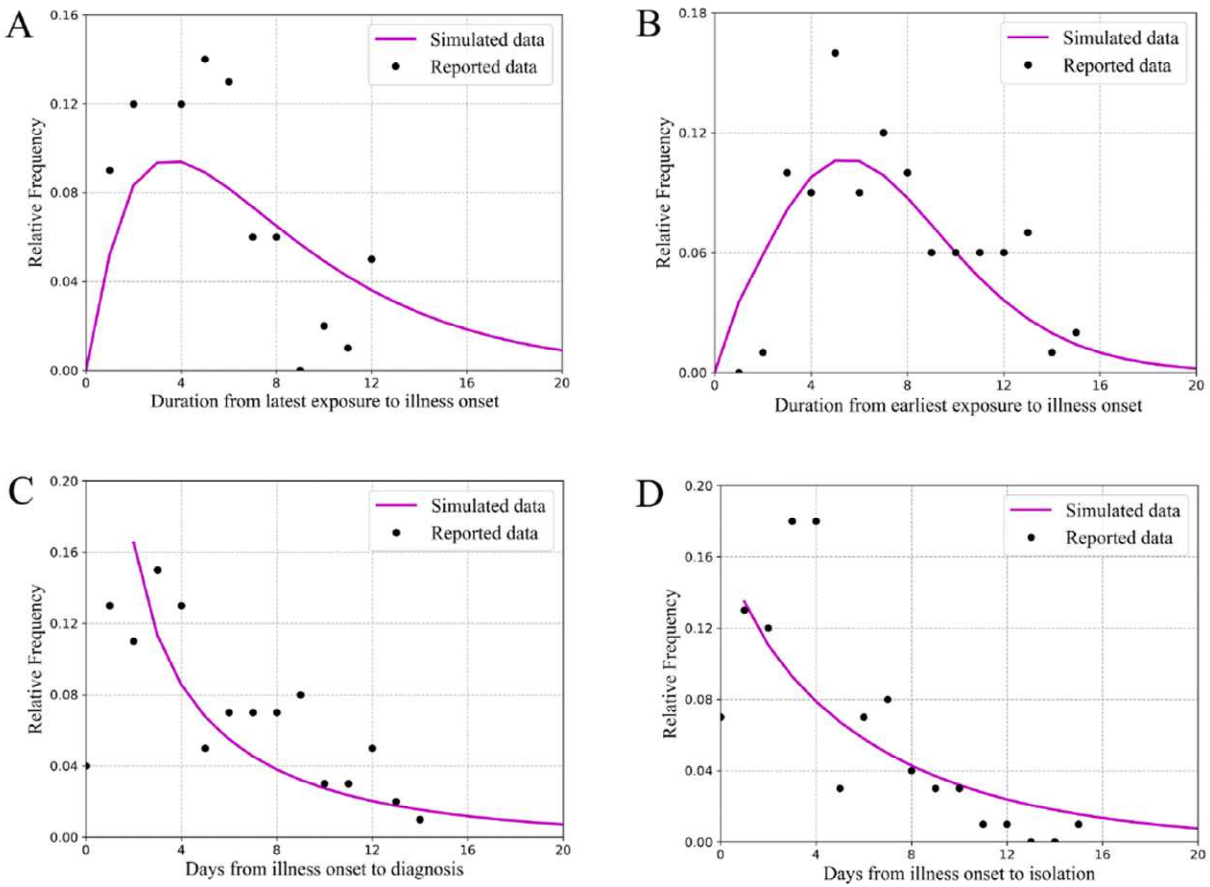
Table 4. Effectiveness of interventions implemented at different time.

