

Original Research

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Investigation on the Control of COVID-19 in Wuhan: Number of Infections Outside Hospitals and the Reproduction Number

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Abstract

COVID-19 is erupting globally, and Wuhan successfully controlled it within a month. Infections arose from infectious persons outside hospitals. After data revision, data-based and model-based analyses were implemented, and the conclusions are as follows. The incubation period of most infected people may be 6–7 days. The number of infectious persons outside hospitals in Wuhan on January 20, 2020 was about 10000 and reached more than 20000 on the day of Lockdown; it exceeded 72000 on February 4. Both data-based and model-based analyses gave out the evolution of the reproduction number, which was over 2.5 in early January, went down to 1.62 in late January and 1.20 in early February, with a sudden drop to less than 0.5 due to the strict Stay-at-home management after February 11. Strategies of Stay-at-home, Safe-protective measures, and Ark hospitals were the main contributions to control COVID-19 in Wuhan. In Wuhan, 2 inflection points of COVID-19, exactly correspond to February 5 and February 15, the 2 days when Ark hospitals were introduced, and the complete implementation of Stay-at-home. Based on the expression of the reproduction number, group immunity is also discussed. It shows that only when the group immunization rate is over 75% can COVID-19 be under control; group immunity would be full infection and the total deaths will be 220000 for a city as big as Wuhan. Sensitivity analysis suggests that 30% of people staying at home in combination with better behavior changes, such as social-distancing and frequent handwashing, can effectively contain COVID-19. However, only when this proportion is over 60% can the controlled effect and efficiency like Wuhan be obtained.

COVID-19, an epidemic of human infections with the virus SARS-CoV-2, has erupted in many countries and regions. On December 31, 2019, China reported several cases of unexplained pneumonia in Wuhan, Hubei Province. As at January 3, 2020, a total of 44 patients with pneumonia of unknown etiology have been reported to WHO by China.¹ A novel coronavirus (nCoV, 2019-nCoV) was isolated by Chinese scientists on January 7, 2020. By March 7, 2020, globally confirmed cases of COVID-19 had surpassed 100000. On the evening of March 11, local time, WHO announced in Geneva that COVID-19 had become a global pandemic. By March 20, 2020, more than 210000 cases had been reported to WHO and more than 9000 people had lost their lives.² There were 332935 confirmed cases, 14510 confirmed deaths, and 190 countries, areas, or territories with cases by March 23 2020, 09:03 GMT-7.³ By April 29, there were 3018681 confirmed cases globally, and 207973 deaths,⁴ with a wild increase in the number of infected people. A year later, as at February 9, 2021, there had been 106008943 confirmed cases of COVID-19 worldwide, including 2316389 deaths. As COVID-19 cases continued to increase, life changed dramatically. More and more countries asked their people to stay at home, to work from home, and to have lessons online. Social disruption caused by COVID-19 was unimaginable. However, Wuhan, once known as the city of severe outbreaks, continues to report no new cases since March 18, 2020. For this reason, it is of great significance to investigate the control process and experience in Wuhan.

There are some instructions: the confirmed case is a person with laboratory confirmation (PCR-testing) of COVID-19; the probable case is a suspected case for whom testing could not be performed or testing for the SARS-CoV-2 virus is inconclusive; the clinically diagnosed case is a suspected case whose lung CT has pneumonia imaging features of COVID-19 but the nucleic acid test is negative or nucleic acid testing has not been performed; the asymptomatic person refers to a person who has no clinical symptoms but has a positive pathogenic test for the new coronavirus in respiratory specimens. It is of note that the so-called asymptomatic infections may include some latency who will have symptoms in the next few days. In this paper, the asymptomatic persons are those who will never have symptoms or who do not need to see doctors for their very mild symptoms.

We obtained data and information related to COVID-19 mainly from official websites of Wuhan Municipal Health Commission,⁵ and National Health Commission of the People's

Republic of China.⁶ During the control process in Wuhan, there were some important days as follows:

(T_1) On January 20, 2020, National Health Commission of the People's Republic of China organized a high-level expert group to hold a press conference. Academician Zhong Nanshan confirmed that the 2019-nCoV was spreading from person to person.⁷

(T_2) On January 23, Wuhan closed the out-of-city corridor, and public transportation in the city also stopped.⁸

(T_3) The Vulcan Mountain Hospital and the Thunder God Mountain Hospital, which were built at miracle speed, had been in operation since February 4 and February 8, for the treatment of critically ill patients of COVID-19.⁹

(T_4) The first Ark hospital started operation on the evening of February 5. There were once 16 Ark hospitals operating in Wuhan. As of March 9, these Ark hospitals had treated more than 12000 patients with mild coronary pneumonia.

(T_5) On February 6, the comprehensive finding of every probable case at community level in Wuhan began.¹¹

(T_6) The closed community management started on February 11. Only 1 person per household was allowed to go out to buy food and necessities every 3 days.¹²

(T_7) The completely closed community management started on February 15 after clearing inventory. Daily necessities were delivered by dedicated persons.¹³

(T_8) From February 12, Hubei authorities included clinically diagnosed cases into the confirmed cases.¹⁴

(T_9) On March 18, the number of new confirmed cases in Wuhan was 0 for the first time, and the number of new suspected cases continued to be 0 from March 16.

At the introduction of Ark hospitals, from February 5, the mode of treatment was changed as follows: For suspected patients, they were first screened in their communities, and then either isolated in communities or transferred to hospitals. For mild patients, they entered Ark hospitals for isolation, observation, and treatment. For the severely ill patients, the treatment was concentrated in designated hospitals. So far, Wuhan's treatment of COVID-19 was gradually on the fast track.

The symbols and their representations used in this article are presented in Table 1.

Data-based analysis

Data processing

Confirmed cases rarely infect others; infections are mainly caused by infectious persons outside hospitals. To clarify the spread of COVID-19 in Wuhan, we tried to estimate the number of potential infections on January 20, the day (T_1) when Academician Zhong Nanshan, the leader of the high-level expert group formed by National Health Commission of the People's Republic of China, awakened the awareness of Chinese people, and China began to take measures to prevent and control COVID-19.^{15,16}

It was noticed that Wuhan Municipal Health Commission started the daily outbreak report from January 23 on its official website, and the National Health Commission of the People's Republic of China presented the outbreak notification from Wuhan Municipal Health Commission from January 11 to January 20, followed by the national reports starting on January 21. Furthermore, clinically diagnosed confirmed cases were included on January 17, 18, and 19, then cancelled, and re-added

from February 12.^{17,18} Therefore, there were missing data, which was confusing, in the first few days in Wuhan, and we decided to revise and complement these data from January 20 to 22 first. Also, since the new confirmed cases suddenly increased to 892 on January 27, it also needed to be amended. After all, these patients already existed, and we failed to confirm them in time. Based on the reported cumulative laboratory confirmed cases from January 23 to February 3, we obtained a best Gauss fitting function which is $C(t) = 132100 \exp(-((t - 42.16)/17.3)^2)$ (Goodness of fit: SSE: $3.12e + 05$, R-square: 0.9924, Adjusted R-square: 0.9907, RMSE: 186.2). We used it for the short-term backtracking of the cumulative laboratory confirmed cases from January 20 to January 22 and got 195, 262, and 348, respectively. The revised cumulative confirmed cases from January 15 to February 3 are presented in Table 2.

As clinically diagnosed cases were incorporated into the confirmed cases and the demand for clearing inventory, we see a spike in the new confirmed data on February 12.¹⁹ We explored the trend of laboratory confirmed cases from January 23 to February 14, excluded the clinically diagnosed cases from January 12 to 14 with the purpose of maintaining the statistical consistency, and found there is a good continuity (See Figure 1). There were 20630, 21960, and 22961 laboratory confirmed cases from January 12 to 14. Since clinically diagnosed cases were added, an additional fitting from February 12 was obtained, which is provided in Appendix A2. We observed that the data of laboratory confirmed cases with clinically diagnosed cases from February 3 to February 11 were 7898, 9904, 12244, 14900, 17822, 20935, 24141, 27326, and 30375 respectively. Figure 14 in Appendix A2 illustrates the fitting effect. So far, data was revised and we figured out the evolution of cumulative confirmed cases from January 20 to February 26 in Wuhan in Figure 1.

Let $\Gamma(t)$ be the revised evolution curve of cumulative confirmed cases for t starting on January 20. We can see from Figure 1 that $\Gamma(t)$ changes its trend (from an accelerated rise to a decelerated rise) and appears as an inflection point on February 7. Another feature is that curve $\Gamma(t)$ starts to flatten after February 22, which means the increment is very small. In general, the epidemic inflection points are the days when new infections begin to decline and the days when there are few new cases; both cannot be accidental and should be sustainable. For a smooth $\Gamma(t)$, they correspond to $\Gamma''(t) = 0$ and $\Gamma'(t) \ll \varepsilon$, ε is small and positive. Therefore, Figure 1 shows that while the first epidemic inflection point appeared on February 7 and the second would be on February 23, it also indicates that infections declined from February 7 and new infections rarely occurred in an incubation period before February 23. That is, COVID-19 in Wuhan was almost under control by the end of February.

It can also be detected from Figure 2 that the number of new laboratory-confirmed cases declined after February 7. Figure 2 directly presents the evolution of reported new laboratory confirmed cases before February 12. Figure 3 also verifies that China had contained COVID-19 in Wuhan by the middle of February. We can see from Figure 3 that medical capacity was sufficient after February 16 and the vacancy rate of beds in hospitals remained over 20% after February 23.

It shows February 7 as an inflection point of cumulative confirmed curve $\Gamma(t)$, and the increase in the number of confirmed patients would tend to alleviation after February 20. There are few new confirmed patients after February 23.

It only presents the number of new laboratory-confirmed cases from January 23 to February 11 because the confirmation criteria

Table 1. Symbol description

$C(t)$	Number of cumulative confirmed cases in day t
N_t	Number of infectious persons outside hospitals
C_t	Number of new confirmed cases per day
α	Growth rate of N_t
a	Hospital admission rate in early January
m	Disease incubation period
A	Recruitment of births per day
q	Awareness-protective rate of people
θ	Removed rate due to Stay-at-Home
β	Coefficient of disease incidence
μ	Transmission rate of latency
c	Daily release rate of close contacts
b	Confirmation rate of close contacts
ε	Conversion rate of latency
p	Proportion of the asymptomatic
δ	Admission rate of visiting patients
γ_1	Self-healing rate of the asymptomatic
γ_2	Self-healing rate of mildly infected person
γ_3	Curative rate of patients in designated hospitals
r	Ratio of close contacts to confirmed cases
ρ	Death rate of patients in designated hospitals
d	Natural death rate

Table 2. The revised cumulative laboratory confirmed cases from January 15 to February 3

Date	Revised Number	Reported Number	Date	Revised Number	Reported Number
15	41	41	25	786	618
16	57	45	26	1018	698
17	78	62*	27	1310	1590
18	107	121*	28	1673	1905
19	145	198*	29	2123	2261
20	195		30	2677	2639
21	262		31	3352	3215
22	348		1	4170	4109
23	459	495	2	5152	5142
24	603	572	3	6324	6384

*Clinically diagnosed cases are added in these data. Although the number of reported cases is more than the revised one on January 19 by 53, and more than the revised one on January 23 by 36, we think we can refer to these data because the revised data are laboratory confirmed cases and the reported number of 495 on January 23 includes some clinical diagnosis cases added before. After smoothing the reported new 892 cases on January 27, the corresponding new confirmed cases from January 23 to January 31 were 155, 198, 240, 272, 296, 319, 356, 378, and 576 respectively. See Figure 13 in Appendix A1 for the revision effect.

changed after February 12. An abnormal data on January 27 is excluded. It can be captured that there is a decline after February 7.

