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 are 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 Jan.20 is about 10000 and reached more than 20000 on the day of Lockdown, it exceeded 72000 on Feb.4. Both data-based and model-based analyses gave out the evolution of the reproduction number, which is over 2.5 in early January, then go down to 1.62 in late January and 1.20 in early February, a sudden drop to less than 0.5 due to the strict Stay-at-home management after Feb.11. Strategies of Stay-at-home, Safe-protective measures and Ark hospitals are the main contributions to control COVID-19 in Wuhan. Two inflection points of COVID-19 in Wuhan exactly correspond to Feb.5 and Feb.15, the two days when Ark hospitals were introduced and the complete implementation of Stay-at-home. Based on the express of the reproduction number, group immunity also is discussed. It shows that only when the group immunization rate is over 75 percent can COVID-19 be under control, group immunity actually would be full infection and the total deaths will be 220,000 for a city as big as Wuhan. Sensitivity analysis suggests that 30 percent of people staying at home in combination with better behavior changes, such as social-distancing and frequent hand-washing, can effectively contain COVID-19. But only when this proportion is over 60 percent can the control effect and efficiency like Wuhan be obtained.

Keywords New coronavirus; COVID-19; Disease reproduction number; Data-based; Model-based; Stay-at-home

1 Introduction

COVID-19, an epidemic of human infections with the virus SARS-CoV-2, is erupting in many countries and regions. On 31 December 2019, China reported several cases of unexplained pneumonia in Wuhan, Hubei Province. As of 3 January 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 7 January 2020. As of 7 March 2020, globally confirmed cases of COVID-19 has surpassed 100,000. On the evening of March 11, local time, WHO announced in Geneva that COVID-19 has formed a global pandemic. As of 20 March 2020, more than 210,000 cases have been reported to WHO and more than 9,000 people have lost their lives [2]. There are 332,935 confirmed cases, 14,510 confirmed deaths and 190 countries, areas or territories with cases as of 23 March 2020, 09:03 GMT -7 [3]. As of 29 April, there are 3,018,681 confirmed cases globally and 207,973 deaths [4]. The number of infected people has increased wildly. A year later, as of 9 February 2021, there have been 106,008,943 confirmed cases of COVID-19 worldwide, including 2,316,389 deaths. As COVID-19 cases continue to increase, life is changing dramatically. More and more countries ask their people to stay at home, to work from home and to have lessons online. Social disruption caused by COVID-19 is unimaginable. However, Wuhan, once the severe outbreak city, continues to report no new cases since 18 March 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: A person with laboratory confirmation (PCR-testing) of COVID-19; The probable case: A suspected case for whom testing could not be performed or testing for the SARS-CoV-2 virus is inconclusive. The clinically diagnosed case: 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. Noticing 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 the 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 are some important days as follows.

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(T_1). On Jan.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 is spreading from person to person [7].

(T_2). On Jan.23, Wuhan closed the out-of-city corridor, then 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 Feb.4 and Feb.8, for the treatment of critically ill patients of COVID-19 [9].

(T_4). The first Ark hospital started operation on the evening of Feb.5. There were once 16 Ark hospitals operating in Wuhan. As of Mar.9, these Ark hospitals had treated more than 12,000 patients with mild coronary pneumonia [10].

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

(T_6). The closed community management started on Feb.11. Only one person per household is allowed to go out to buy food and necessities every 3 days [12].

(T_7). The completely closed community management started on Feb.15 after clearing inventory. Daily necessities are delivered by the dedicated persons [13].

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

As the introduction of Ark hospitals, from Feb.5, the mode of treatment was changed as follows: For suspected patients, they were first screened in communities and then determined to be isolated in communities or transferred to hospitals. For mild patients, 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.

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

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

2 Data-based Analysis

2.1 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 Jan.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].