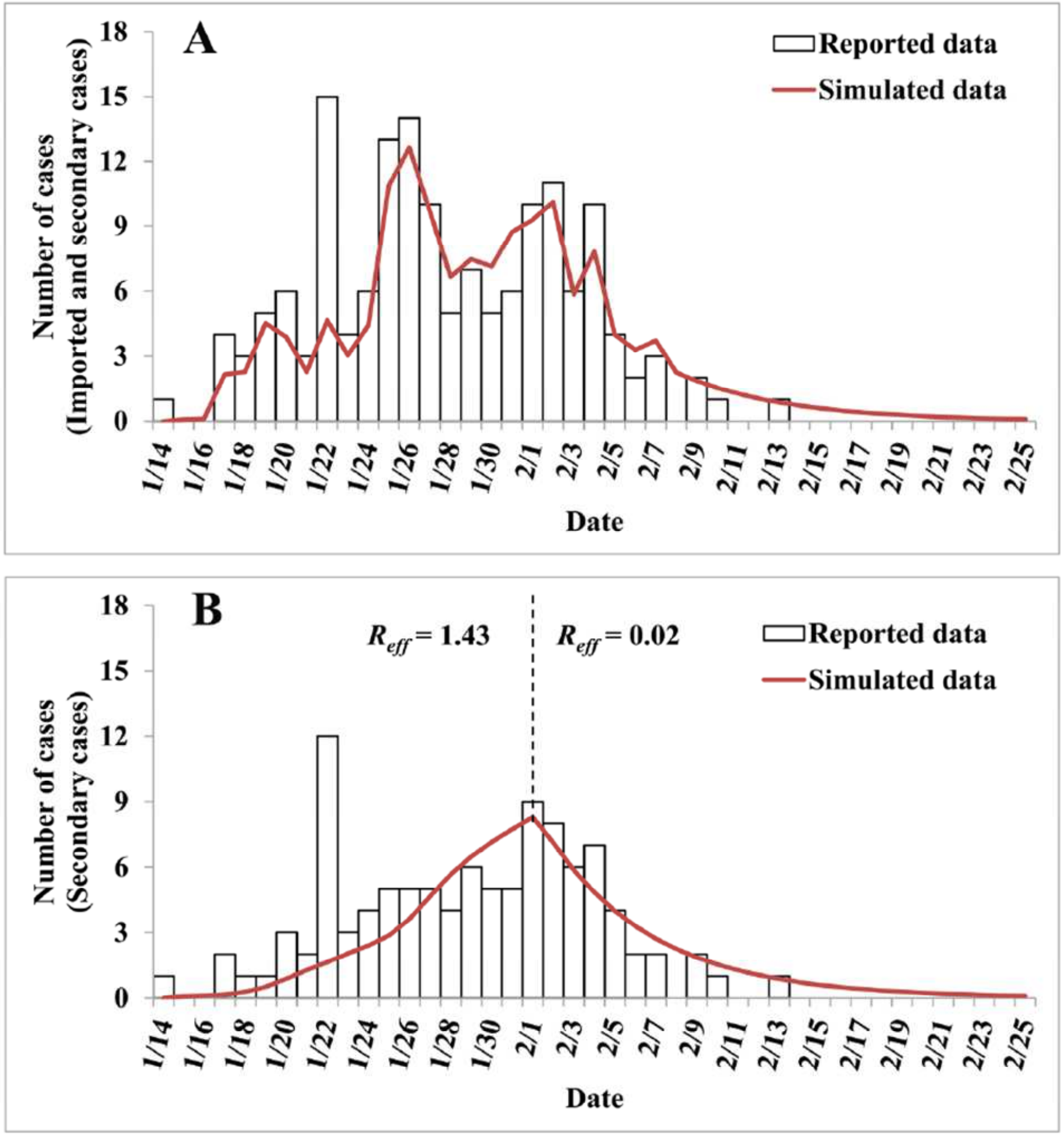
	$R_{eff} = 1.43$			$R_{eff} = 2.20$			$R_{eff} = 3.58$		
	Number of cases	TAR (%)	DO (days)	Number of cases	TAR (%)	DO (days)	Number of cases	TAR (%)	DO (days)
Reported data	157	0.0019	31	157	0.0019	31	157	0.0019	31
$t = 30$	343	0.0042	49	1302	0.0159	59	13499	0.1646	73
$t = 60$	1812	0.0221	88	51285	0.6254	109	4375366	53.3581	130
$t = 90$	8233	0.1004	126	1492328	18.1991	155	6553084	79.9157	141
$t = 120$	36086	0.4401	163	5268580	64.2510	182	6564749	80.0579	147
$t = 150$	153075	1.8668	201	5695610	69.4587	197	6564851	80.0592	153
$t = 180$	584939	7.1334	237	5716242	69.7103	212	6564852	80.0592	154
$t = 210$	1642857	20.0348	270	5717231	69.7223	227	6564852	80.0592	154
$t = 240$	2811023	34.2808	299	5717278	69.7229	242	6564852	80.0592	154
$t = 270$	3379328	41.2113	324	5717281	69.7229	242	6564852	80.0592	154
$t = 300$	3556361	43.3703	347	5717281	69.7229	242	6564852	80.0592	154
No intervention	3620333	44.1504	497	5717281	69.7229	242	6564852	80.0592	154