Wuhan government increased the number of designated hospitals on February 2, 3, 8, 9, 9, 10, 12, 15, 16, and 20 respectively. Data comes from Wuhan Municipal Health Commission.²⁰ There is no running of medical resources after February 16.

Discuss the proportion of the asymptomatic

There is an argument about asymptomatic infections. The infectivity of the asymptomatic is certain,²¹ but the proportion is not clear.

On February 17, China CDC published a paper in the Chinese Journal of Epidemiology, and mentioned that there were 889 cases of asymptomatic infections in the total 72314 domestic reported cases as of February 11, accounting for about 1.2%.²² The preprint platform medRxiv which released a study by research teams at Kyoto University in Japan, Georgia State University in the United States, and Oxford University in the United Kingdom, claimed that the asymptomatic rate was 17.9%.²³ An article published in Nature on March 20, 2020 warned that the asymptomatic or mild symptoms may account for 30-60% and the ability to spread the virus is not weak.²⁴

Although the proportion of asymptomatic infections is not clear, there are mainly 2 ways to confirm the asymptomatic. A way is the detection of close contacts and another is the port input detection. The ratio of close contacts to confirmed cases was approximately 3.29:1 in Hubei province as of February 16,²⁵ and this ratio was slightly higher in Wuhan. It was 6.65 in late January, 4.75 in February, and 3.62 after February 15 by data analysis directly. A follow-up survey by the China-WHO Joint Expert Group found that approximately 1 to 5% of close contacts were diagnosed with COVID-19, and many of them are asymptomatic.²⁶ Assuming that the confirmed cases found by detecting close contacts are all asymptomatic, the proportion would not exceed 33%. As for cases found by the entry detection, academician Zhong Nanshan said that 50% of imported cases did not have fever, and only the mild symptoms such as cough and cold, were detected by nucleic acid testing after entering the country.²⁷

There is also an important fact from children’s COVID-19 cases. Most investigations confirmed that children’s cases are mainly asymptomatic or mild, and their symptoms are generally milder than adults. Children’s Medical Center in Shanghai studied more than 700 infected children in China, and found that 56% of children had mild or asymptomatic conditions.²⁸ A research by Lu *et al.* suggested that 15.8% of infected children had no symptoms, 19.3% only had upper respiratory symptoms, and 7% had only CT features without any symptoms.²⁹ Raccardo *et al.* also clarified that most children with COVID-19 presented with mild symptoms³⁰; Xu *et al.* stated that symptoms in children cases were nonspecific and no children required respiratory support or intensive care.³¹

Based on these analyses, we deem the most possible value of p is $p \leq 0.55$ for all infections.

Determination of the disease incubation period m

Due to the reason that COVID-19 in Wuhan was in the waning stage in March, without loss of generality, it is supposed that $(1 - p)N_t \leq \sum_{i=t+1} C_i$ within 14 days before March 18. We begin investigations from January 23. It is obvious that $N_{56} = 0$ and $N_{55} = 0$ because there were no new confirmed cases after March 18.

By the above presented timelines, we know the inventory was cleared and medical demands were basically met after February 15. It also can be seen from Figure 3 that available beds in hospitals continued to increase after February 16 and the vacancy rate remained above 20% after February 23. In other words, Wuhan achieved the timely confirmation and complete admission for visiting patients after February 15. Since there were no new cases after March 18, we believe there were few asymptomatic infections at that time. Also, since almost N_{t-1}/m persons will feel sick on day t in terms of probability, then $C_t \leq N_{t-1}/m$ in March. Thus,

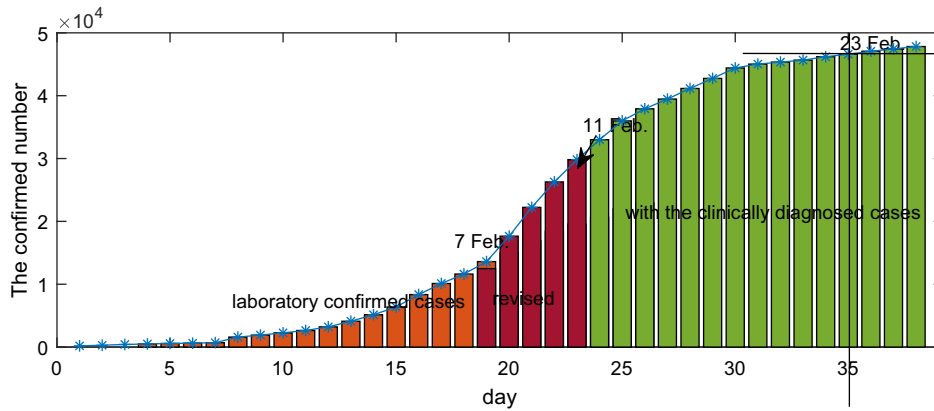


Figure 1. The evolution of cumulative confirmed cases.

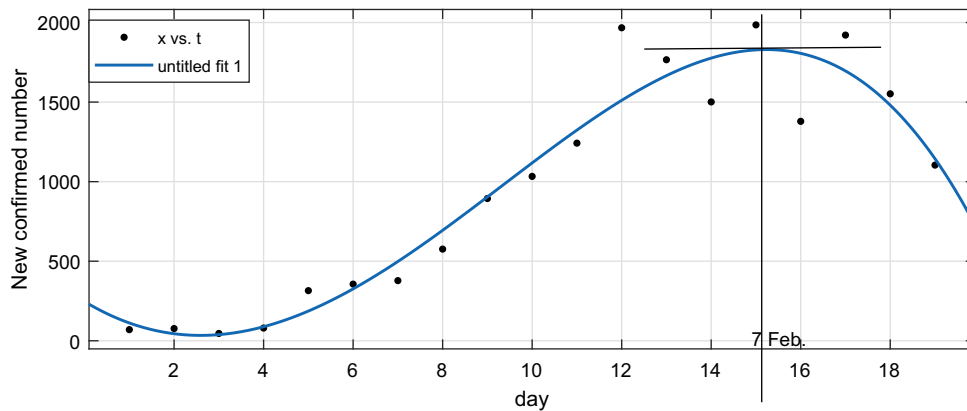


Figure 2. The evolution of new laboratory confirmed cases.

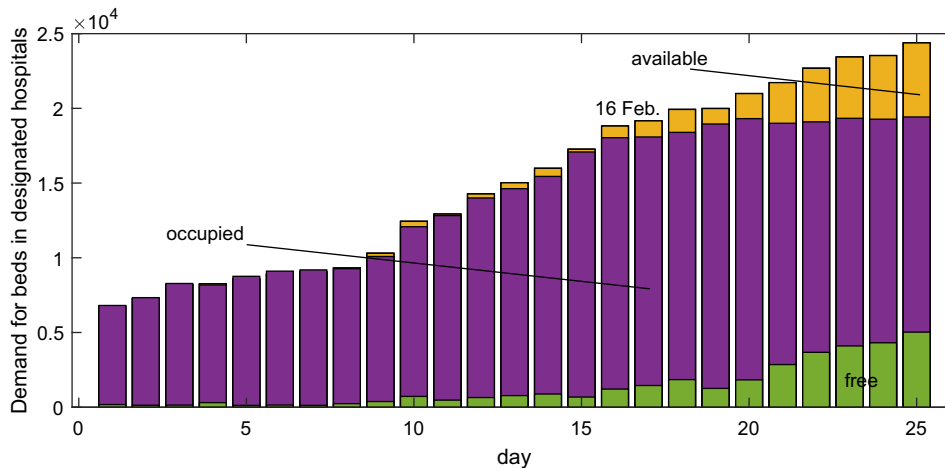


Figure 3. Capacity and occupation of beds in designated hospitals in Wuhan.

there is $(1-p)mC_{t+1} \leq \sum_{i=t+1} C_i$ within 14 days before March 18. The relationship between the number of infectious persons outside hospitals N_t and the number of new confirmed cases per day C_t is provided in Table 3.

By the direct calculation, we can get $(1-p)m \leq 2.9441$, where 2.9441 is the median value. Thus, $m \leq 2.9441 / (1-p) \leq 6.667$.

That is, the incubation period of most infected persons is not more than 7 days. Therefore, we use $m=7$ for reference.

Estimation of N_0 and R_0

N_0 expresses the number of infectious persons outside hospitals on January 22, before the day of Lockdown. R_0 is the basic reproduction number of a disease, which reflects the initial infectivity of the disease.

On January 31, the third batch of 14 designated hospitals began to treat patients with COVID-19, providing nearly 10000 available beds. The first 2 batches provided a total of about 4000 beds.³²

Table 3. The relationship between C_t and N_t in March

Date	C_t	$\sum_{i=t+1} C_i$	N_t
18	0	0	0
17	1	0	0
16	1	1	M
15	4	2	M
14	4	6	4m
13	4	10	4m
12	5	14	4m
11	8	19	5m
10	13	27	8m
9	17	40	13m
8	36	57	17m
7	41	93	36m
6	74	134	41m
5	126	208	74m
4	131	334	126m
3	114	464	131m

Then, more dedicated hospitals, including the Vulcan Mountain Hospital, Thunder God Mountain Hospital (after February 4, (T_3)), and some Ark hospitals (The first 1 started operation on the evening of February 5, (T_4)) began to treat patients with COVID-19 in succession. We believe medical capacities in the first part of February increased gradually and met demands after February 15 (which also can be detected from Figure 3). Therefore, considering the inventory and the asymptomatic, the daily new confirmed cases C_t would satisfy:

$$C_t \geq \begin{cases} \frac{a}{m}(1-p)N_{t-1}, & t : \text{Jan.23 to Jan.30,} \\ \frac{a+0.025(t-8)}{m}(1-p)N_{t-1}, & t : \text{Jan.31 to Feb.5,} \\ \frac{a+0.15+0.06(t-14)}{m}(1-p)N_{t-1}, & t : \text{Feb.6 to Feb.15,} \end{cases} \quad (1)$$

where a is the average hospital admission rate in January. According to a report from Wuhan Municipal Health Commission, there is a 5% chance that fever patients were admitted to hospitals from January 22 to 27.³³ We get $a = 0.063$ by report-based numbers of visiting patients and left-observing patients, which are provided in Table 5 in Appendix A3. Therefore, it is reasonable to argue that $a = 0.063$ in late January. Thus, in January there is

$$N_{t-1} \leq \frac{mC_t}{a(1-p)} \leq 247C_t.$$

Hence, it is possible that the number of infectious persons outside the hospitals may be 17290 on January 22. That is, infected people who were not diagnosed were already very many before the day of Lockdown. Also, a series of values of N_t can be given. Now, to estimate the contagion of SARS-CoV-2 virus, let α be the daily growth rate of infectious persons outside hospitals; we define N_t as:

$$N_t = N_{t-1}(1 + \alpha) - C_t. \quad (2)$$

As the revised cases presented in Table 2 represent the definitive confirmed ones, we used these data for further investigation. Then, with Eq. (2) and these data, based on the Principle of Least Squares, using LINGO (Adobe Inc., San Jose, California, USA) for optimization, by programming and operating, beginning with 17290 on January 22, we have the optimal value of

$\alpha = 0.16025$ in late January after January 23, 0.3332 from January 16 to 22, and 0.2864 on January 23. Further estimating, there were 10448 infected persons on January 20 and 22242 on January 23. We also calculated the greatest number of infected patients outside hospitals ia over 72000 on February 4.

