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Modelling the evolution trajectory of COVID-19 in Wuhan, China: experience and suggestions

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ABSTRACT

Objectives: In December 2019, a novel coronavirus disease (COVID-19) emerged in Wuhan city, China, which has subsequently led to a global pandemic. At the time of writing, COVID-19 in Wuhan appears to be in the final phase and under control. However, many other countries, especially the US, Italy and Spain, are still in the early phases and dealing with increasing cases every day. Therefore, this article aims to summarise and share the experience of controlling the spread of COVID-19 in Wuhan and provide effective suggestions to enable other countries to save lives.
Study design: Data from the National Health Commission of China are used to investigate the evolution trajectory of COVID-19 in Wuhan and discuss the impacts of the intervention strategies.
Methods: A four-stage modified Susceptible-Exposed-Infectious-Removed (SEIR) model is presented. This model considers many influencing factors, including chunyun (the Spring festival), sealing off the city and constructing the Fangcang shelter hospitals. In addition, a novel method is proposed to address the abnormal data on 12–13 February as a result of changing diagnostic criteria. Four different scenarios are considered to capture different intervention measures in practice. The exposed population in Wuhan who moved out before sealing off the city have also been identified, and an analysis on where they had gone was performed using the Baidu Migration Index.
Results: The results demonstrate that the four-stage model was effective in forecasting the peak, size and duration of COVID-19. We found that the combined intervention measures are the only effective way to control the spread and not a single one of them can be omitted. We estimate that England will be another epicentre owing to its incorrect response at the initial stages of COVID-19. Fortunately, big data technology can help provide early warnings to new areas of the pandemic.
Conclusions: The four-stage SEIR model was effective in capturing the evolution trajectory of COVID-19. Based on the model analysis, several effective suggestions are proposed to prevent and control the pandemic for countries that are still in the initial phases.

Introduction

In December 2019, there was an outbreak of pneumonia of unknown cause in Wuhan, the capital city of Hubei province in China, with an initial epidemiological link to the local Huanan Seafood Wholesale Market, where there was also the sale of live animals. On 12 February 2020, the World Health Organization named this new coronavirus COVID-19.[1] To date (18th April 2020, 11:00 am Beijing time), COVID-19 has spread to more than 200 countries around the world, with 84,180 confirmed cases in China and 2,162,470 outside of China. Meanwhile, 4642 and 149,167 deaths have been reported in and outside of China, respectively.[2]

The Chinese government took rapid public health measures, including intensive surveillance, epidemiological investigations and closure of the Huanan Seafood Wholesale Market, at the beginning of the COVID-19 outbreak.[3] However, the authorities soon found that these measures were not sufficient to control the spread of the epidemic. The annual period of mass migration for the

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Spring festival holidays (chunyun) was also fast approaching. To mitigate the spread of COVID-19, the Chinese government implemented unprecedented intervention strategies. The authorities sealed off Wuhan city and several nearby cities on the morning of 23 January 2020 (09:00 am Beijing time). Millions of people were required to stay home until further notice. More than 40,000 medical staff members, including doctors and nurses, and countless medical supplies were sent to Hubei province from other provinces/regions of the country. Moreover, the government decided to extend the national holiday, adopt strict measures to limit travel and public gatherings, close all public places of entertainment and implement rigorous temperature monitoring nationwide.[4] Although there were several criticisms declaring that China was over-reacting to the outbreak, these measures had a significant impact on mitigating the spread of COVID-19.

The outbreak of COVID-19 brings back memories of severe acute respiratory syndrome (SARS) in 2003 and Middle East respiratory syndrome (MERS) in 2012.[5] SARS infected more than 8000 people and resulted in 800 deaths in more than 37 countries, while MERS caused 2494 infections and 858 deaths, with the majority of them in the Kingdom of Saudi Arabia (2073 cases and 772 deaths).[6] All three of these epidemics are zoonotic viruses and epidemiologically similar. The difference is that COVID-19 seems to be more infectious. To date, COVID-19 in China is now in the final stages of the epidemic because no additional new local cases have been reported since 20 March 2020. However, the situations in other countries are totally different, especially in the US, Italy, Spain, Germany, France, England, Iran and South Korea.