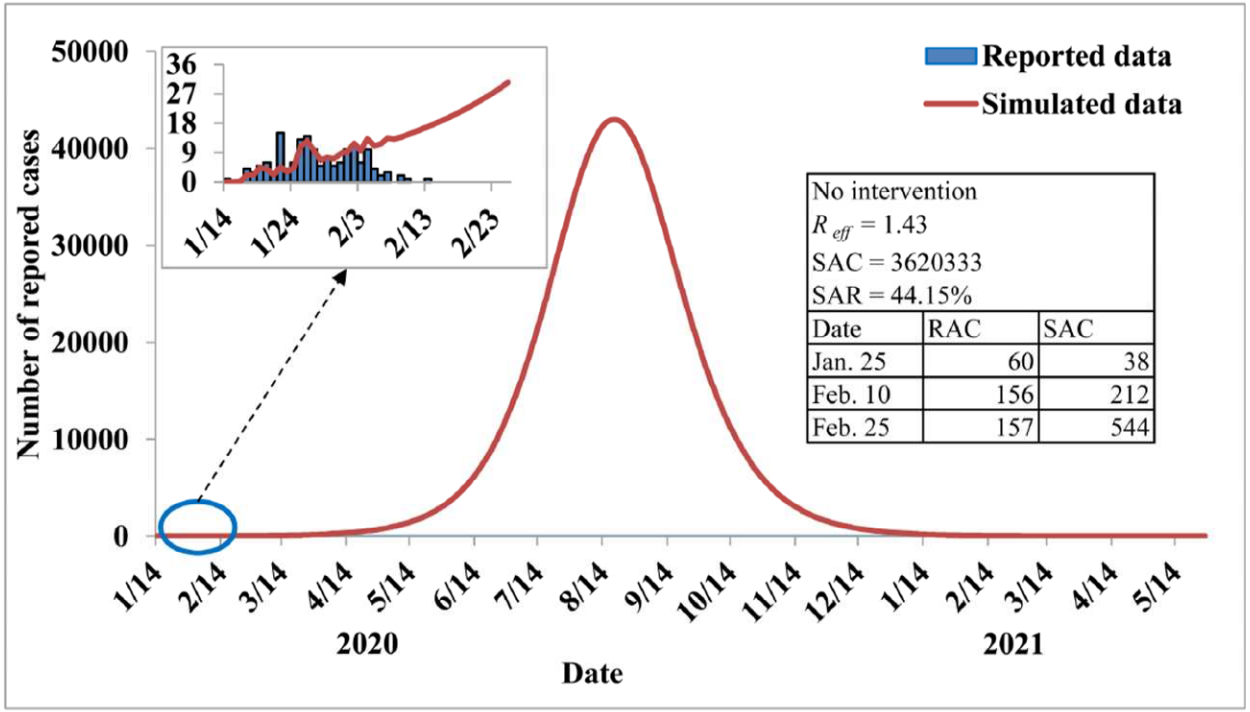


Secondary cases
Imported cases
Asymptomatic
Number of cases
30
25
20
15
10
5
0
Suspension of public transportation between counties
High speed intersection closed
Shuttle bus canceled among cities
Keep social distance
Highest emergency response in Ningbo; Wuhan lock down
Suspension of high speed railway
Closed management of community
Closed parks
The railway out of service
Suspicious Clue Self Reporting System online
Medicine restricted in drugstores
Resumption of economic activity
Restore public transport
Restore subways
1/10
1/14
1/18
1/22
1/26
1/30
2/3
2/7
2/11
2/15
2/19
2/23
Illness onset date


100
80
60
40
20
0
Percentage (%)
$\frac{dp}{dt} = 0.5858p\left(1 - \frac{p}{M}\right)$
1/12
1/15
1/18
1/21
1/24
1/27
1/30
2/2
2/5
2/8
2/11
2/14
2/17
2/20
2/23
Date


A
B
C
D
Simulated data
Reported data
Relative Frequency
Duration from latest exposure to illness onset
Duration from earliest exposure to illness onset
Days from illness onset to diagnosis
Days from illness onset to isolation