Studies have shown that the proportion of people who carried the virus for more than 14 days of latency was very small (there were only 13 cases in more than 1000 cases)³⁴; it is supposed that the infected persons are no longer infectious after 14 days. Considering this natural elimination rate of virus toxicity, the infection rate may be $\alpha + 1/14$. Thus, the effective reproduction number R_e in late January is approximately $R_e = m(\alpha + 1/14) = 7 \times (0.16025 + 0.07143) = 7 \times 0.2317 = 1.62$ and the basic reproduction number $R_0 = m(\alpha + 1/14) = 7 \times (0.3332 + 0.07143) = 7 \times 0.4046 = 2.83$ in the early outbreak, and $7 \times (0.2864 + 0.07143) = 2.50$ on January 23. Similarly, $R_e = 1.20$ in early February and about 0.33 in late February.

Results

Suppose $p = 0.55$. Data-based and intervention-based retrospective studies have concluded that the average incubation period of COVID-19 in Wuhan was approximately 6-7 days; the basic reproduction number R_0 is about 2.83, and the effective reproduction number R_e dropped to 1.62 in late January with human intervention. According to the numbers, there were nearly 10000 infected persons when people were informed of the risk of a new coronavirus on January 20, over 20000 infected persons when Wuhan was locked down on January 23, and the number of most infectious persons were over 72000 on February 4.

Model-based analysis

A deterministic compartmental model was designed based on interventions and disease control processes. The main control measures are the intensive contact tracing followed by quarantine and isolation, stay-at-home, closed community managements, and Ark hospitals for treating mild COVID-19 patients.

Functions of the removed rate $\theta(t)$ and the admission rate $\delta(t)$

On December 31, 2019, people heard that unexplained pneumonia occurred in Wuhan which was related to Wuhan’s South China Seafood Market and were not worried about it. On January 20, Zhong Nanshan confirmed the human-to-human transmission of the SARS-CoV-2 virus and urged the public not to go to Wuhan and to wear masks.¹⁵ These words really awakened Chinese people. On the same day, Chinese Premier Li Keqiang presided over an executive meeting of the State Council to deploy the COVID-19 epidemic prevention and control, and China began the difficult control process.¹⁶ The lives of 1.3 billion Chinese people were destroyed in the next 2 months.

On January 23, a city-wide closure notice was issued by Wuhan government. People were scared. In view of the panic, coupled with the need to buy daily necessities, seek medical treatment, and the shortage of hygienic protective articles, we assumed that the removed proportion may be increased to 30% as of January 31. Since the closed management of residential communities started on February 11 and every household was allowed 1 person to go out to buy necessities every 3 days (referring to $(T_3), (T_4), (T_6)$), we assumed that at least 60% of

the people will be removed from those susceptible to the virus, taking into account family size in China. Furthermore, because the completely closed community management started on February 15, and no was allowed to go out (see (T_7)) except the required staff, we suggested that 90% of the people could avoid being infected. The removed rate θ of those susceptible to the virus is defined as $\theta(t)$, as follows:

$$\theta(t) = \begin{cases} 0.30(t-1)/8, & t : \text{Jan.23 to Jan.31,} \\ 0.30, & t : \text{Feb.1 to Feb.10,} \\ 0.60, & t : \text{Feb.11 to Feb.15,} \\ 0.90, & t : \text{AfterFeb.15.} \end{cases} \quad (3)$$

According to the analysis above, the admission rate of visiting patients was 0.063 before February. Noticing that the average daily detection capacity increased 10 times in 6 days in Wuhan from January 22 to January 27,³⁵ the Vulcan Mountain Hospital and the Thunder God Mountain Hospital had been in operation since February 4 and February 8, and Ark hospitals started operations on February 5, it means the admission rate slowly increased before February 5 and it was growing faster after the 5th. This happened even though Wuhan had the capability of timely detection and admission of all patients after February 15. Hence, the admission rate of visiting patients δ is defined as the following, $\delta(t)$:

$$\delta(t) = \begin{cases} 0.063, & t : \text{Jan.23 to Jan.30,} \\ 0.063 + 0.025(t-8), & t : \text{Jan.31 to Feb.5,} \\ 0.063 + 0.15 + 0.06(t-14), & t : \text{Feb.6 to Feb.15,} \\ 1, & t : \text{Feb.16 to Mar.17.} \end{cases} \quad (4)$$

The model

Susceptible people may be infected in contact with latency, the asymptomatic, and the infectious patients outside hospitals. Close contacts may be quarantined, including infected and uninfected. Infected close contacts would be confirmed by PCR-testing, and uninfected ones will return to being susceptible after isolation. Infected people may show symptoms after the incubation period or may be asymptomatic. Of course, asymptomatic infections have no medical demands. Typical patients will visit doctors, some are admitted to hospitals, while others are not admitted. Hospitalized patients will not infect others (disregarding infections of medical staff). Due to information disclosure, social-distancing, and stay-at-home, some people can avoid being infected and the contact rate and infection rate will also be reduced.

We divided individuals in Wuhan into the susceptible S , the latent E , the asymptomatic I_a , the not admitted patients I_m , the hospitalized patients I_h , the awareness protective population S_p , the quarantined contacts S_q , and the recovered people R . Based on intervention, control process, and individual status, the COVID-19 transmission mechanism in Wuhan is presented in Figure 4, and the corresponding epidemic model is as follows:

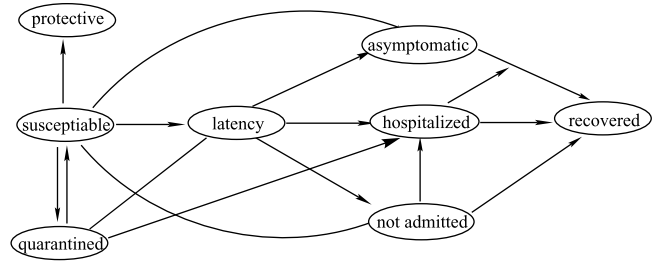


Figure 4. Spread mechanism of COVID-19 in Wuhan.

$$\begin{cases} \frac{dS}{dt} = A - \beta(1-q)S(\mu E + I_a + I_m) - \theta S - (1-b)r(\delta I_m + bcS_q) + (1-b)cS_q - dS, \\ \frac{dE}{dt} = \beta(1-q)S(\mu E + I_a + I_m) - br(\delta I_m + bcS_q) - \varepsilon E - dE, \\ \frac{dI_a}{dt} = \varepsilon p E - \gamma_1 I_a - dI_a, \\ \frac{dI_m}{dt} = \varepsilon(1-p)E - \delta I_m - \gamma_2 I_m - dI_m, \\ \frac{dI_h}{dt} = \delta I_m + bcS_q - \gamma_3 I_h - \rho I_h - dI_h, \\ \frac{dS_p}{dt} = \theta S - dS_p, \\ \frac{dS_q}{dt} = r(\delta I_m + bcS_q) - cS_q - dS_q, \\ \frac{dR}{dt} = \gamma_1 I_a + \gamma_2 I_m + \gamma_3 I_h - dR, \end{cases} \quad (5)$$

with the initial conditions $S(0) > 0, E(0) > 0, I_a(0) > 0, I_m(0) > 0, I_h(0) > 0, S_p(0) > 0, S_q(0) > 0, R(0) > 0$. It is obvious that all solutions initiating in R_+^8 exist for all $t \geq 0$ in R_+^8 . Where: $R_+^8 = \{(x, y, z, u, v, w, s, t) \in R^8 : x \geq 0, y \geq 0, z \geq 0, u \geq 0, v \geq 0, w \geq 0, s \geq 0, t \geq 0\}$.

Noticing that Wuhan had achieved the complete admission of visiting patients after February 15, then the disease incidence item $\beta(1-q)S(\mu E + I_a + I_m)$ in model (5) should be changed to $\beta(1-q)S(\mu E + I_a)$. I_m can be regarded as the mild patients in Ark hospitals, δ is the conversion rate from mild to severe, and the quarantine item $r(\delta I_m + bcS_q)$, will be replaced with $r(\varepsilon(1-p)E + bcS_q)$. See said model as (5+) presented in Appendix A4.