In this study, a four-stage modified Susceptible-Exposed-Infectious-Removed (SEIR) model is presented to capture the evolution trajectory of COVID-19 in Wuhan, China. This will show how the intervention measures implemented by the government in China have impacted the development of the COVID-19 epidemic in Wuhan. Moreover, we want to share the experiences and lessons learned from Wuhan and thus provide effective policy suggestions for other countries.

Methods

Model assumptions

Fig. 1 illustrates our modified SEIR model. We assume that all people who 'move in' to Wuhan are susceptible (S_{in}).[7] However, we suppose that people who 'move out' from Wuhan include both the susceptible (S_{out}) and the exposed (E_{out}). We further assume that the exposed people are asymptomatic but infectious.[1] Therefore, we have two propagation coefficients between the compartments S and E. We assume all infected individuals seeking treatment are hospitalised based on the availability of space in the hospitals (I_h). We suppose that the hospitalised people are quarantined and cannot infect people outside the hospital again. We also assume that individuals who are not hospitalised (I_o) will remain in the community and spread the disease further.[8] Finally, the removed individuals include two components, the recovered people (R_r) and the death cases (R_d). The detail of our modified SEIR model is shown in the online supplementary file material.[9,10,11]

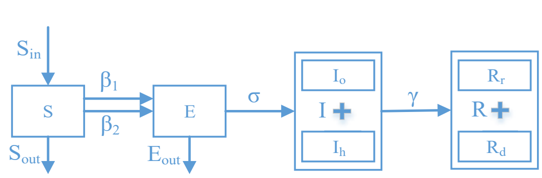

Fig. 1. Schematic diagram of the Susceptible-Exposed-Infectious-Removed (SEIR) model.

Data sources and parameter estimates

All the epidemiological data related to COVID-19 are based on daily reports from the website of the National Health Commission of China.[12] We estimate the transmission rate $\beta_1 = \beta_2 = 0.2225$.[4] As the incubation period of COVID-19 has been reported to be between two and 14 days, we chose the midpoint of 8 days, and thus, we have $\sigma = 1/8$. Similarly, $1/\gamma$ is the average treatment time that has been reported to be 10 days. We suppose that $\gamma = 1/10$. The total number of people at the first stage is 14 million; this number declines to nine million at the third stage. The number of people who move in and move out is obtained from the Baidu website.[13] The proportion of infected people who are not hospitalised $\lambda(t)$ is dependent on the number of quarantined beds at time t (the number of quarantined beds is reported daily on the website of the Health Commission of Hubei province).[14] Moreover, we assume that each infected person has contacted 10 susceptible people before he/she is quarantined.[15]

Results

Data process

The new confirmed cases on the 12th and 13th of February increased significantly in Wuhan when compared with the previous day (1104 new cases on 11 February; 13,436 on 12 February and 3910 on 13 February) as a result of changes to the diagnostic criteria. The sudden increase in new confirmed cases poses a disruption to accurately forecast the evolution trajectory of the epidemic. To address this problem, we apportion the newly added clinical diagnosis cases on the 12th and 13th February to the previous 14 days (including 12–13 February) based on the longest incubation period. The result is illustrated in Table 1. The adjustment principle uses a weighted moving average method, a widely used forecasting method, in reflection of a fundamental forecast principle that the more recent data are more reliable.

Model validation

The predicted data were validated against the actual outbreak data in terms of the number of infected individuals on these days (from 8 December 2019 to 14 March 2020),[8] which contains 98

Table 1
The new confirmed cases before and after adjustment.

Date	No. of newly confirmed cases	
	Before	After
31/1/2020	576	710
1/2/2020	894	1161
2/2/2020	1033	1434
3/2/2020	1242	1777
4/2/2020	1967	2635
5/2/2020	1766	2568
6/2/2020	1501	2436
7/2/2020	1985	3054
8/2/2020	1379	2582
9/2/2020	1920	3256
10/2/2020	1552	3022
11/2/2020	1104	2708
12/2/2020	13,436	2810
13/2/2020	3910	4113

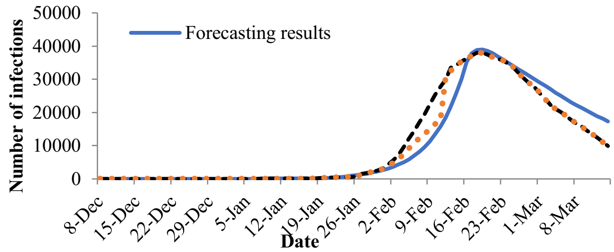

Fig. 2. Comparison of the number of infected cases in Wuhan. The dotted orange line is the official report data, while the dashed black line represents the approximate real data. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