A
Reported data
Simulated data
Number of cases
(Imported and secondary cases)
18
15
12
9
6
3
0
1/14
1/16
1/18
1/20
1/22
1/24
1/26
1/28
1/30
2/1
2/3
2/5
2/7
2/9
2/11
2/13
2/15
2/17
2/19
2/21
2/23
2/25
Date
B
R_{eff} = 1.43
R_{eff} = 0.02
Reported data
Simulated data
Number of cases
(Secondary cases)
18
15
12
9
6
3
0
1/14
1/16
1/18
1/20
1/22
1/24
1/26
1/28
1/30
2/1
2/3
2/5
2/7
2/9
2/11
2/13
2/15
2/17
2/19
2/21
2/23
2/25
Date


Reported data
Simulated data
50000
40000
30000
20000
10000
0
Number of repored cases
36
27
18
9
0
1/14
1/24
2/3
2/13
2/23
No intervention
R_{eff} = 1.43
SAC = 3620333
SAR = 44.15%
Date | RAC | SAC
Jan. 25 | 60 | 38
Feb. 10 | 156 | 212
Feb. 25 | 157 | 544
1/14
2/14
3/14
4/14
5/14
6/14
7/14
8/14
9/14
10/14
11/14
12/14
1/14
2/14
3/14
4/14
5/14
2020
2021
Date

