Basic Reproduction Number of the 2019 Novel Coronavirus Disease in the Major Endemic Areas of China: A Latent Profile Analysis

Honglv Xu 1†, Yi Zhang 2,3†, Min Yuan 4, Liya Ma 2,3, Meng Liu 2,3, Hong Gan 2,3, Wenwen Liu 2,3, Gillian Gianna Anne Lum 5 and Fangbiao Tao 2,3,4*

1 School of Medicine, Kunming University, Kunming, China, 2 Key Laboratory of Population Health Across Life Cycle, Ministry of Education of the People’s Republic of China, Anhui Medical University, Hefei, China, 3 Department of Maternal, Child and Adolescent Health, School of Public Health, Anhui Medical University, Hefei, China, 4 School of Health Service Management, Center for Big Data Science in Health, Anhui Medical University, Hefei, China, 5 The Colonial War Memorial Hospital, Suva, Fiji

Objective: The aim of this study is to analyze the latent class of basic reproduction number ($R_0$) trends of the 2019 novel coronavirus disease (COVID-19) in the major endemic areas of China.

Methods: The provinces that reported more than 500 cases of COVID-19 till February 18, 2020 were selected as the major endemic areas. The Verhulst model was used to fit the growth rate of cumulative confirmed cases. The $R_0$ of COVID-19 was calculated using the parameters of severe acute respiratory syndrome (SARS) and COVID-19. The latent class of $R_0$ was analyzed using the latent profile analysis (LPA) model.

Results: The median $R_0$ calculated from the SARS and COVID-19 parameters were 1.84–3.18 and 1.74–2.91, respectively. The $R_0$ calculated from the SARS parameters was greater than that calculated from the COVID-19 parameters ($Z = -4.782$ to $-4.623$, $p < 0.01$). Both $R_0$ can be divided into three latent classes. The initial value of $R_0$ in class 1 (Shandong Province, Sichuan Province, and Chongqing Municipality) was relatively low and decreased slowly. The initial value of $R_0$ in class 2 (Anhui Province, Hunan Province, Jiangxi Province, Henan Province, Zhejiang Province, Guangdong Province, and Jiangsu Province) was relatively high and decreased rapidly. Moreover, the initial $R_0$ value of class 3 (Hubei Province) was in the range between that of classes 1 and 2, but the higher $R_0$ level lasted longer and decreased slowly.

Conclusion: The results indicated that the overall $R_0$ trend is decreased with the strengthening of comprehensive prevention and control measures of China for COVID-19, however, there are regional differences.

Keywords: 2019 novel coronavirus disease, basic reproduction number, latent categories, trends, epidemiology
INTRODUCTION

Of particular concern is the 2019 novel coronavirus disease (COVID-19) outbreak in Wuhan, Hubei province at the end of 2019, it is quickly spread to all over the country of China (1, 2). COVID-19 is an infectious disease caused by 2019-nCoV that can be transmitted through droplets, aerosols, and contact (3, 4). The main clinical features of the case are fever, dry cough, and fatigue. There are also mild features as well as asymptomatic pathogen carriers (5, 6). Evidence demonstrates that COVID-19 is extremely infectious even during the incubation period, and the entire population is susceptible (7, 8). It has a higher case-fatality rate and poses great threats to public health, and as a result it has attracted enormous concerns (9). According to previous studies, in the USA, the case-fatality rate for COVID-19 varies markedly by age, ranging from 0.3 death per 1,000 cases among patients aged from 5 to 17 years to 304.9 deaths per 1,000 cases among patients aged 85 years or older in the USA (10). Among the hospitalized patients in the intensive care units, the case fatality increases up to 40% (10). In addition, Yang et al. (9) reported that Wuhan had higher case fatality than other cities. Overall, a difference of the case-fatality rates was observed between different age groups, cities, and counties, at the rates more than 15% (11). At present, COVID-19 has become widespread around the globe (12, 13). For a new infectious disease, it is important to identify the epidemic characteristics and transmission dynamics of the disease, to implement appropriately for the prevention and control measures (14).