Noticing that Wuhan Municipal Health Commission started the daily outbreak report from Jan.23 on its official website, and National Health Commission of the People’s Republic of China presented the outbreak notification from Wuhan Municipal Health Commission from Jan.11 to Jan.20, followed by the national reports starting on Jan.21. And, the clinically diagnosed confirmed cases were included on Jan.17, 18 and 19, then cancelled, and re-added from Feb.12 [17,18].
Therefore, there are data missing and confusing in the first few days in Wuhan, we should revise and complement these data from Jan.20 to 22 firstly. And, the new confirmed cases suddenly increased to 892 on Jan.27, it also needs to be smoothed. After all, these patients already existed and we failed to confirm them in time. Based on the reported cumulative laboratory confirmed cases from Jan.23 to Feb.3, we get a best Gauss fitting function which is $C(t) = 132100 \exp\left(-\frac{(t-42.16)^2}{17.3}\right)$ (Goodness of fit: SSE: 3.12e + 05, R-square: 0.9924, Adjusted R-square: 0.9907, RMSE: 186.2). We use it for the short-term backtracking that the cumulative laboratory confirmed cases from Jan.20 to Jan.22 are 195, 262 and 348, respectively. The revised cumulative confirmed cases from Jan.15 to Feb.3 are presented in Table 2 as follows.

### Table 2: The revised cumulative laboratory confirmed cases from Jan.15 to Feb.3

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

*: Clinically diagnosed cases are added in these data.

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

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 Feb.12 [19]. We explored the trend of laboratory confirmed cases from Jan.23 to Feb.14 and still excluded the clinically diagnosed cases from Jan.12 to 14 in purpose of maintaining the statistical consistency and found there is a good continuity (See Fig.1). There are 20630, 21960 and 22961 laboratory confirmed cases from Jan.12 to 14. Since clinically diagnosed cases were added, an additional fitting from Feb.12 is obtained, which is provided in Appendix A2. We get data of laboratory confirmed cases with clinically diagnosed cases from Feb.3 to Feb.11 are 7898, 9904, 12244, 14900, 17822, 20935, 24141, 27326 and 30375, respectively. Fig.14 in Appendix A2 illustrates the fitting effect. So far, data is revised and we figure out the evolution of cumulative confirmed cases from Jan.20 to Feb.26 in Wuhan in Fig.1.

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

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

### 2.2 Discuss the proportion of the asymptomatic $p$

There is an argument about asymptomatic infections. The infectivity of the asymptomatic is certain [21], but the proportion is not clear. On Feb.17, China CDC published a paper in the Chinese Journal of Epidemiology, mentioned that there were 889 cases of asymptomatic infections in the total of 72314 domestic reported cases as of Feb.11, accounting for about 1.2 percent [22]. The preprint platform medRxiv 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 percent [23]. An article published in Nature on 20 March 2020 warned that the asymptomatic or mild symptoms may account for 30-60 percent and the ability to spread the virus is not weak [24].

Although the proportion of asymptomatic infections is not clear, there are mainly two ways to confirm the asymptomatic. One is the detection of close contacts and another is the port input detection. The ratio of close contacts to confirmed cases is approximately 3.29:1 in Hubei province as of Feb.16 [25], and this ratio is slightly higher in Wuhan. It is 6.65 in late January, 4.75 in February and 3.62 after Feb.15 by data analysis directly. A follow-up survey by the China-WHO Joint Expert Group found that approximately 1 to 5 percent of close contacts were diagnosed with COVID-19 and many of them are asymptomatic [26]. Assumed that the confirmed cases found by detecting close contacts are all asymptomatic, the proportion would not exceed 33 percent. As for cases found by the entry detection, academician Zhong...
Fig. 1: The evolution of cumulative confirmed cases

It shows Feb.7 is a flexion point of cumulative confirmed curve $\Gamma(t)$ and the increase in number of confirmed patients would tend to alleviation after Feb.20. There are few new confirmed patients after Feb.23.

Fig. 2: The evolution of new laboratory confirmed cases

It only presents number of new laboratory confirmed cases from Jan.23 to Feb.11 because the confirmation criteria changed after Feb.12. An abnormal data on Jan.27 is excluded. It can be captured that there is a decline after Feb.7.