Figures

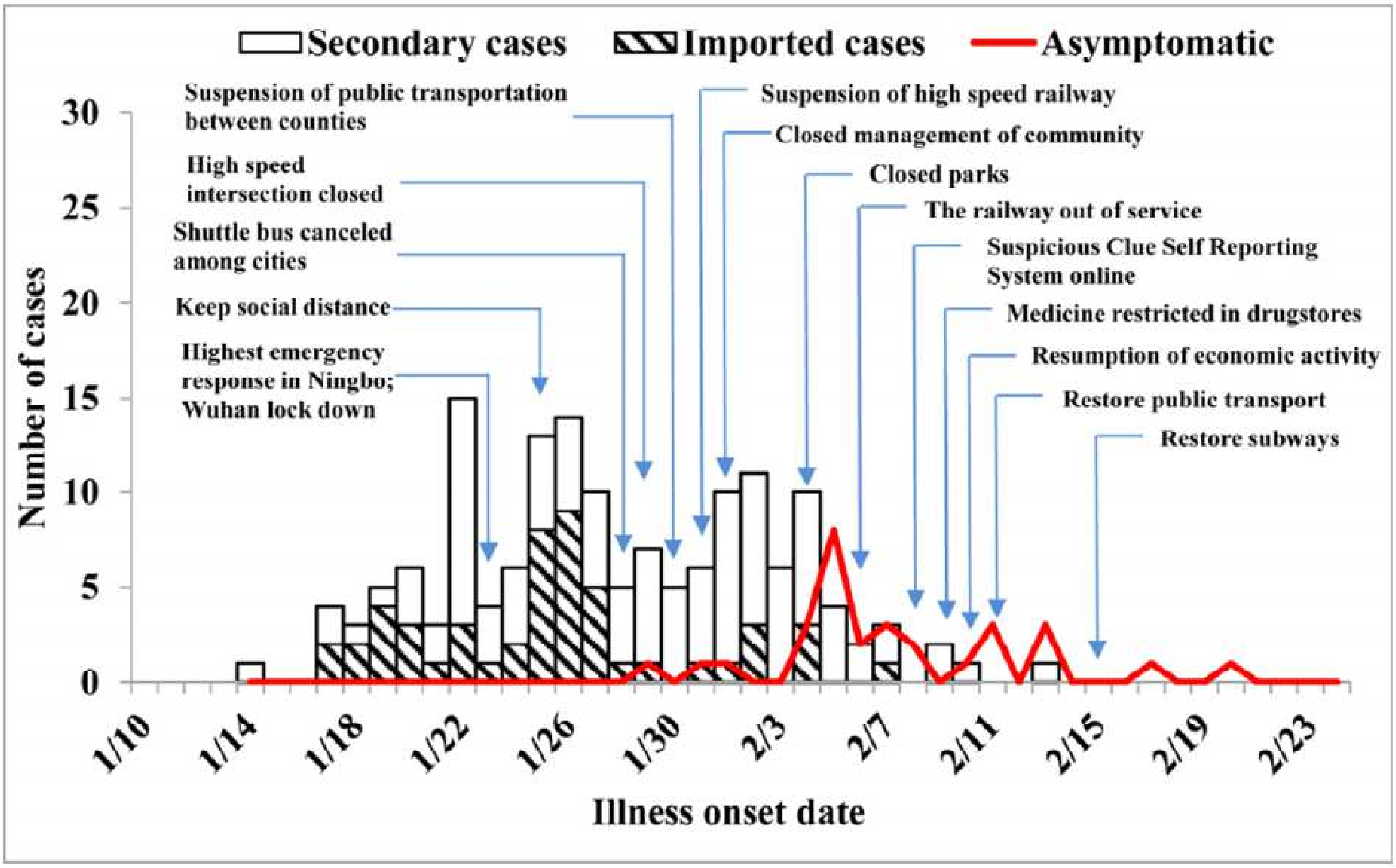


Figure 1

Epidemic curve of reported cases of COVID-19 in Ningbo City, China.

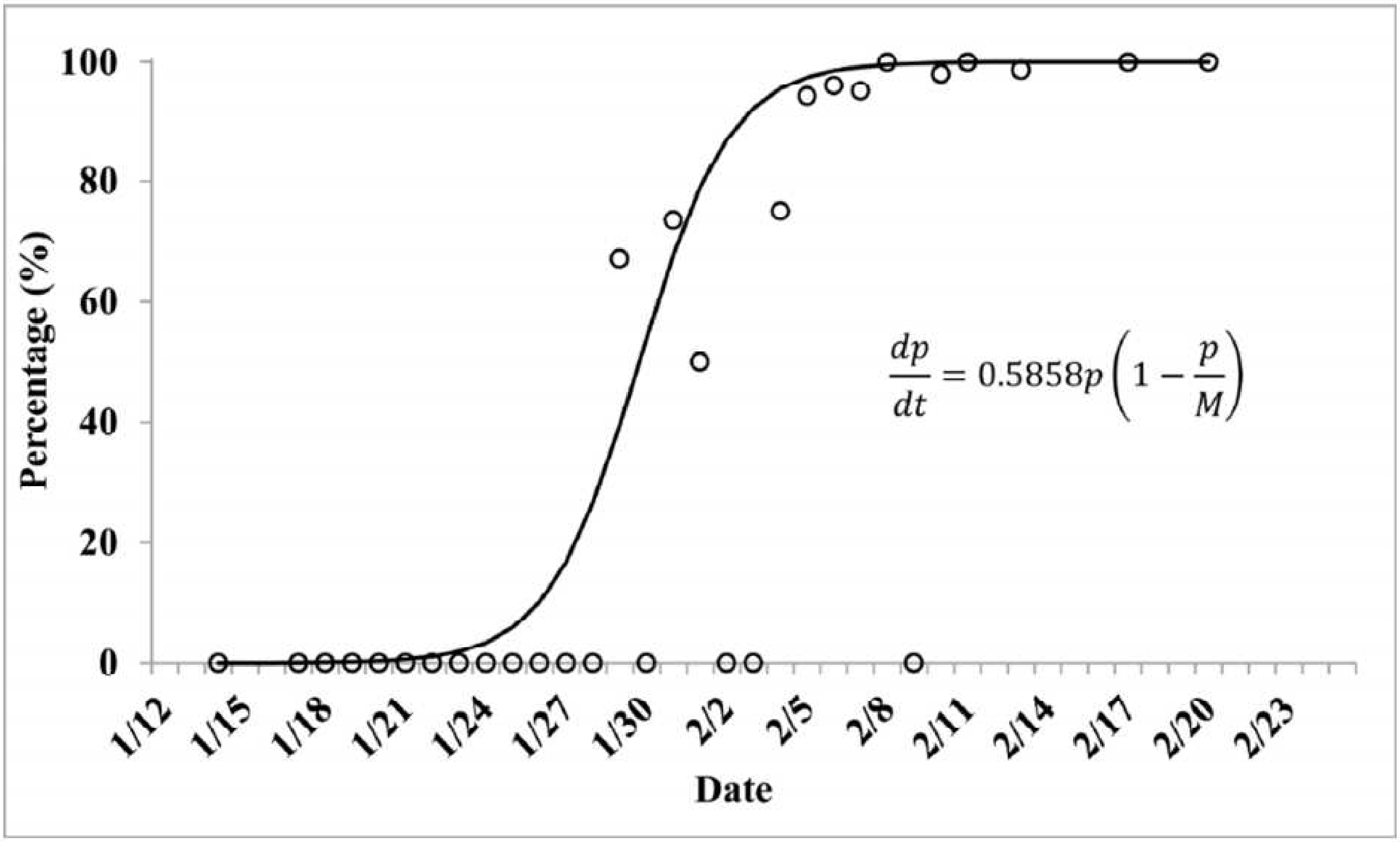


Figure 2

The temporal distribution of the proportion of asymptomatic infection of COVID-19 in Ningbo City, China.