The effective reproduction number R_e

It is straightforward to get the disease-free equilibrium (DFE) point M_0 . System (5) can be written in a vector form as

$$\frac{dX}{dt} = F(X)$$

with $X = (S, E, I_a, I_m, I_h, S_p, S_q, R)^T$

Computing the effective reproduction number R_e using the method of van den Driessche and Watmough,³⁶ a subsystem which consisted of the infectious compartments E, I_a and I_m of system (5) is presented as:

$$\frac{dx_i}{dt} = F(x_i) - V(x_i), i = 1, 2, 3.$$

Hence,

$$\mathcal{F} = \begin{pmatrix} \beta(1-q)S(\mu E + I_a + I_m) \\ 0 \\ 0 \end{pmatrix}, \mathcal{V} = \begin{pmatrix} \varepsilon E + dE \\ \gamma_1 I_a + dI_a - \varepsilon p E \\ \delta I_m + \gamma_2 I_m + dI_m - \varepsilon(1-p)E \end{pmatrix}.$$

The associated next-generation matrices are

$$F = \left(\frac{\partial \mathcal{F}}{\partial x_i} (M_0) \right) = \begin{pmatrix} \mu\beta(1-q)S_0 & \beta(1-q)S_0 & \beta(1-q)S_0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix},$$

$$V = \left(\frac{\partial \mathcal{V}}{\partial x_i} (M_0) \right) = \begin{pmatrix} \varepsilon + d & 0 & 0 \\ -\varepsilon p & \gamma_1 + d & 0 \\ -\varepsilon(1-p) & 0 & \delta + \gamma_2 + d \end{pmatrix}.$$

Giving out

$$FV^{-1} = \frac{1}{(\varepsilon+d)(\gamma_1+d)(\delta+\gamma_2+d)} \begin{pmatrix} (\gamma_1+d)(\delta+\gamma_2+d) & 0 & 0 \\ \varepsilon p(\delta+\gamma_2+d) & \varepsilon+d & 0 \\ \varepsilon(1-p)(\gamma_1+d) & 0 & (\varepsilon+d)(\gamma_1+d) \end{pmatrix}.$$

The effective reproduction number R_e is determined as the spectral radius $\rho(FV^{-1})$, thus we obtain:

$$R_e = \rho(FV^{-1}) = \beta(1-q)S_0 \left(\frac{\mu}{\varepsilon+d} + \frac{\varepsilon p}{(\varepsilon+d)(\gamma_1+d)} + \frac{\varepsilon(1-p)}{(\varepsilon+d)(\delta+\gamma_2+d)} \right).$$

Let the transmission rate of latency be $\mu = 2/m$ because the infected persons have been contagious 2 days before onset,³⁷ and the conversion rate $\varepsilon = 1/m$ as m is the incubation period. Therefore,

$$R_e = \frac{m\beta(1-q)S_0}{1+dm} \left(\frac{2}{m} + \frac{p}{m(\gamma_1+d)} + \frac{1-p}{m(\delta+\gamma_2+d)} \right). \quad (6)$$

It shows that the awareness-protective rate q will affect R_e greatly, and the admission rate δ of mild patients will also contribute to decrease R_e . Based on the estimated parameters in the next subsection, surface $R_e(q, \delta)$, and curve $R_e(q, \delta) = 1$ are depicted in Figure 5. We can see that the maximum value of R_e may exceed 4, it is possible to make $R_e < 1$ if the awareness-protective rate q is over 60% for high medical admission rate δ . It should be 75% for low medical admission rate.

R_e will exceed 4 for the low q and δ . It will decrease with the increasing q and δ . $R_e < 1$ only when $q > 0.6$. It should be $q > 0.75$ for the low δ .

With respect to the dynamics of infectious diseases, at the beginning of the outbreak, Eq. (6) expresses the basic reproduction number R_0 , reflects the ability of an infectious disease to invade a population, and is 'the expected number of secondary cases produced, in a completely susceptible population, by a typical infective individual.'³⁸ S_0 is generally taken as the total population. On day t , we can hold Eq. (6) and replace S_0 with $(1-\theta)S_0$ to claim the control reproduction number R_e by Eq. (6) because some susceptible people can avoid being infected due to protective measures and staying at home. In this paper, q is defined as the awareness-protective rate of the susceptible population, then it also is the removed rate of the susceptible population in Eq. (6) when we use Eq. (6) for referring to the control reproduction number R_e . Therefore, the representation in Figure 5 tells us that it is necessary to Stay-at-Home in the case of limited medical resources, and protective measures such as social distancing, wearing masks, and washing hands are also necessary. Using q in Eq. (6) can also be interpreted as the group immunity rate because the reduction in susceptible population is mainly due to the immunization of the recovered persons if there is no implementation of Stay-at-Home. Therefore, we conclude that COVID-19 would be controlled only

when the group immunity rate is over 75% of total population if most mild patients are allowed to heal themselves at home.

The awareness-protective rate q can be referred to the decline of infection rate from early January to late January mentioned above; we took $q = 0.3$ for reference. It could also be detected from Figure 8 for the sound fitting of data in January. For the following estimated β , $\gamma_{1,2}$, and Eq. (3,4,6), R_e is figured out roughly in Figure 6. The depiction is consistent with the above-mentioned estimation of R_e by the method of Least Squares. We can see that the strict Stay-at-home orders starting on February 11 quickly made $R_e < 1$ so that COVID-19 in Wuhan could finally be contained within 1 month. Figure 6 (b) clearly shows that the increasing removal rate of the susceptible is extremely effective in reducing infections. Hence, it is very important to stay at home.

Figure 7 presents the evolution of COVID-19 without active interventions (corresponding to $\theta = 0, q = 0, \delta = 0.063$). From Figure 7(a), we can further observe that the number of infections will reach 75% after 37 days, and the latency at its peak will take up 60% of the total population. Visiting patients will get to the maximum after 2 months with 15.8% day visit and the maximum number of daily hospitalized patients will be 8%, as no country or region has the capability to support such huge medical demands. Peak of death will come 100 days after the outbreak, with daily deaths of 2500 which would fall below 100 after 7 months.

The low admission rate corresponds to $\delta = 0.063$. Graphics show the severeness of the corresponding infection if COVID-19 is treated as a cold or flu and there is no appropriate response ($\theta = 0, q = 0$). (a) $2.8 \times 10^6 / 11.081 \times 10^6 = 0.25, 6.65 / 11.081 = 0.6, 1.75 / 11.081 = 0.158, 8.53 \times 10^5 / 11.081 \times 10^6 = 0.08$. (b) Proportion of infections will be over $10/11 = 0.909$. Top 3 curves include the recovered population. So, it also verifies the high self-healing rate and cure rate of COVID-19.

Figure 7 also hints that group immunity would be all people's infections. In theory, $R_e < 1$ means that if an infected individual can produce less than 1 new infected individual in his infectious period, then the infection cannot grow. As for group immunity, it seems there will not have new infections after 75% of people have been infected conceptually. Simulations tell us that the proportion needs to be 3 out of 4 and infection continues. The total deaths will be 220000 by curve fitting and integral calculation. It is the result of group immunity for a city with a total population of 11081000, such as Wuhan. In fact, there were no COVID-19 patients and the cumulative deaths were 3869 as of May 1 with the comprehensive and strong interventions in Wuhan. Figure 7 (b) also shows that COVID-19 patients have higher self-healing rate and cure rate, and the increasing admission rate can significantly reduce infections.

Of course, $R_e = \frac{m\beta(1-q)S_0}{1+dm} \left(\frac{2}{m} + \frac{p}{m(\gamma_1+d)} \right)$ if all infected people with symptoms are admitted, corresponding to model (5+). It means the reproduction number R_e will significantly be reduced. Also, R_e will be further reduced if the mild infected person can wear a mask consciously or even self-isolate to avoid spreading the virus to others. Therefore, for the existence of an uncertain large proportion of the asymptomatic, and the easy spread of the new coronavirus SARS-CoV-2, it is very important to call on all people to take measures to avoid being infected or spreading COVID-19.

Parameter determination and estimation

Since SARS-CoV-2 virus is susceptible to all people (the youngest patient in Wuhan was just 17 days old), daily births need to be considered. At the end of 2018, the population of Wuhan was

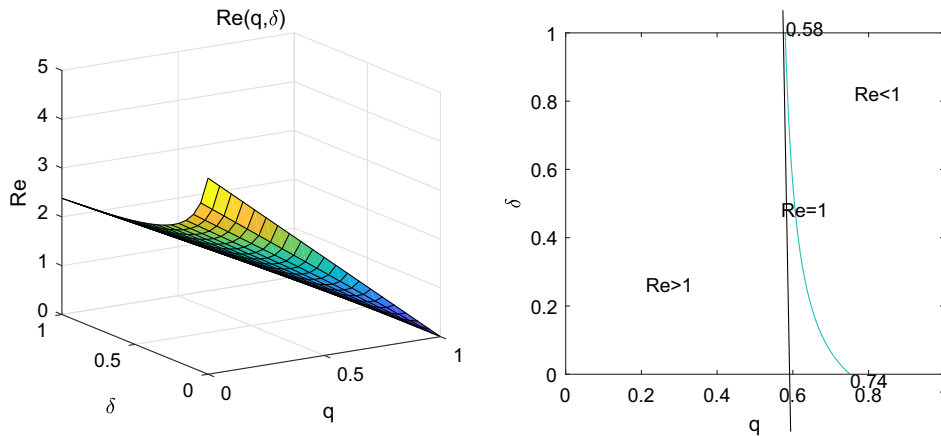


Figure 5. The control reproduction rate R_e .

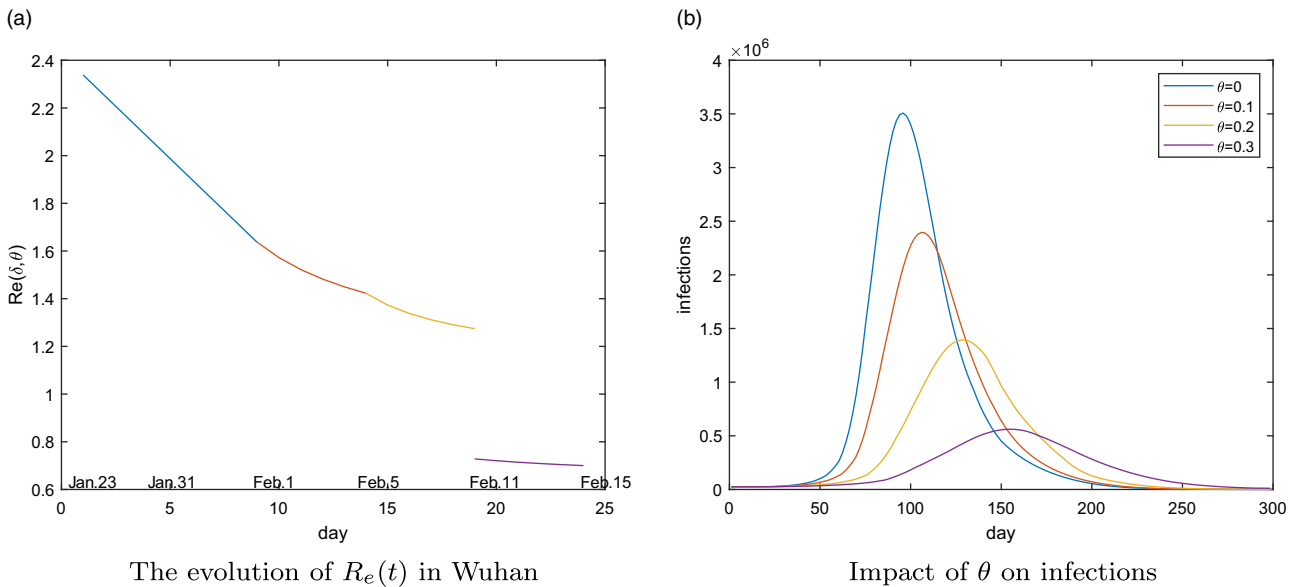


Figure 6. Evolution of the reproduction number R_e and the necessary of θ . (a) Curve $R_e(t)$ continues falling with the recruitment of designated hospitals and temporary hospitals. The sudden drop comes from the strict implementation of the Stay-at-home order which was issued on February 11 in Wuhan. (b) Here, evolutions of $E(t)+I_a(t)+I_m(t)+I_h(t)$ are depicted to illustrate infections. Depictions show that infections will obviously decrease with the removed rate.