Fig. 3: Capacity and occupation of beds in designated hospitals in Wuhan

Wuhan government increased number of designated hospitals on Feb. 2, 3, 8, 9, 10, 12, 15, 16 and 20, respectively. Data comes from Wuhan Municipal Health Commission [20]. There is no the running of medical resources after Feb.16.
Nanshan said that 50 percent 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 COVID-19 cases. Most investigations confirmed that children cases are mainly asymptomatic or mild, and symptoms in children are generally milder than adults. Children’s Medical Center in Shanghai studied more than 700 infected children cases in China, found that 56 percent of children had mild or asymptomatic conditions [28]. A research by Lu X. et al. suggested that 15.8 percent of children infections had no symptoms, 19.3 percent only had upper respiratory symptoms and 7 percent had only CT features without any symptoms [29], Raccardo and Martina et al. also clarified that most children with COVID-19 presented with mild symptoms [30], Xu Y. 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.

### 2.3 Determination of the disease incubation period $m$

For the reason that COVID-19 in Wuhan was on the closing stage in March, without loss of generality, it is supposed that $(1 - p)N_i \leq \sum_{t=t+1}^m C_i$ within 14 days before Mar.18. We begin investigations from Jan.23. It is obvious that $N_{t=0} = 0$ and $N_{t=55} = 0$ because there are no new confirmed cases after Mar.18.

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

$$(1 - p)mC_{t+1} \leq \sum_{i=t+1} C_i$$

within 14 days before Mar.18. The relationship between the number of infectious persons outside hospitals $N_i$ and the number of new confirmed cases per day $C_i$ is provided in Table 3.

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

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 take $m = 7$ for reference.

### 2.4 Estimation of $N_0$ and $R_0$

$N_0$ express the number of infectious persons outside hospitals on Jan.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 Jan.31, the third batch of 14 designated hospitals began to treat patients with COVID-19, providing nearly 10,000 available beds. The first 2 batches provided a total of about 4,000 beds [32]. Then, more dedicated hospitals, including the Vulcan Mountain Hospital and Thunder God Mountain Hospital (after Feb.4, $T_3$) and some Ark hospitals (The first one started operation on the evening of Feb.5, $T_4$) began to treat patients with COVID-19 in succession. We believe medical capacities in the first half of February increased gradually and met demands after Feb.15 (which also can be detected from Fig.3). Therefore, taking into account the inventory and the asymptomatic, the daily new confirmed cases $C_t$ would satisfy:

$$C_t \geq \begin{cases} \frac{a}{m}(1 - p)N_{t-1}, & t : Jan.23 \text{ to Jan.30}, \\ \frac{a+0.025}{m+0.54}(1 - p)N_{t-1}, & t : Jan.31 \text{ to Feb.5}, \\ \frac{a+0.06}{m+0.12}(1 - p)N_{t-1}, & t : Feb.6 \text{ to Feb.15}, \\ \end{cases}$$

where $a$ is the average hospital admission rate in January. According to a report from Wuhan Municipal Health Commission, there is 5 percent’s fever patients were admitted to hospitals from Jan.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 take $\alpha = 0.063$ in late January. Thus, in January there is

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

Hence, it is possible that the infectious persons outside hospitals may be 17290 on Jan.22. That is, the existed infectious persons was already very large and basically not be diagnosed before the day of Lockdown. Also, series of values of $N_t$ can be given. Now, we will estimate the contagion of SARS-CoV-2 virus. Let $\alpha$ be the daily growth rate of infectious persons outside hospitals, we define

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

Because the revised cases presented in Table 2 represent the definitive confirmed ones, we use these data for further investigation. Then, with Eq. (2) and these data, based on the Principle of Least Squares, using software of LINGO for optimization, by programming and operating, beginning with 17290 on Jan.22, we have the optimal value

$$\alpha = 0.160246$$

in late January after Jan.23, 0.3332 during Jan.16 to Jan.22 and 0.2864 on Jan.23. Further estimating, there is 10448 infected persons on Jan.20 and 22242 on Jan.23. We also obtain the most number of infected patients outside hospitals is over 72000 on Feb.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 1,000 cases) [34], it is supposed that the infected persons are no longer infectious after 14 days. Taking into account this natural elimination rate of virus toxicity, the infection rate may be