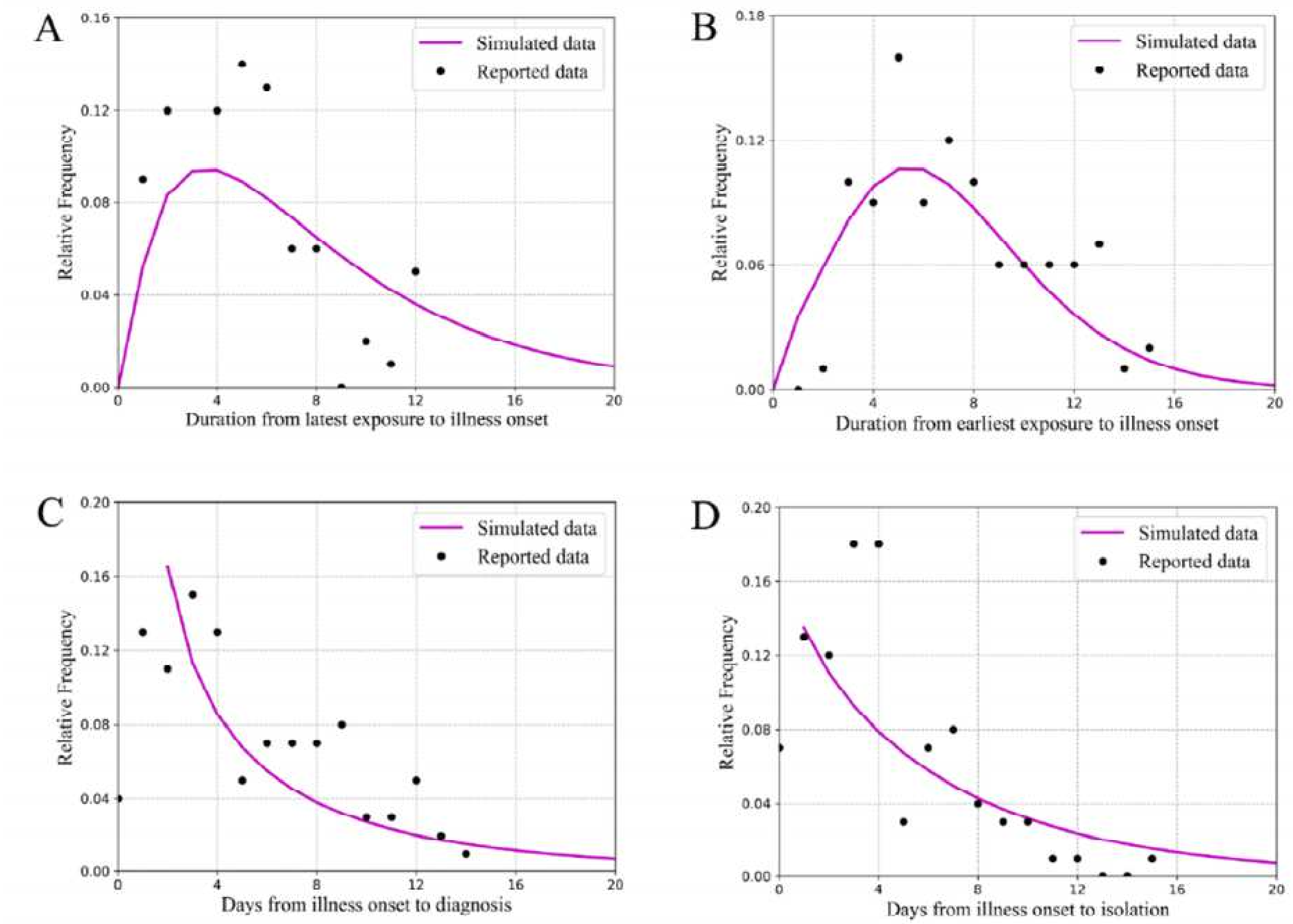


Figure 3

Key time-to-event distributions. The estimated short incubation period distribution (i.e., the time from latest exposure to illness onset) is shown in Panel A. The estimated long incubation period distribution (i.e., the time from earliest exposure to illness onset) is shown in Panel B. The estimated distribution of times from illness onset to diagnosed date is shown in Panel C. The estimated distribution of times from illness onset to isolated date is shown in Panel D.