It is generally known that the basic reproduction number \( R_0 \) is an important parameter that studies the dynamics of infectious disease transmission by describing the ability to spread an infectious source (15, 16). \( R_0 \) is defined as the average number of secondary cases produced by an infected subject over his/her infectious period in a susceptible and an uninfected population (17). There has been an increasing concern that the \( R_0 \) of COVID-19 is used to assess the spread of infectious diseases, to predict epidemic trends and to evaluate the effectiveness of the prevention and control measures that have been established (18, 19). Although a few previous studies have investigated the \( R_0 \) of COVID-19, the results of these previous studies on the \( R_0 \) of COVID-19 were inconsistent (20–23). For instance, Wu et al. (20) used susceptible-exposed-infectious-recovered metapopulation model to analyze the confirmed cases from December 31, 2019 to January 28, 2020, the results reported that the \( R_0 \) of COVID-19 was 2.68 (95%CI: 2.47–2.86); Zhao et al. (21) used an intrinsic growth rate \( (\gamma) \) to the analyzed \( R_0 \) of the confirmed cases from January 10, 2020 to January 24, 2020, the results reported that the \( R_0 \) of COVID-19 was in the range of 2.24–3.58 (21). Moreover, there is no research to explore the variance in the \( R_0 \) of COVID-19 in the different regions of China. Consequently, this study analyzed the latent class of \( R_0 \) of COVID-19 in the major endemic areas of China that reported more than 500 cases. The results of this study can evaluate the effectiveness of the prevention and control measures of China against COVID-19 to a certain extent and provide a support for previously related studies and a reference for other countries to learn from the prevention and control measures of China. In addition, it provides a basis for further prevention and control of COVID-19 and other emerging infectious diseases.

MATERIALS AND METHODS

Materials

The major endemic areas of COVID-19 were defined as the areas where the cumulative number of cases of COVID-19 with more than 500 has been diagnosed within 24h on February 18, 2020. These areas include Guangdong Province, Jiangxi Province, Hunan Province, Chongqing Municipality, Sichuan Province, Hubei Province, Anhui Province, Zhejiang Province, Jiangsu Province, Henan Province, and Shandong Province. We collected the cumulative number of cases of COVID-19 from official health commission websites, with the data on the main prevention and control measures for COVID-19 within these areas and sourced from provincial government websites.

Methods

The Verhulst model was used to fit the growth rate of the cumulative number of cases (24, 25). The Verhulst curvilinear equation is as follows:

\[
y = \frac{a}{1 + \left(\frac{b}{c} - 1\right)e^{-cx}}
\]

where \( a, b, \) and \( c \) are the parameter constants and \( r \) is the growth rate. We calculated the \( R_0 \) of COVID-19 using the following equation (26):

\[
R_0 = \left(1 + r \times IP\right) \times \left(1 + r \times SI\right)
\]
the 75th percentile ($P_{75}$) to describe the distribution of $R_0$. The Wilcoxon signed-rank test was used to compare the differences of $R_0$ calculated from the COVID-19 parameter and the SARS parameter. A latent profile analysis (LPA) was used to analyze the latent class of the $R_0$ trend in the Mplus software.

RESULTS

The Trend of the Cumulative Number of Cases

Figure 1 shows the trend of the cumulative number of COVID-19. It shows an S-shaped growth. The Hubei Province has the
The largest cumulative number of cases and the fastest growth. The trends of the cumulative number of cases in several other provinces except the case of Hubei Province were observed in the phenomenon of classification. The number of cases in class 1 (Henan Province, Zhejiang Province, and Guangdong Province) was relatively large and has increased rapidly. The number of cases in class 2 (Anhui Province, Hunan Province, and Jiangxi Province) and the growth rate were at a medium level. The number of cases in class 3 (Shandong Province, Jiangsu Province, Sichuan Province, and Chongqing Municipality) and the growth rate were relatively low. In general, the major endemic areas except the case of Hubei Province of COVID-19 in China reached the highest peaks of the "S" curve around February 15, 2020.

**The Growth Rate Trend of the Cumulative Number of Cases**

The growth rate of the cumulative number of COVID-19 in Hubei Province is 0.03–0.20. Especially, the growth rate of 0.24 continued until January 26, 2020, whereas the growth rate of 0.23–0.22 continued until January 31, 2020. Then, the growth rate shows a clear downward trend in Hubei Province. The initial growth rates (0.25–0.32) of all other provinces except the cases of Chongqing Municipality, Sichuan Province, and Shandong Province (the growth rates were 0.14–0.20) were higher than those of Hubei Province, however, these rates started to decline rapidly after 2–3 days (Figure 2).