$$\text{over 72000 on Feb.4.}$$

The removed rate

$$\theta(t)$$

and the admission rate

$$\delta(t)$$

are assumed to be

$$\text{on Feb.15. and no one can be allowed to go out(see (T))}$$

and the shortage of hygienic protective articles, we assume

$$\text{the need to buy daily necessities and seek medical treatments, and the shortage of hygienic protective articles, we assume}$$

the removed proportion due to awareness and protection may gradually increase to 30 percent as of Jan.31. Because the closed management of residential communities started on Feb.11 and every household was allowed one person to go out to buy necessities every three days (referring to $(T_3)$, $(T_4)$, $(T_6)$), we assume at least 60 percent people will be removed from the susceptible taking into account family size in China. Further, the completely closed community management started on Feb.15, and no one can be allowed to go out(see $(T_2)$) except the required staff, we suggest 90 percent people can avoid being infected. The removed rate $\theta$ of the susceptible is defined as $\theta(t)$ as follows.

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

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

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

### 3.2 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 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, others are not admitted. Hospitalized patients will not infect others if not considering 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 decreased.

We divide 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 Fig.4, and the corresponding epidemic model is as follows.

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

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

Noticing that Wuhan had achieved the complete admission of visiting patients after Feb.15, then the disease incidence item $\beta(1-q)S(\mu E + I_a + I_m)$ in model (5) should be changed as $\beta(1-q)S(\mu E + I_a)$. $I_m$ can be regarded as the mild patients in Ark hospitals, $\delta$ is the conversion rate from mild to severe. And, the quarantine item $r(\delta I_m + bcS_q)$ will be replaced with $r(\varepsilon (1-p)E + bcS_q)$. Denote it as model (5+) presented in Appendix A4.
3.3 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 $X = (S, E, I_a, I_m, I_h, S_p, S_q, R)^T$.

Now we will compute the effective reproduction number $R_e$. Using the method of van den Driessche and Watmough [30], a subsystem 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,

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

The associated next-generation matrices are

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

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

Giving out

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

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

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

Let the transmission rate of latency be $\mu = 2/m$ because the infected persons have been contagious two 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 the awareness-protective rate $q$ will affect $R_e$ greatly, the admission rate $\delta$ of mild patients also will contribute to decrease $R_e$. Based on the estimated parameters in next subsection, surface $R_e(q, \delta)$ and curve $R_e(q, \delta) = 1$ are depicted in Fig.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 percent for high medical admission rate $\delta$ and it should be 75 percent for low medical admission rate.

In sense of dynamics of infectious disease, 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, 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 susceptible population, then it also is the removed rate of the susceptible in Eq. (6) when we use Eq. (6) for referring to the control reproduction number $R_e$. Therefore, the representation in Fig.5 tell us that it is necessary for 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. $q$ in Eq. (6) also can 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 have the conclusion that COVID-19 would be controlled only when the group immunity rate is over 75 percent 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 take $q = 0.3$ for reference. We also can detect it from Fig.8 for the sound fitting of data in January. For the following estimated $\beta$ and $\gamma_{1,2}$ and Eq. (3,4,6), $R_e$ is figured out roughly in Fig.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 Feb.11 quickly made $R_e < 1$ so that COVID-19 in Wuhan could finally be contained within one month.
\( R_e \) will exceed 4 for the low \( q \) and \( \delta \). It will decrease with the increasing \( q \) and \( \delta \). \( R_e < 1 \) only when \( q > 0.6 \). It should be \( q > 0.75 \) for the low \( \delta \).

Figure 5: The control reproduction rate \( R_e \)

Figure 6: Evolution of the reproduction number \( R_e \) and the necessary of \( \theta \)

(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 Stay-at-home order which was issued on Feb.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 decrease with the removed rate obviously.
include the recovered population. So it also verifies the high self-healing rate and cure rate of COVID-19.

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

Fig. 7 also hints group immunity would actually be all people’s infections. In theory, $R_e < 1$ means an infected individual can produce less than one 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 two-thirds of people have been infected conceptually. Simulations tell us that the proportion needs to be 3 out of 4 and infection still continues. The total deaths will be 220,000 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 is no COVID-19 patients and the cumulative deaths were 3869 as of May 1 with the comprehensive and strong interventions in Wuhan. Fig. 7 (b) also shows 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 viruses to others. And, for the existence of an uncertain large proportion of the asymptomatic and the easily spread of 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.