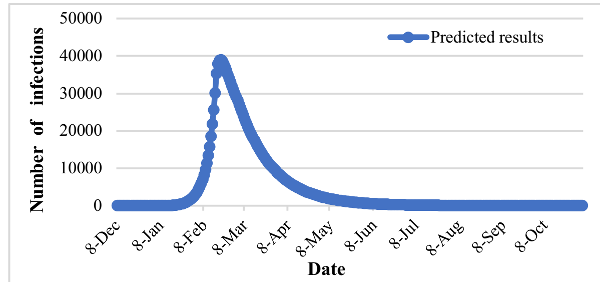

Fig. 3. Number of infections predicted for Wuhan.

time-series data points. After data processing, there is also an approximation of real data for the epidemic in Wuhan.

Fig. 2 shows that the predicted data are almost the same as the actual data at the first 45 time-series data points. Subsequently, the forecasting results show a slight underestimation from 18th January to 16th February, followed by a marginal overestimation compared with the actual outbreak data. The forecasted peak period ranges from 18 to 23 February, which is exactly the same as the actual data. During that period, there were between 37,000 and 39,000 active infective patients in Wuhan. The paired *t*-test results in Table 2 prove that our model provides statistically similar results with respect to the outbreak data for the time period. Because all *P*-values are greater than 0.05, it illustrates that there is no significant difference among the predicted data, the approximate real data and the actual outbreak data. Therefore, our model provides a good fit for the number of infected individuals in the affected area.

Forecasting result

Fig. 3 provides the forecasted number of infected individuals in Wuhan in the next few months. With the strengthening of intervention measures and the improvement of people's awareness, the number of confirmed cases in Wuhan will approach zero in June; this is totally different from estimations in the existing literature.[16,17,18] Actually, owing to continuous improvement in the medical environment, the time for clearing the confirmed cases may be further ahead.

Discussion

Impact of different interventions

To compare the effectiveness of different interventions, four scenarios were created. The first intervention measure was to seal off the city of Wuhan. All departure routes from Wuhan were closed, including planes, trains, ships and road traffic. People were isolated in their homes, thus reducing exposure to the environment and contact with others. All public places of entertainment, such as restaurants, bars and cinemas, were closed to limit public gatherings. The second intervention measure was to provide enough medical resources, including doctors, nurses, drugs, masks, protective clothing, ventilators and sufficient isolated rooms and beds. The third intervention was the combination of interventions one and two (i.e., sealing off the city and providing enough medical support, simultaneously). Finally, the fourth scenario was an assumption that the authorities did nothing to control the epidemic. Results are presented in Fig. 4.

The results show that if the only intervention implemented was to seal off the city of Wuhan with limited medical resources, the peak time of the epidemic would be delayed to the end of May, and more than 270,000 people would be infected during the peak period. In addition, the outbreak would last until the end of this year. This result has great implications for Italy, Iran and other countries that have limited medical resources. These countries should prepare for a long-term battle to eliminate COVID-19.

However, if the Chinese government did not seal off Wuhan city but simply provide enough medical support, the situation would be a little better. It can be seen that the peak time of the epidemic would also be delayed to May and the maximum number of cases would reach approximately 170,000. This finding may be important for some developed countries, such as Germany and Japan, that have abundant medical resources, but they may still pay a heavy price for the epidemic spread.

When these two intervention measures are combined, it can be seen that the scale of the epidemic would be greatly compressed and the peak period is much earlier. Results show that the maximum number of cases is no more than 40,000 in this combined scenario. In addition, the peak period of the epidemic was in the middle of February. This predicted result is quite consistent with the real situation that was seen in Wuhan. Similarly, we consider that the combined interventions in Wuhan bring great inspiration to South Korea. The COVID-19 epidemic in South Korea also grew rapidly at the beginning; however, after implementing a similar combined measure, the growth trend was well controlled.

Finally, if no interventions were implemented, the results show that the peak period of the epidemic would be at the end of April. In

Table 2
Statistical test of our predicted data and outbreak data.