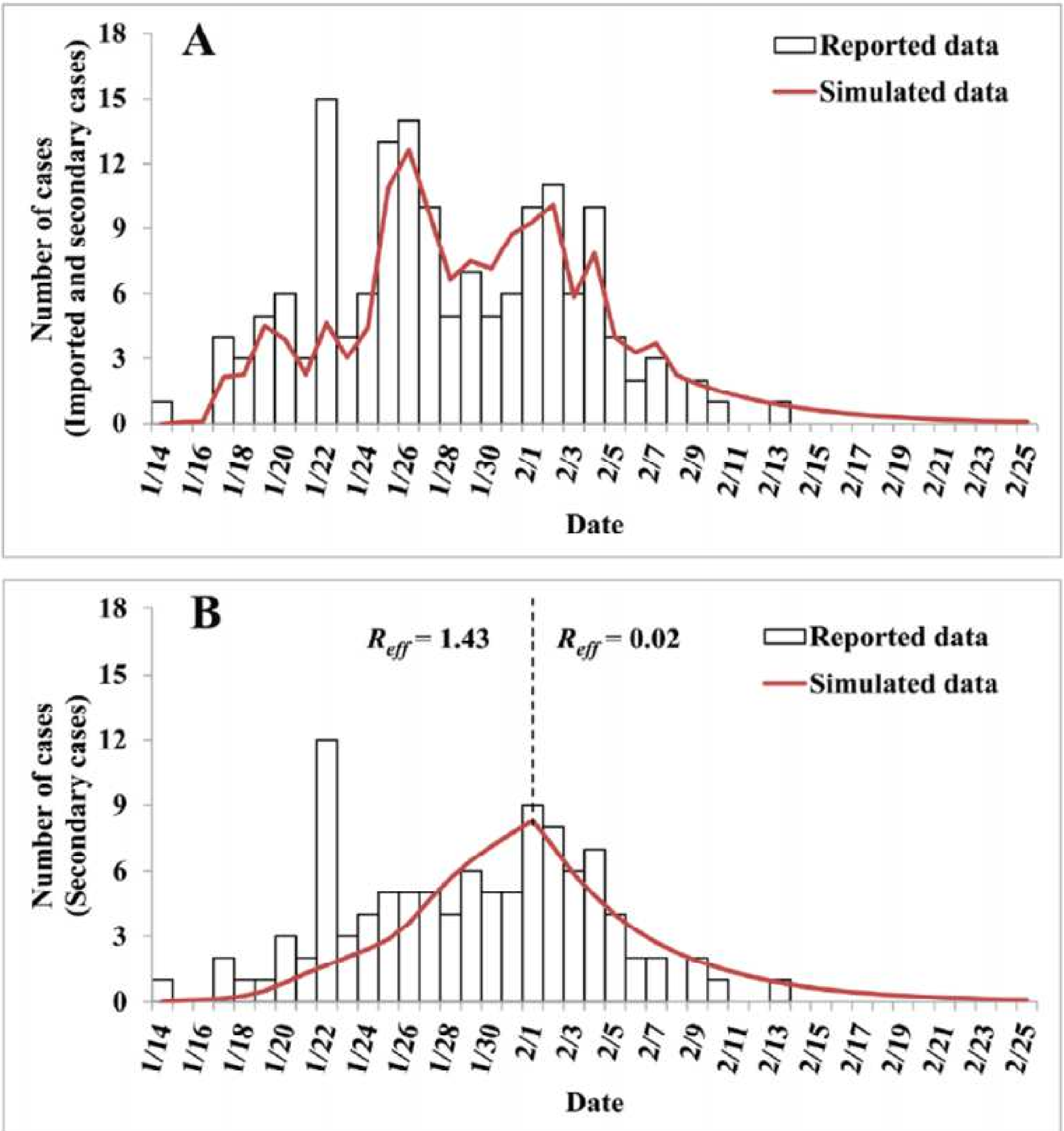


Figure 4

Results of curve fitting of the SEIAR model with the reported data. A: curve fitting with imported and secondary cases; B: curve fitting with secondary cases.