### 3.4 Parameter determination and estimation

Because SARS-CoV-2 virus is susceptible to all people, the youngest patient in Wuhan was just 17 days old, daily births needs to be considered. At the end of 2018, the population of Wuhan was 11.081 million and the births was 119,400 [39]. We refer to $S(0) = 11.081$ million and $A = 375$. The average life expectancy is 81 years old in Wuhan, so $d = 1/81 \approx 0.0012348$.

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

For the above estimated incubation period $m = 7$, the incidence of latency will be $\epsilon = 1/7$. 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 is

![Figure 7: Evolution of the epidemic on the low admission rate](https://example.com/figure7.png)
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 is few people who carried the virus for more than 14 days [34], taking into account the incubation period, we suppose 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 [42] and the average time for patients from onset to seeing doctors is 5 days [43], then the mean hospitalized days of the deaths would be 14. Case fatality in Wuhan is about 4.05 percent [44], then 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 Jan.23, we take $I_7(0) = 440$ because the cumulative confirmed cases in Wuhan as of Jan. 23 is 495 and it should exclude the discharged 31 and the deaths 24. $R(0) = 31$. Let $S_0(0) = 2776 \times 495/549 = 2503$ because there are 2776 close contacts under observation on Jan. 23 and 549 cumulative confirmed cases in Hubei as of Jan. 23. We take the number of infected persons outside hospitals on Jan. 23 $N_1 = 22242$ as $E(0)$, $I_7(0)$ and $I_m(0)$ arose from $N_0 = 17290$ on Jan. 22, then $I_n(0) = p \cdot N_0/7 = 0.55 \times 17290/7 = 1358$, $I_m(0) = (1 - p)N_0/7 = 1112$.

By above estimated infection rate $\alpha$, 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 get 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 $2.15 \times 10^{-8}$ at the end of January with human interventions. The sound fitting effects can be observed from Fig.15 in Appendix A5 or Fig.8.

### 3.5 Sensitivity analysis

In this section, we will investigate effects of some important control measures including Staying-at-home, Social-distancing, Hand-washing, Mask-wearing and Temporary hospitals corresponding to parameters $\theta$, $q$ and $\delta$. We can observe from Fig.8 and Fig.9 that the highest daily new confirmed cases will exceed 25,000 and the expected removed susceptible population at least should be 50 percent, so an administrative ban is needed. It also can be detected from Fig.9 that total number of infections will exceed 120,000 (Estimated by integral) for the 60 percent’s removal rate, therefore Wuhan implemented the strict community management of Stay-at-home after Feb.11 to avoid more infections. Details are also presented in Fig.10. Fig.10 shows 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 Fig.11(a), we can see that the increasing admission rate $\delta$ accelerated the findings of cases so that peak of new confirmed cases will come in advance with a larger value, but greatly shortened the control period and reduced the total infections. Fig.11(b) indicates 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 percent) 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.

Fig.12(a) investigates the role of temporary hospitals. It is clear the recruitment of temporary hospitals greatly reduce infections. Fig.12(b) illustrates that calling for protective behaviors such as social-distancing can continue to reduce number of infections by nearly half in the premise of complete admission of patients. But 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 percent is enough to control COVID-19.

The most effective control strategy for COVID-19 is Stay-at-home, but at least 60 percent of removed rate should be required to achieve a control effect similar to that of Wuhan. The removed rate only needs to be 30 percent if social-distancing and personal hygiene can be maintained successfully. That is, as long as some not-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. In order to end COVID-19 and restart economy as soon as possible, it is necessary for the admission of patients. But admission alone cannot be very effective because of the extremely spread of the SARS-CoV-2 virus and the presence of asymptomatic infections.