11.081 million and the number of births was 119400.³⁹ We refer to $S(0) = 11.081$ million and $A = 375$. The average life expectancy is 81 years old in Wuhan, so $d = 1/81 * 365 \approx 0.0000338$.

For the 14 days quarantine, the daily release rate of close contacts is $c = 1/14$. A study showed that the infection ratio of close contacts to confirmed cases is 6.3%.⁴⁰ Liang Wannian, the leader of the expert group for the treatment of COVID-19 in China, introduced that approximately 1 to 5 percent of close contacts are confirmed with SARS-CoV-2 virus infections.²⁸ Then, we take the confirmation rate of close contacts as $b = 0.05$.

For the above estimated incubation period $m = 7$, the incidence of latency will be $\varepsilon = 1/7$. The transmission rate of latency is $\mu = 2/m = 2/7$. Because the average length of hospital stay for discharged patients is 20 days in Wuhan and 9 days in other provinces outside Hubei,⁴¹ we suppose the curative rate of mild patients is $\gamma_2 = 1/9$ and the curative rate of patients in designated hospitals is

$\gamma_3 = 1/20$. As mentioned above, there are few people who carried the virus for more than 14 days,³⁴ considering the incubation period, hence we can assume that the self-healing rate of the asymptomatic is $\gamma_1 = 1/7$.

The median time from onset of symptoms to death was 18.5 days and the average time for patients from onset to seeing doctors was 5 days,^{42,43} so the mean hospitalized days of the deaths would be 14. Case fatality in Wuhan was about 4.05%,⁴⁴ and the death rate of patients in designated hospitals is $\rho = 0.0405/14 = 0.00289$. Let the ratio of close contacts to confirmed cases be 4.54 as introduced above.

Beginning with January 23, we take $I_h(0) = 440$ because the cumulative confirmed cases in Wuhan as of January 23 was 495 (excluding the 31 discharged and the 24 deaths). $R(0) = 31$. Let $S_q(0) = 2776 * 495/549 = 2503$ because there were 2776 close contacts under observation on January 23 and

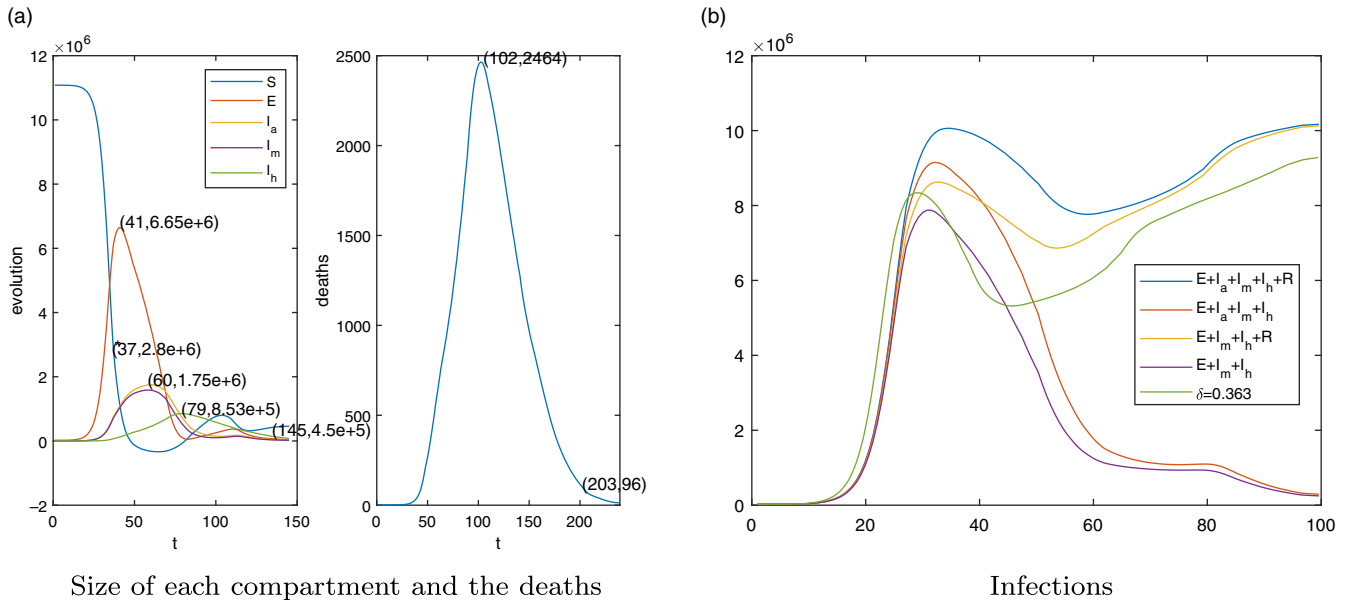


Figure 7. Evolution of the epidemic on the low admission rate.

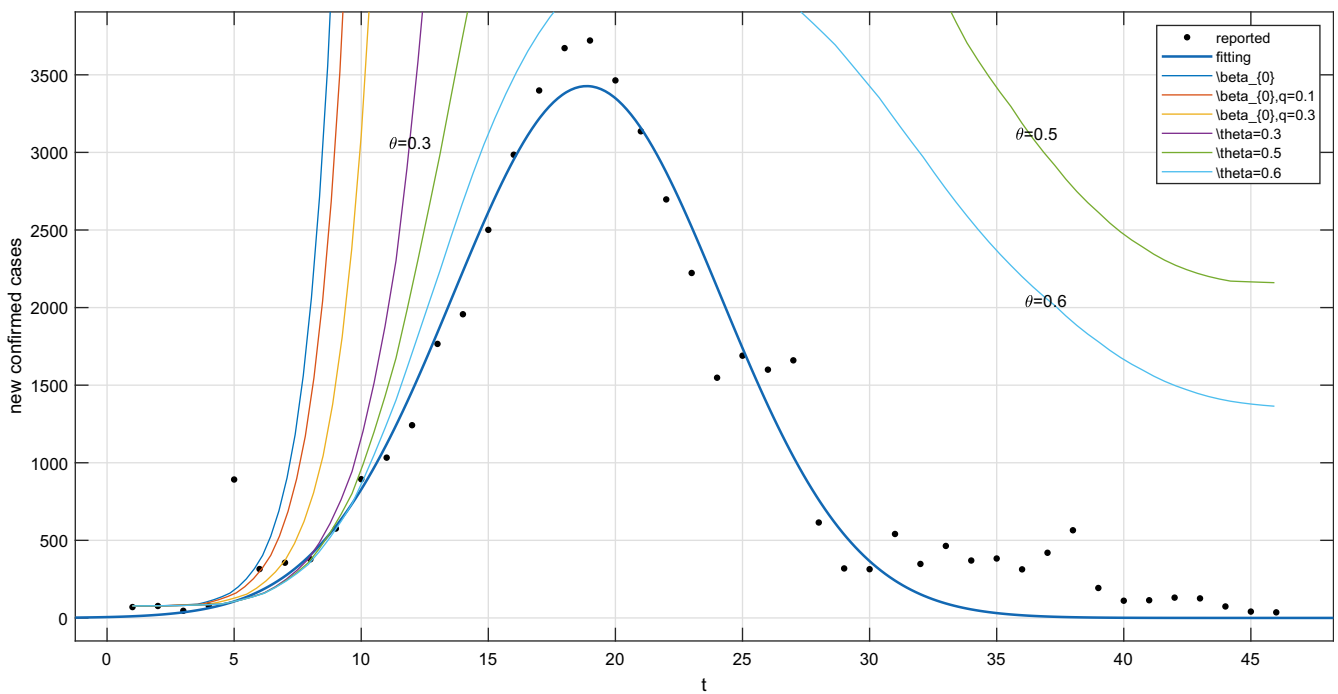


Figure 8. Control of COVID-19 in Wuhan.

549 cumulative confirmed cases in Hubei by January 23. We take the number of infected persons outside hospitals on January 23 as: $N_1 = 22242$ as $E(0)$, $I_a(0)$, and $I_m(0)$ arose from $N_0 = 17290$ on January 22, then $I_a(0) = p \cdot N_0 / 7 = 0.55 \times 17290 / 7 = 1358$, $I_m(0) = (1 - p)N_0 / 7 = 1112$.

According to the estimated infection rate α , the coefficient of incidence rate may be $\beta = 0.4046 / K = 3.65 \times 10^{-8}$, K is the total population in Wuhan. On this basis, fitting model (5) to new confirmed cases in January, we determine that the appropriate coefficient of incidence rate would be $\beta = 3.33 \times 10^{-8}$ at the beginning of the outbreak in Wuhan, and will reduce to 2.15×10^{-8} at the end of

January with human interventions. The sound fitting effects can be observed from Figure 15 in Appendix A5 or Figure 8.

Sensitivity analysis

In this section, we will investigate the effects of some important control measures including Staying-at-home, Social-distancing, Handwashing, Mask-wearing, and Temporary hospitals corresponding to parameters θ , q and δ . We can observe from Figure 8 and Figure 9 that the highest daily new confirmed cases will exceed 25000 and the expected removed susceptible population should be

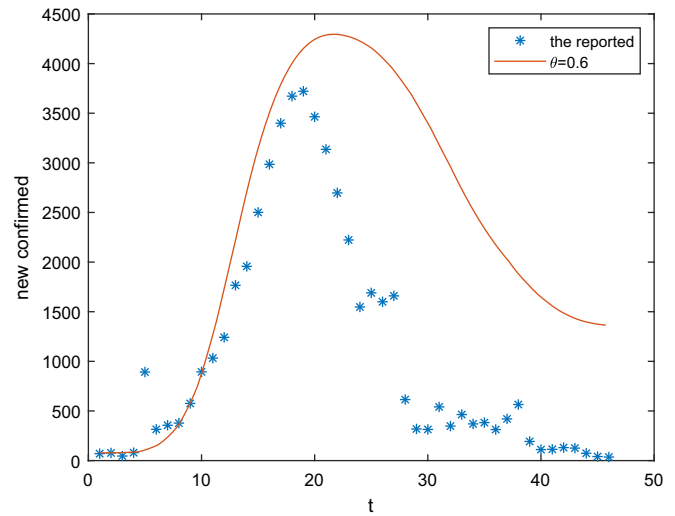
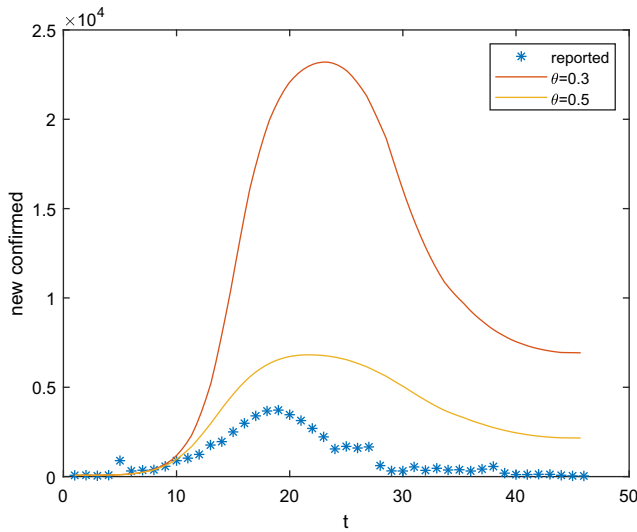


Figure 9. Comparison of removal effect and actual data.