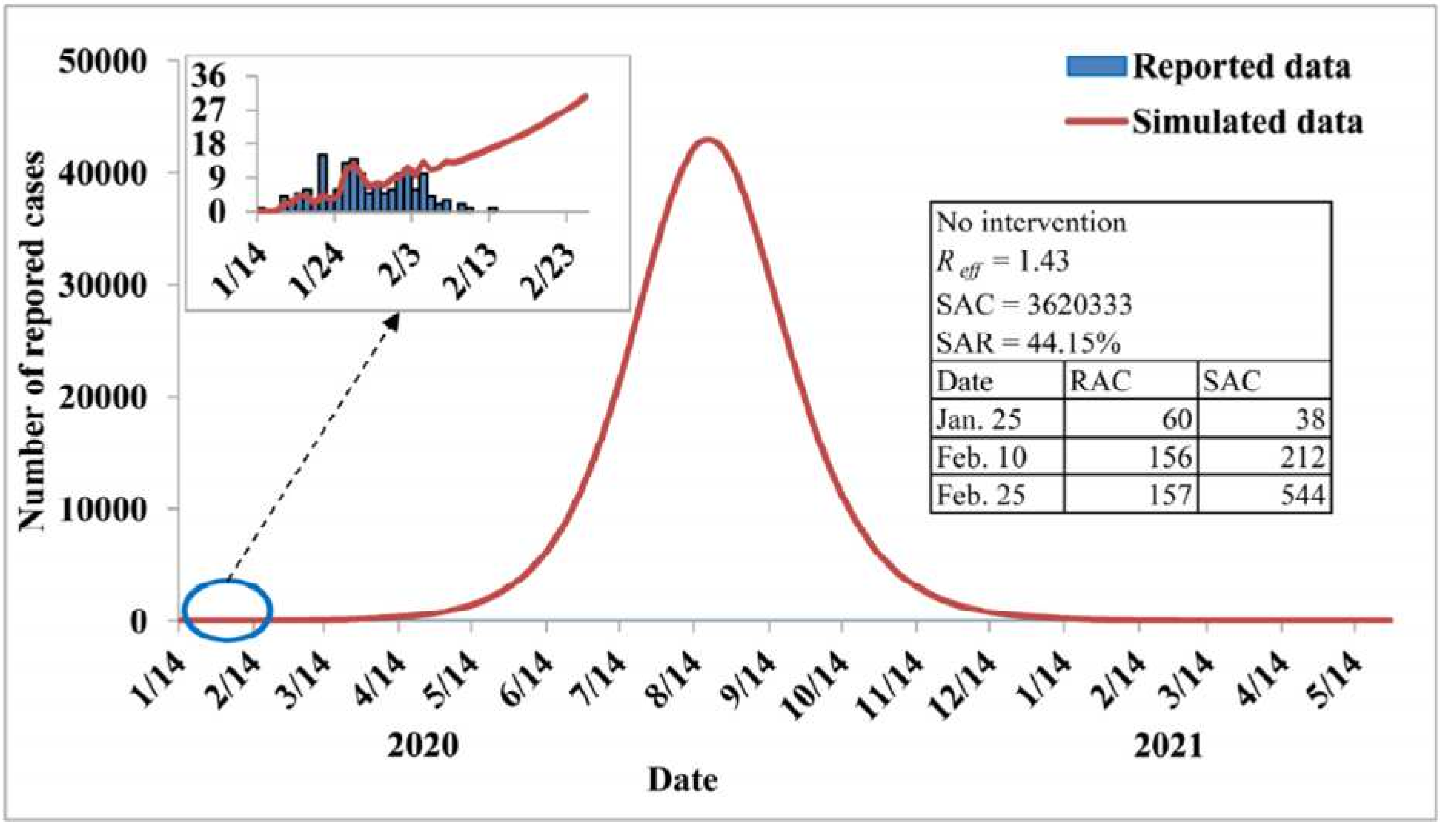


Figure 5

Effectiveness of countermeasures implemented in Ningbo City, China. Reff: effective reproduction number; SAC: simulated accumulative cases; SAR: simulated attack rate; RAC: reported accumulative cases.