### 4 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 percent. The reproduction number also had typical characteristics of control strategies. It was at least 2.5 before Jan.23, then decreased to 1.62 in late January and continued to decline to 1.2 in early February, a sudden drop to far less than 1 because of the strict implementation of Stay-at-home after Feb.11, so that COVID-19 in Wuhan was under control within one month.
Social effects and individual awareness caused by the epidemic information can play a certain role. Fitting based on the data in January hints the awareness-protective rate $q$ may decrease 30 percent of infection rate. The removal rate of susceptible population should be at least 50 percent in purpose 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 contribute to disease control. But at least 60 percent of removed rate $\theta$ can effectively control COVID-19. $q$ expresses the awareness-protection rate, it can be aroused by behavior changes. $\theta$ in combination with $q$ may be more effective.

Figure 10: Importance of $\theta$ and $q$

The increasing admission rate $\delta$ raises the peak and speeds up the arrival of the peak, but reduces infections and accelerates control process. (b) Certain values of $\theta$ and $q$ can effectively reduce the incidence of infections. 30 percent of people’s staying at home and 30 percent’s effect of protection measures can reduce the maximum number of daily new cases to 2000.

Figure 11: The admission rate and the awareness effect on the disease control
Infections are caused by infectious persons outside hospitals. Estimations show there are 22242 outside patients in Wuhan on the day of Lockdown and the most number of infected patients outside hospitals is 72306 on Feb.4, then decreased with medical capacity expansion and the decline of infection rate.

Feb.5 and Feb.15 are the two important days in view of disease control in Wuhan. Authorities concerned accelerated hospital capacity and patient admission from Feb.5, and started fully closed community managements on Feb.15 after clearing inventory. After data revision, the complete evolution of cumulative confirmed cases is presented in Fig.1, which indicates that infections declined from Feb.7 and new infections have rarely occurred from Feb.15 in Wuhan. The actual control of COVID-19 in Wuhan coincides with the two important intervention time points of Feb.5 and Feb.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.

By 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 percent. And, group immunization in reality is all infections. It will result in 220,000 deaths for a city as large as Wuhan.

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

Pandemic of COVID-19 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.

Author Contributions
Formal analysis, Y.C.; Funding acquisition, Y.W. and Y.C.; Data processing, H.Z., J.W. C.L and N.Y.; Writing, Y.C. All authors have read and agreed to the published version of the manuscript.

Data Availability
Data of COVID-19 cases and the related information in Wuhan are collected from Wuhan Municipal Health Commission [45], it can be referred to 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 columns of Outbreak notification and Prevention and Control Dynamics. All used data and information are annotated in this article.

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

Acknowledgments
Authors are thankful to the learned reviewers for their useful suggestions and comments. Thanks for Pro. Song-Ying Li of University of California, Irvine, for his valuable comments. This work was supported by the China Scholarship Council
(grant no. CSC201908350034), the National Natural Science Foundations of China (project no.: 32071892) and and the Natural Science Foundations of Fujian Province (project no. 2021J01126). And, as a visiting scholar of University of California, Irvine, the first author thanks to the Department of Mathematics in the School of Physical Sciences at the University of California, Irvine, for space and hospitality.

Appendix

A1. Effect of data revision for data missing and confusing.

![Fig. 13: Data revision for confirmed cases in Wuhan in January, 2020](image)

Left: Revision for cumulative confirmed cases from Jan.15 to Feb.4; Right: Data revision for new confirmed cases from Jan.23 to Feb.4.

A2. Based on data from Wuhan Municipal Health Commission, there are 32994, 35991 and 37914 cumulative confirmed cases in Wuhan from Feb.12 to Feb.14, including the laboratory and clinically confirmed ones. The new cases are 13436, 3910 and 1923, respectively. These patients exactly existed a few days ago and need to be allocated to the previous few days. We carry out a fitting of reported cumulative cases from Feb.12 to Feb.26 and obtained a best Gauss function as follows:

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

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 Feb.3 to Feb.26

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<th>6</th>
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A3. Referring to the admission rate in Table 5.

Table 5: Admission in fever clinics in January in Wuhan

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A4.
Accumulated cases Feb.1 to Feb.26

Fig. 14: Revision of cumulative confirmed cases including clinically diagnosed ones from Feb.1 to Feb.26

Illustration of the incidence coefficient

Fig. 15: Illustration of the incidence coefficient

The changed model after complete admission of patients.

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

A5.

Parameter inversion of incidence coefficient $\beta$ is 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 interventions. It can be observed from Fig.15.
References