**The R0 Trend of COVID-19**

Table 1 shows the distribution of R0. The median R0 calculated from the SARS parameters is 1.84–3.18, and the R0 calculated from the COVID-19 parameters is 1.74–2.91. Overall, the former is greater than the latter (Z=−4.782 to −4.623, p < 0.01). Figure 3 shows the R0 trend collected from the COVID-19 and SARS parameters. The trends of R0 calculated from the two parameters are basically consistent. It showed a gradual downward trend of R0 in each province from January 20, 2020 to February 18, 2020. The R0 in Hubei Province showed a slow decline before January 31, 2020, then showing a significant downward trend. The initial R0 in all other provinces except the cases of Chongqing Municipality, Sichuan Province, and Shandong Province was higher than that of Hubei Province, however, but the declining rate of R0 in all other provinces...
TABLE 1 | The distribution of $R_0$ of 2019 novel coronavirus disease (COVID-19).

| Province   | $R_0$ from SARS parameters | $R_0$ from COVID-19 parameters | Z  | P    |
|------------|-----------------------------|--------------------------------|----|------|
|            | **Range** | **$P_{25}$** | **$P_{50}$** | **$P_{75}$** | **Range** | **$P_{25}$** | **$P_{50}$** | **$P_{75}$** |    |      |
| Hubei      | 1.23–3.87 | 1.90   | 3.18   | 3.76   | 1.20–3.51 | 1.80   | 2.91   | 3.41   | −4.782 | <0.01 |
| Guandong   | 1.02–4.48 | 1.16   | 2.13   | 3.93   | 1.02–4.04 | 1.15   | 2.00   | 3.56   | −4.782 | <0.01 |
| Sichuan    | 1.07–3.32 | 1.28   | 2.01   | 2.94   | 1.06–3.03 | 1.25   | 1.90   | 2.71   | −4.782 | <0.01 |
| Anhui      | 1.04–4.43 | 1.24   | 2.44   | 4.03   | 1.03–3.99 | 1.22   | 2.26   | 3.65   | −4.782 | <0.01 |
| Shandong   | 1.24–2.51 | 1.53   | 1.99   | 2.36   | 1.21–2.33 | 1.47   | 1.88   | 2.20   | −4.782 | <0.01 |
| Jiangxi    | 1.03–4.76 | 1.21   | 2.49   | 4.34   | 1.03–4.28 | 1.19   | 2.31   | 3.92   | −4.782 | <0.01 |
| Zhejiang   | 1.01–5.10 | 1.08   | 1.85   | 4.25   | 1.01–4.57 | 1.07   | 1.75   | 3.84   | −4.782 | <0.01 |
| Henan      | 1.03–4.51 | 1.19   | 2.19   | 3.96   | 1.03–4.06 | 1.17   | 2.05   | 3.59   | −4.703 | <0.01 |
| Hunan      | 1.02–4.43 | 1.15   | 2.00   | 3.78   | 1.02–4.00 | 1.13   | 1.88   | 3.43   | −4.703 | <0.01 |
| Chongqing  | 1.05–3.46 | 1.20   | 1.84   | 2.93   | 1.04–3.15 | 1.18   | 1.74   | 2.69   | −4.703 | <0.01 |
| Jiangsu    | 1.05–3.92 | 1.25   | 2.12   | 3.43   | 1.05–3.56 | 1.22   | 1.99   | 3.13   | −4.623 | <0.01 |

except the cases of Chongqing Municipality, Sichuan Province, and Shandong Province is higher than that of Hubei Province. As of February 18, 2020, except the cases of Hubei Province ($R_0 = 1.20$) and Shandong Province ($R_0 = 1.21$), $R_0$ (1.01–1.06) were approximately equal to 1 in all other provinces.