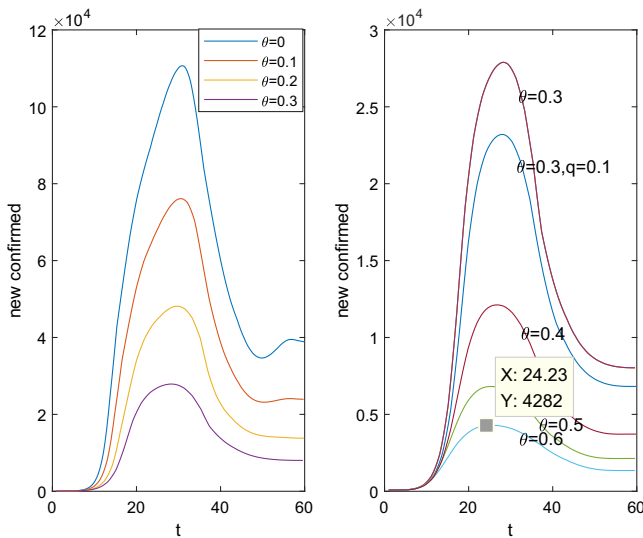


Figure 10. Importance of θ and q .

at least 50%, so an administrative ban is needed. It also can be detected from Figure 9 that the total number of infections will exceed 120000 (Estimated by integral) for the removal rate of the 60%, therefore Wuhan implemented the strict community management of Stay-at-home after February 11 to avoid more infections. Details are also presented in Figure 10. Figure 10 shows that the awareness-protective rate q can reduce infections effectively, so the awareness protection measures should be encouraged. Publicity, social-distancing, and hand hygiene are required.

From Figure 11(a), we can see that the increasing admission rate δ accelerated the findings of cases so that the peak of new confirmed cases will come in advance with a larger value, but greatly shortened the control period and reduced the total infections. Figure 11(b) indicates that personal protection measures other than Stay-at-home can really reduce infections. It can be observed that a certain percentage of people staying at home (only 30%) with well-implemented protective behaviors can sufficiently control COVID-19. We can see new cases will not

exceed 2000 with $\theta=0.3$ and $q=0.3$. That is, it is necessary for the public to maintain physical distance, to wash hands frequently, and to wear masks.

Figure 12(a) investigates the role of temporary hospitals. It is clear the recruitment of temporary hospitals greatly reduces infections. Figure 12(b) illustrates that calling for protective behaviors such as social distancing can continue to reduce the number of infections by nearly 50% in the premise of complete admission of patients. However, the control results that can be achieved by Stay-at-home are much more significant. A complete admission in combination with a removed rate of 20% is enough to control COVID-19.

The most effective control strategy for COVID-19 is Stay-at-home, but at least 60% of removed rate should be required to achieve a control effect like that of Wuhan. The removed rate only needs to be 30% if social-distancing and personal hygiene can be maintained successfully. That is, if some non-required people need to stay at home. It means it is possible for us to minimize social disruption and economic loss while controlling COVID-19. To end COVID-19 and restart the economy as soon as possible, it is necessary for the admission of patients. However, admission alone cannot be very effective because of the extremely fast spread of the SARS-CoV-2 virus and the presence of asymptomatic infections.

Social effects and individual awareness caused by the epidemic information can play a certain role. Fitting based on the data in January hints that the awareness-protective rate q may decrease 30% of infection rate. The removal rate of susceptible population should be at least 50% in pursuit of controlling COVID-19.

The removal rate of susceptible population should be at least 50 percent; it requires the guarantee of some administrative bans.

The strategy of Stay-at-home really guarantees the removal of most susceptible people and contributes to disease control. At least 60% of removed rate θ can effectively control COVID-19. q expresses the awareness-protection rate, it can be aroused by behavior changes. θ in combination with q may be more effective.

Model (5+) corresponds to the case of complete admission. (a) Infections can be greatly reduced with the introduction of temporary hospitals. (b) It is obvious that strategy of stay-at-home can control COVID-19 more effectively.

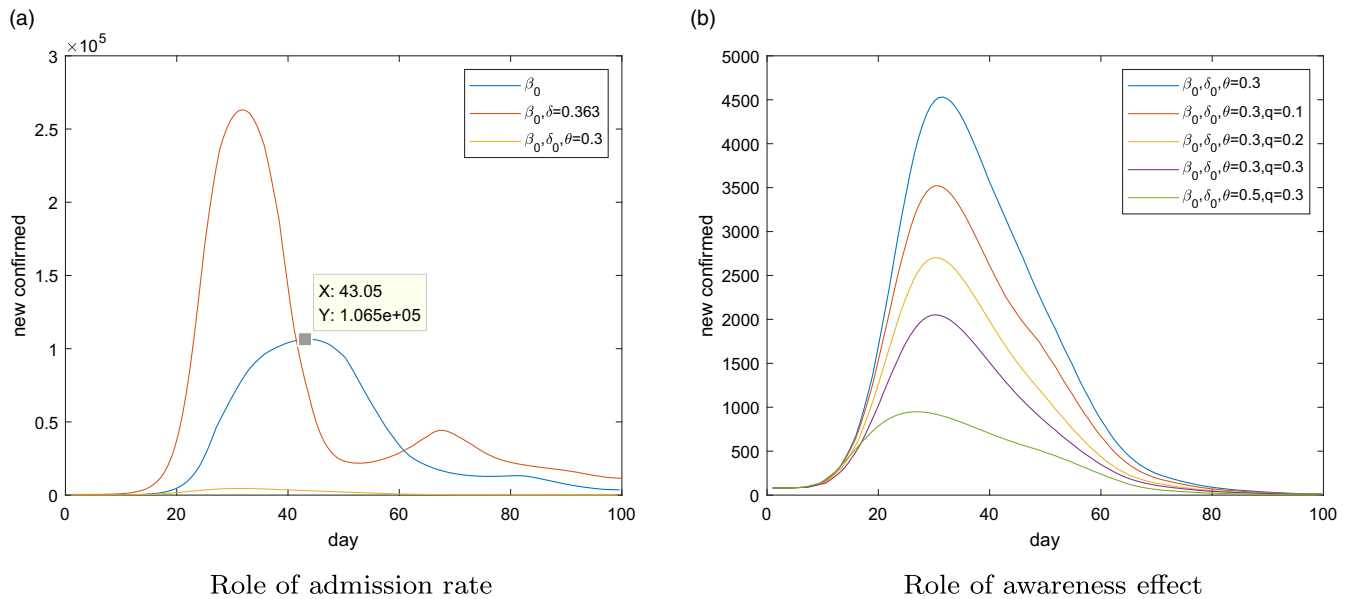


Figure 11. The admission rate and the awareness effect on the disease control. (a) The increasing admission rate δ raises the peak and speeds up the arrival of the peak but reduces infections and accelerates control process. (b) Certain values of θ and q can effectively reduce the incidence of infections. 30% of people’s staying at home and 30% of the effect of protection measures can reduce the maximum number of daily new cases to 2000.

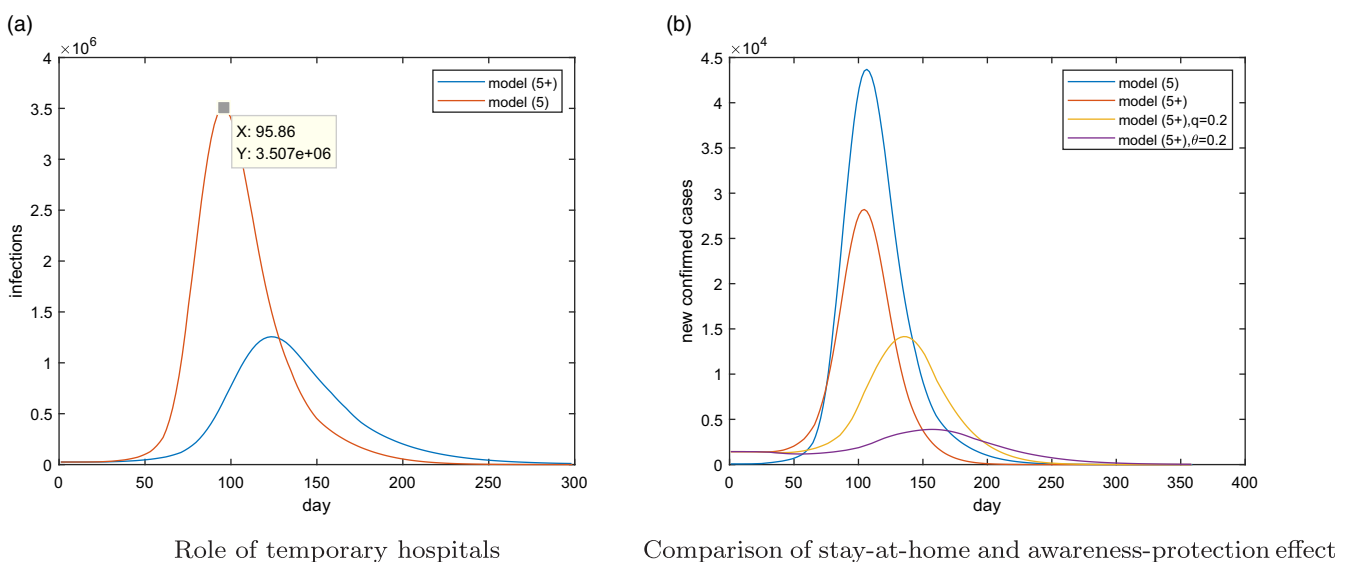


Figure 12. The admission rate and the awareness effect on the disease control.

Conclusion

In the controlling of COVID-19, Wuhan government locked down the city, required the public to wear masks, tracked, and isolated close contacts as much as possible, performed the strict community investigation and management, quickly built temporary hospitals to treat patients, and so on. It is obvious that active interventions effectively controlled COVID-19 and guaranteed people’s lives.

Based on actual control strategies and data at the beginning and end of the outbreak, we suggest that the median incubation period would be 6-7 days and the feasible proportion of the asymptomatic may be 55%. The reproduction number also had typical characteristics of control strategies. It was at least 2.5 before January 23, then decreased to 1.62 in late January, and continued to decline to 1.2 in

early February, with a sudden drop to far less than 1 because of the strict implementation of Stay-at-home after February 11, so that COVID-19 in Wuhan was under control within 1 month.