Comparison	Mean		Paired *t*-test	
Test 1	Forecasting result	Approximate real data	t-stat	*P*-value
	10,332	10,609	−0.1427	0.8867
Test 2	Forecasting result	Official report data	t-stat	*P*-value
	10,332	10,108	0.1165	0.9074
Test 3	Approximate real data	Official report data	t-stat	*P*-value
	10,609	10,108	0.2607	0.7946

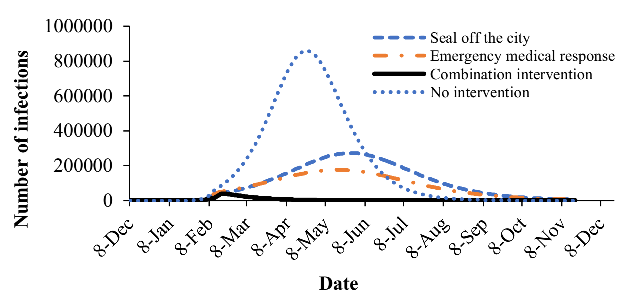

Fig. 4. Number of infections with different interventions.

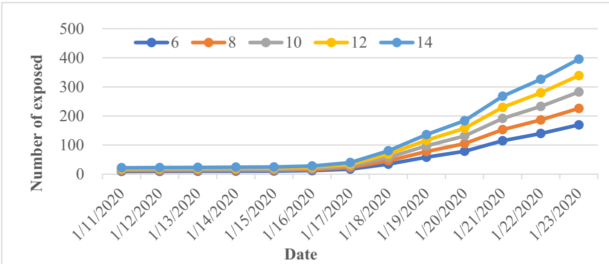

Fig. 5. Number of exposed people to move out of Wuhan before the city was sealed off. Key represents the average contact number for an infected individual (ranging from six to 14).

such a scenario, millions of people would be infected with COVID-19 and the maximum number of cases could be more than 850,000 in Wuhan. Think about that, no city in any country has such a strong medical capacity to deal with such a serious situation. Owing to incorrect responses at the initial stage, unfortunately, we estimate that England will be another epicentre in future weeks.

Impact of the move-out population

Fig. 5 demonstrates sensitivity analysis for the number of exposed people who moved out of Wuhan before the city was sealed off. It can be seen that when the average contact number of an infected individual increases from six to 14, more and more potential patients leave Wuhan during the period of chunyun (Spring festival).

To effectively control the spread of the epidemic, it is important to find out where these exposed population who left Wuhan have gone. The Baidu Migration Index can help identify the outflow directions of the potential patients through location-based service (LBS) data from millions of mobile phones.[13] Table 3 demonstrates that infected patients from Wuhan travel to other provinces all over the country. In total, 67.43% went to cities in the local Hubei province, the most popular being Xiaogan, Huanggang and Xianning (11.53%, 9.91% and 5.84%, respectively). As expected, these cities became the most severely affected areas of the COVID-19 epidemic, after Wuhan. The remaining 32.75% of the move-out population travelled to 30 other provinces around China, including Hong Kong, Macao and Taiwan. Among them, Henan, Hunan and Anhui were the three most popular areas because these provinces are neighboured with Hubei province. Not surprisingly, these provinces were also severely impacted by the COVID-19 epidemic.

A similar situation is occurring in Europe. Lombardy is another 'Wuhan' city in Italy, while the other states in Italy can be similarly addressed as the other cities in Hubei province. Similarly, other countries in Europe can be treated as the other provinces in China. Therefore, it can be found that all countries around Italy, without exception, have been submerged by the epidemic.

Table 3
Statistical result of the move-out population on Jan 11–23.

Risk ranking	In Hubei province		Out of Hubei province	
	Total	67.43%	Total	32.57%
	City	Percent	Province	Percent
1	Xiaogan	11.53%	Henan	4.92%
2	Huanggang	9.91%	Hunan	3.59%
3	Xianning	5.84%	Anhui	2.26%
4	Jingzhou	5.75%	Guangdong	2.22%
5	Ezhou	5.72%	Jiangxi	2.15%
6	Huangshi	4.37%	Jiangsu	1.78%
7	Xiangyang	3.34%	Zhejiang	1.38%
8	Yichang	2.67%	Sichuan	1.28%
9	Jingmen	2.52%	Chongqing	1.20%
10	Suizhou	2.19%	Beijing	1.16%
11	Xiantao	2.16%	Shandong	1.12%
12	Shiyan	1.78%	Hebei	0.99%
13	Enshi	1.49%	Guangxi	0.98%
14	Tianmen	1.26%	Shanghai	0.97%
15	Qianjiang	1.03%	Fujian	0.87%

Table 4
Estimation of the basic reproduction number R0.