Infections are caused by infectious persons outside hospitals. Estimations show there were 22242 outside patients in Wuhan on the day of Lockdown and the most number of infected patients outside hospitals was 72366 on February 4, then decreased with medical capacity expansion, and the decline of infection rate.

February 5 and February 15 were the 2 important days in view of disease control in Wuhan. Authorities concerned accelerated hospital capacity and patient admission from February 5 and started fully closed community managements on February 15 after clearing inventory. After data revision, the complete evolution of cumulative confirmed cases is presented in Figure 1, which indicates that infections declined from February 7, and new infections

rarely occurred from February 15 in Wuhan. The actual control of COVID-19 in Wuhan coincides with the 2 important intervention time points of February 5 and February 15. That is, the effective control of COVID-19 in Wuhan is the result of people's active interventions. The complete admission of patients and the strict stay-at-home management are very important for containing the high spread of SARS-CoV-2 virus.

Based on dynamics theories and model-based analysis, expression and depiction of the effective reproduction number R_e are presented. The removed rate, the awareness-protective rate, and the admission rate will contribute to decrease R_e . For low admission rate, COVID-19 can be contained only when the group immunity rate is more than 75%. Also, group immunization in reality is all infections. It will result in 220000 deaths for a city as large as Wuhan.

In view of control strategies for COVID-19, the most effective 1 is the Stay-at-home strategy. At least 30% of people staying at home in combination with safe protection measures can effectively contain the spread of COVID-19 (Figure 11(b)). Furthermore, since only some non-essential people are required to stay at home. COVID-19 can be under control as long as enough temporary hospitals are supplemented (Figure 12(b)). It means it is possible to minimize the impact on society and economy.

The COVID-19 Pandemic is still ongoing. It requires the joint efforts of all mankind. We believe changes in people's awareness and behaviors brought by COVID-19 will help prevent seasonal influenza and avoid the next influenza pandemic.

Data availability. Data of COVID-19 cases and the related information in Wuhan were collected from Wuhan Municipal Health Commission,⁴⁵ it can be referred to under the columns of Outbreak notification, Prevention, and Control Dynamics, and Announcement. Data and information also come from National Health Commission of the People's Republic of China,⁴⁶ it can be referred to under the columns of Outbreak notification, Prevention, and Control Dynamics. All used data and information are annotated in this article.

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Conflicts of interest. Authors declare that they have no conflicts of interest.

References

1. **World Health Organization (WHO).** *Emergencies preparedness, response. Pneumonia of unknown cause-China, Disease outbreak news, 5 January 2020.* <https://www.who.int/csr/don/05-january-2020-pneumonia-of-unknown-cause-china/en/>. Accessed March 23, 2020.
2. **World Health Organization (WHO).** *Director General's opening remarks.* <https://www.who.int/dg/speeches/detail/who-director-general-s-opening-remarks-at-the-media-briefing-on-covid-19-20-march-2020>. Accessed March 22, 2020.
3. **World Health Organization (WHO).** *Home/Emergencies/Diseases/Coronavirus disease 2019.* <https://www.who.int/emergencies/diseases/novel-coronavirus-2019>. Accessed March 23, 2020.
4. **World Health Organization (WHO).** *Coronavirus situation reports.* <https://www.who.int/docs/default-source/coronaviruse/situation-reports/20200429-sitrep-100-covid-19.pdf>. Accessed May 3, 2020.
5. **World Health Organization (WHO).** *Prevention and control of new coronavirus pneumonia. Outbreak notification.* <http://wjw.wuhan.gov.cn/front/web/list3rd/yes/802>. Accessed March 23, 2020.
6. **Wuhan Municipal Health Commission.** *Prevention and control of new coronavirus pneumonia. Outbreak notification.* <http://www.nhc.gov.cn/xcs/yqtb/.shtml>.
7. **Xinhuanet.** *New coronavirus infection pneumonia epidemic: human-to-human and medical personnel infections have been confirmed.* <http://www.xinhuanet.com/politics/2020-01/20/c1125487200.html>. Accessed April 15, 2020.
8. **Tencent.** *Ten o'clock today! Wuhan is closed! All exits from Han are temporarily closed until further notice.* <https://new.qq.com/omn/20200123/20200123A02DXS00.html>. Accessed March 23, 2020.
9. **Wuhan Municipal Health Commission.** *Prevention and control of new coronavirus pneumonia. Prevention and Control Dynamics.* <http://wjw.wuhan.gov.cn/front/web/showDetail/2020020509410>. Accessed March 23, 2020.
10. **Wuhan Municipal Health Commission.** *Prevention and control of new coronavirus pneumonia. Prevention and Control Dynamics.* <http://wjw.wuhan.gov.cn/front/web/showDetail/2020031110051>. Accessed April 15, 2020.
11. **Wuhan Municipal Health Commission.** *Home. Prevention and control of new coronavirus pneumonia. Prevention and Control Dynamics.* <http://wjw.wuhan.gov.cn/>. Accessed April 25, 2020.
12. **Wuhan Municipal Health Commission.** *Home. Prevention and control of new coronavirus pneumonia. Notice.* <http://wjw.wuhan.gov.cn/ztz28/fk/tzgg/2020004/t20200431197130.shtml>. Accessed March 26, 2020.
13. **Wuhan Municipal Health Commission.** *Prevention and control of new coronavirus pneumonia/Notice.* <http://wjw.wuhan.gov.cn/front/web/showDetail/2020021509576>. Accessed March 26, 2020.
14. **Wuhan Municipal Health Commission.** *Prevention and control of new coronavirus pneumonia/Notice.* <http://wjw.wuhan.gov.cn/front/web/showDetail/2020021309543>. Accessed April 26, 2020.
15. **Guancha Politics.** *Bai Yansong asked Zhong Nanshan: what is the situation of the new type of coronavirus pneumonia?* https://www.guancha.cn/politics/2020_01_21_532437.shtml. Accessed March 13, 2020.
16. **Wuhan State Council.** *State Council executive meeting.* <http://www.gov.cn/guowuyuan/cwhy/20200120c03/index.htm>. Accessed March 23, 2020.
17. **National Health Commission of the People's Republic of China.** *Home. Prevention and control of new coronavirus pneumonia/Notice.* <http://www.nhc.gov.cn/xcs/yqtb/202001/dc9bee1eb2b44098b09661baec9ab4fc.shtml>. Accessed April 13, 2020.
18. **National Health Commission of the People's Republic of China.** *Home. Prevention and control of new coronavirus pneumonia/Notice.* <http://www.nhc.gov.cn/xcs/yqtb/202002/26fb16805f024382bff1de80c918368f.shtml>. Accessed April 23, 2020.
19. **Wuhan Municipal Health Commission.** *Prevention and control of new coronavirus pneumonia/Notice.* <http://wjw.wuhan.gov.cn/front/web/showDetail/2020021309543>. Accessed April 25, 2020.
20. **Wuhan Municipal Health Commission.** *Prevention and control of new coronavirus pneumonia/announcement.* <http://wjw.wuhan.gov.cn/front/web/list3rd/yes/803>. Accessed March 26, 2020.
21. **Hu Z, Song C, Xu C, et al.** *Clinical characteristics of 24 asymptomatic infections with COVID-19 screened among close contacts in Nanjing, China.* *Sci China Life Sci.* 2020; 1661-1664. doi: 10.1007/s11427-020-1661-4. [Epub ahead of print]. Accessed March 23, 2020.
22. **Epidemiology Working Group for NCIP Epidemic Response.** *Chinese Center for Disease Control and Prevention. Zhonghua Liu Xing Bing Xue Za Zhi.* 2020;41(2):145-151. doi: 10.3760/cma.j.issn.0254-6450.2020.02.003
23. **Mizumoto K, Kagaya K, Zarebski A, Chowell G.** *Estimating the asymptomatic ratio of 2019 novel coronavirus onboard the Princess Cruises Ship.* *MedRxiv.* 2020;10.1101/2020.02.20.20025866.
24. **Nature News.** *Covert coronavirus infections could be seeding new outbreaks.* doi:10.1038/d41586-020-00822-x. <https://www.nature.com/articles/d41586-020-00822-x>. Accessed March 20, 2020.

25. **Xinhua News Agency (Xinhuanet)**. Wuhan net-checking. <http://m.xinhuanet.com/2020-02/17/.html>. Accessed May 8, 2020.
26. **National Health Commission of the People's Republic of China**. *New coronavirus pneumonia epidemic prevention and control. Prevention and Control Dynamics*. <http://www.nhc.gov.cn/xcs/fkdt/202002/1fa99f55972740f681d47cde0d1b2522.shtml>. Accessed April 15, 2020.
27. **BBC News Chinese**. Pneumonia outbreak. Does asymptomatic infection cause a second major outbreak? <https://www.bbc.com/zhongwen/simp/chinese-news-52016649>. Accessed March 29, 2020.
28. **Nature News**. <http://www.ebiotrade.com/newsf/2020-3/2020325120039487.htm>. Accessed May 8, 2020.
29. **Xiaoxia L, Liqiong Z, Hui D, et al**. SARS-CoV-2 infection in children. *N Engl J Med*. 2020;382:1663-1665. doi: [10.1056/NEJMc2005073](https://doi.org/10.1056/NEJMc2005073)
30. **Riccardo C, Martina V, Amelia Licari, et al**. Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) Infection in children and adolescents: a systematic review. *JAMA Pediatr*. doi: [10.1001/jamapediatrics.2020.1467](https://doi.org/10.1001/jamapediatrics.2020.1467)
31. **Yi X, Xufang L, Bing Z, et al**. Brief communication: characteristics of pediatric SARS-CoV-2 infection and potential evidence for persistent fecal viral shedding. *Nature Med*. 2020;26:502C505.
32. **Wuhan Municipal Health Commission**. *Prevention and control of new coronavirus pneumonia/announcement*. <http://wjw.wuhan.gov.cn/front/web/showDetail/2020021109510>.
33. **Sina News**. The main battlefield of the epidemic: 48 days of designated hospitals in Wuhan. <https://news.sina.cn/gn/2020-03-09/detail-iimxstf7625588.d.html?pos=108 vt=4>. Accessed April 15, 2020.
34. **Biodiscover News**. Biological exploration-observation. How contagious are asymptomatic people? The latest judgment of Academician Zhong Nanshan. <http://m.biodiscover.com/news/celebrity/736251.html>. Accessed April 8, 2020.
35. **Wuhan Municipal Health Commission**. *Prevention and control of new coronavirus pneumonia. Prevention and Control Dynamics*. <http://wjw.wuhan.gov.cn/front/web/showDetail/2020012909252>. Accessed March 23, 2020.
36. **van den Driessche P, Watmough J**. Reproduction numbers and sub-threshold endemic equilibria for compartmental models of disease transmission. *Math Biosci*. 2002;180:29-48.
37. **China News**. Chinese disease control expert: new coronary pneumonia patients have been contagious two days before onset. <https://m.chinanews.com/wap/detail/zw/gn/2020/02-22/9100652.shtml>. Accessed February 22, 2020.
38. **Diekmann O, Heesterbeek JAP, Metz JAJ**. On the definition and the computation of the basic reproduction ratio R_0 in models for infectious diseases in heterogeneous populations. *J Math Biol*. 1990;28:36.
39. **Wuhan Government website**. *Statistical services. Statistical products. Statistical bulletins*. <http://tjj.wuhan.gov.cn/details.aspx?id=4368>. Accessed March 26, 2020.
40. **ScienceNet**. Focusing on asymptomatic infections: how to prevent and control the "latent" SARS-CoV-2 virus? <http://news.sciencenet.cn/htmlnews/2020/3/437622.shtml>. Accessed March 29, 2020.
41. **Xinhua News Agency (Xinhuanet)**. The average hospitalized patients in China was more than 9 days, and the average in Hubei Province was 20 days. <http://www.xinhuanet.com/politics/2020-02/04/c1125530818.htm>. Accessed March 29, 2020.
42. **Zhou F, Yu T, Du R, et al**. Clinical course and risk factors for mortality of adult inpatients with COVID-19 in Wuhan, China: a retrospective cohort study [published correction appears in *Lancet*. 2020 Mar 28;395(10229):1038]. *Lancet*. 2020;395(10229):1054-1062. doi: [10.1016/S0140-6736\(20\)30566-3](https://doi.org/10.1016/S0140-6736(20)30566-3)
43. **Expert Group on Prevention and Control of New Coronavirus Pneumonia of Chinese Preventive Medicine Association, Chinese Preventive Medicine Association**. New understanding of epidemiological characteristics of new coronavirus pneumonia. *Chin. J. Epidemiol*. 2020;41(2):139-144.
44. **Wuhan Municipal Health Commission**. *Prevention and control of new coronavirus pneumonia. Outbreak notification*. <http://wjw.wuhan.gov.cn/front/web/showDetail/2020020909483>. Accessed March 29, 2020.
45. **Wuhan Municipal Health Commission**. *One heart and one mind, resolutely win the battle for prevention and control of COVID-19*. <http://wjw.wuhan.gov.cn/front/web/ztzl/801>.
46. **National Health Commission of the People's Republic of China**. *Do our best to prevent epidemic of COVID-19*. <http://www.nhc.gov.cn;http://www.nhc.gov.cn/xcs/xgzbd/.shtml>.

Appendix

A1. Effect of data revision for data missing and confusing

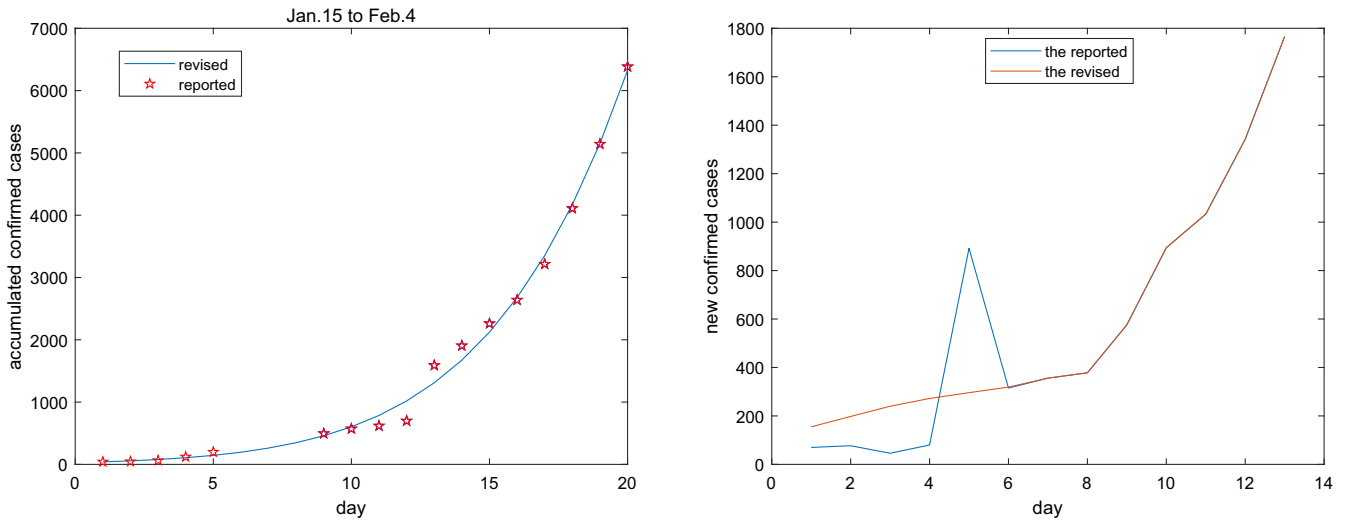


Figure 13. Data revision for confirmed cases in Wuhan in January, 2020. Left: Revision for cumulative confirmed cases from January 15 to February 4; Right: Data revision for new confirmed cases from January 23 to February 4.

A2.

Based on data from Wuhan Municipal Health Commission, there were 32994, 35991 and 37914 cumulative confirmed cases in Wuhan from February 12 to February 14, including the laboratory and clinically confirmed ones. The new cases were 13436, 3910, and 1923, respectively. These patients existed a few days ago and needed to be allocated to the previous few days. We carried out a fitting of reported cumulative cases from February 12 to February 26 and obtained a best Gauss function as follows:

$$f(t) = 47130 \exp(-((t - 16.36)/16.29)^2) + 1198 \exp(-((t - 7.507)/1.699)^2) + 14020 \exp(-((t - 1.956)/7.898)^2),$$

with SSE: $2.374e+05$, R-square: 0.9992, Adjusted R-square: 0.9981 and RMSE: 198.9. The corresponding fitting values and the traced results are presented in Table 4 as follows. The fitting effect can be observed from Fig. 14.

Table 4. The revised cumulative confirmed cases including clinically diagnosed ones from February 3 to February 26

Date	3	4	5	6	7	8	9	10	11	12	13	14
Revised Number	7898	9904	12244	14900	17822	20935	24141	27326	30375	33188	35687	37832
Presented Number	6384	8351	10117	11618	13603	14982	16902	18454	19558	32994	35991	37914
Revised New		2006	2340	2656	2922	3113	3206	3185	3049	2813	2499	2145
Date	15	16	17	18	19	20	21	22	23	24	25	26
Revised Number	39630	41200	42784	44298	45124	45310	45575	46090	46655	47151	47521	47719
Presented Number	39462	41152	42752	44412	45027	45346	45660	46201	46607	47071	47441	47824
Revised New	1798	1570	1584	1514	826	186	265	515	565	496	370	198

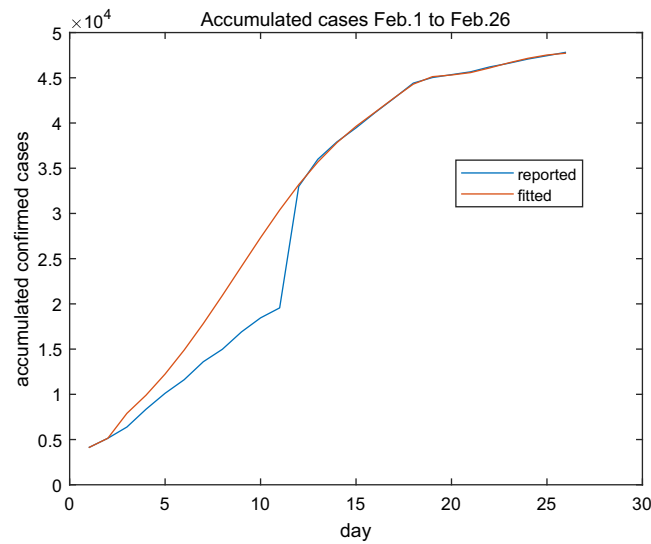


Figure 14. Revision of cumulative confirmed cases including clinically diagnosed ones from February 1 to February 26.

A3. Referring to the admission rate in Table 5

Table 5. Admission in fever clinics in January in Wuhan

Date	26	27	28	24-26	22-27
Visiting	10261	10702	12263	19202	75221
Observing	745	600	741	1460	3883
Admitting rate	0.0726	0.0560	0.0604	0.0760	0.0516

A4. The changed model after complete admission of patients

$$\left\{ \begin{aligned}
 \frac{dS}{dt} &= A - \theta S - \beta(1-q)S(\frac{2}{m}E + I_a) - (1-b)r(\varepsilon(1-p)E + bcS_q) + (1-b)cS_q - dS, \\
 \frac{dE}{dt} &= \beta(1-q)S(\frac{2}{m}E + I_a) - br(\varepsilon(1-p)E + bcS_q) - \varepsilon E - dE, \\
 \frac{dI_a}{dt} &= \varepsilon pE - \gamma_1 I_a - dI_a, \\
 \frac{dI_m}{dt} &= \varepsilon(1-p)E - \delta I_m - \gamma_2 I_m - dI_m, \\
 \frac{dI_h}{dt} &= \delta I_m + bcS_q - \gamma_3 I_h - \rho I_h - dI_h, \\
 \frac{dS_p}{dt} &= \theta S - dS_p, \\
 \frac{dS_q}{dt} &= r(\varepsilon(1-p)E + bcS_q) - cS_q - dS_q, \\
 \frac{dR}{dt} &= \gamma_1 I_a + \gamma_2 I_m + \gamma_3 I_h - dR,
 \end{aligned} \right. \tag{5+}$$

A5. Parameter inversion of incidence coefficient β was carried out based on data of new confirmed cases in the first few days when we began to control COVID-19 in Wuhan. Fixing $\theta=0, q=0$, we can get $\beta=3.3e-8$ in the beginning, and it will decline with human intervention. This can be observed from Figure 15.

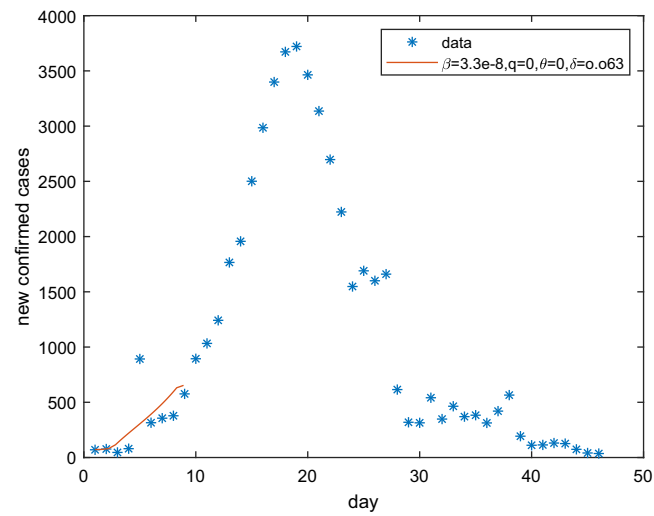


Figure 15. Illustration of the incidence coefficient.