T_g	ρ	$Y(t)$	t	R_0
10	0.65	41	34 (Jan 10)	2.343
9	0.65	1575	47 (Jan 23)	2.827

Estimation of the basic reproduction number (R0)

An important parameter in the epidemic model is the basic reproduction number (R0), which is the estimation number of secondary cases caused by an infectious person. This parameter determines the infectivity of the virus at the beginning, when there is an unexpected epidemic outbreak. According to the equation of R0,[17] we assume that $\rho = 0.65$ and further give the range of T_g to be $[8, 10]$. We use 8 December 2019 as the first day. The test results are shown in Table 4. We find that R0 is in the range of [2.3, 2.9]. Actually, chunyun may result in an increase of R0 value because an infectious person may have more opportunities to contact susceptible people during these days. Overall, the results are consistent with most early reports, which are illustrated in Table 5.

Conclusion

In this article, a modified SEIR model is presented to capture the evolution trajectory of the COVID-19 in Wuhan, China. This model considers many actual influencing factors, including chunyun, sealing off the city and constructing Fangcang shelter hospitals, and a novel method is proposed to address the abnormal data on 12–13 February. The forecasting model was verified with official report data and the approximate real data. Results demonstrate that the four-stage model was effective in forecasting the peak, size and duration of the COVID-19 epidemic. Four different scenarios were investigated to capture different interventions in practice. In addition, the exposed population who moved out of Wuhan before the city was sealed off were analysed and the Baidu Migration Index was used to identify where they had travelled. Furthermore, the basic reproduction number of the epidemic was estimated. To the best of our knowledge, there are rare studies that can accurately simulate the spread of COVID-19. However, the test results demonstrate that our model has significant improvement from the existing literature. Thus, we provide several effective suggestions for other countries to control the COVID-19 epidemic, which are summarised as follows:

Table 5
R0 reported by different research teams at the early stage.

Source	Release time	R_0
WHO, 2020[1]	Jan 24,2020	1.4–2.5
Northeast University[9]	Jan 25,2020	3.6–4.1
Hong Kong University[9]	Jan 27,2020	1.93–2.13
University of Lancaster[9]	Jan 28,2020	3.13
Zhou et al., 2020[17]	Jan 28,2020	2.8–3.3
Zhao et al., 2020[18]	Jan 27,2020	2.24–3.58

(1) The combined intervention measures, including sealing off the affected area and providing enough medical support, are the only effective ways to control the epidemic spread, even if these methods seem traditional and outdated. The results also warn that not a single one of these two measures can be omitted.
(2) It is very important for susceptible people to protect themselves. Washing hands frequently can effectively reduce the infection rate. In addition, people in some areas should change their traditional concepts about wearing masks. Patients and healthy people should all wear masks to prevent infection by infected persons because droplet transmission, caused by sneezing, is one of the main ways for COVID-19 to spread.
(3) The general public should reach a consensus that early identification, reporting, isolation, diagnosis and treatment is the best and most effective way to contain the pneumonia caused by COVID-19. It is also an important measure taken by the country to fight the virus. Therefore, the authorities in some countries should change the current medical resource allocation strategy. It is also important to identify and treat patients in the early stages of COVID-19 as much as possible and not let them return home until completely recovered. Obviously, this will lead to a surge in demand for the isolated beds. Fangcang shelter hospitals were quickly constructed by reforming some large gyms; thus, the imbalance between supply and demand can be alleviated.
(4) Big data technology can help decision-makers to understand the number and direction of population migration and thus give early advance warnings to the most popular areas where people are travelling. LBS for mobile communication can help provide big data for population migration. It is important to implement strict control measures in the areas seeing large inflows of potentially infectious people to avoid further spread of the virus.
(5) It is necessary to establish a joint epidemic prevention and control mechanism to share related information. Different from natural disasters, prevention and control of infectious diseases needs more cooperative operations among different organisations. As an old Chinese saying goes, there is no one who can be alone in the face of disaster. This means that, if only one area does well while the others do not, the epidemic will continuously spread and finally the area that initially did well will be infected again. This is the core reason why China is willing to help other countries to fight COVID-19 as soon as it has recovered from the same epidemic.

Author statements

Ethical approval

None sought.

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Competing interests

None declared.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.puhe.2020.05.001.

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