The Latent Class of $R_0$
We constructed five latent class models in the LPA. The three-class model was finally selected according to the model fitting index, latent class probability, and the interpretability of the model. Table 2 presents the fitting index and latent class probability of the model. There are three latent classes of the $R_0$ calculated from the SARS parameters and COVID-19 parameters. Class 1 includes Shandong Province, Sichuan Province, and Chongqing Municipality. Class 2 includes Anhui Province, Hunan Province, Jiangxi Province, Henan Province, Zhejiang Province, Guangdong Province, and Jiangsu Province. Class 3 includes Hubei Province. Figure 4 shows the $R_0$ trend in different latent classes. The initial value of class 1 $R_0$ was relatively low and decreased slowly. The initial value of class 2 $R_0$ was relatively high and decreased rapidly. The initial value of class 3 $R_0$ was in the range between classes 1 and 2, but high $R_0$ levels lasted longer and declined slowly.

DISCUSSION
The present study suggests that the $R_0$ of COVID-19 calculated from the SARS parameters is greater than the $R_0$ calculated from the COVID-19 parameters (the medians of $R_0$ are 1.84–3.18 and 1.74–2.91, respectively). Our findings may indicate that the epidemiological characteristics of COVID-19 and SARS are different. Coronavirus has caused three large-scale epidemics within the human population in the past 20 years, including SARS in 2002, Middle East respiratory syndrome (MERS) in 2012, and COVID-19 in 2019 (28, 29). From the number of infections, deaths, and endemic areas, COVID-19 threatens human health more than SARS and MERS (30–32). The $R_0$ of COVID-19 in our study is lower than that of SARS (3.1–4.2) and MERS (2.0–6.7) (17, 33, 34). These findings are consistent with previous studies, which also demonstrate that the infection capacity of COVID-19 is lower than that of SARS and MERS (23). Additionally, the $R_0$ calculated from the COVID-19 parameters in this work is similar to the $R_0$ (2.38–2.72 and 2.47–2.86) estimated in other studies in China (20, 35). In addition, it is also similar to the $R_0$ (2.4–2.8) of COVID-19 in Japan (36). Nevertheless, our calculated $R_0$ is lower than the estimated $R_0$ using the epidemic values observed in the early epidemic period of COVID-19 within Wuhan ($R_0 = 1.4–3.9$), Hubei Province ($R_0 = 2.80–4.48$), and China as a whole (2.8–3.3) (23, 37).

Overall, the $R_0$ of COVID-19 in each province is gradually decreasing. It is believed that the combined prevention and control measures adopted for COVID-19 by the Chinese government have brought about these obvious effects. We believe these combined prevention and control measures for COVID-19, which are put in place by the Chinese Government, can provide a reference for other countries in their fight against the deadly virus. These measures include activating first-level public health emergency response, wearing masks, conducting epidemiological investigations, screening of key populations, temporary traffic control, closing public places (e.g., cinemas, internet cafe, etc.), monitoring body temperature, symptom screening, medical observation, the “four early” measures (early detection, early reporting, early isolation, and early treatment), the “four concentrated” treatment measures (concentrated cases, concentrated experts, concentrated resources, and concentrated treatment), quarantine oneself, lockdown a city, disinfection in public areas, etc. There is substantial evidence that implementing these combined measures could significantly reduce the number of cases found within a country (38, 39). A study conducted in Singapore showed that these combined interventions will reduce the estimated number of infections in comparison with the baseline scenario by 99.3%, 93.0%, and 78.2% when $R_0$ was 1.5, 2.0, and 2.5, respectively (39). Some researchers suggest that the isolation of cases, contact tracing, and social distancing can control outbreaks of infectious diseases (38). Specifically, contact tracing is believed to be a key factor in reducing the spread of the epidemic. A new study from the UK suggests that to control the...
FIGURE 3 | The $R_0$ trend from COVID-19 and SARS parameters. (A) Cumulative number of COVID-19 in each province; (B) Cumulative number of COVID-19 everyday.
The majority of COVID-19 outbreaks, for an $R_0$ of 3.5 more than 90% of the contacts had to be traced, and for an $R_0$ of 2.5 more than 70% of the contacts had to be traced (40).

The results of the LPA reported that there are three latent classes of $R_0$, and the trends of $R_0$ in each latent class have their own unique characteristics. The observed findings indicate that although the Chinese government has adopted the overall prevention and control measures of "a board of chess in China, suit one's measures to local conditions," the effects are not entirely consistent. Specifically, the initial value of $R_0$ in class 1 was relatively low and had a slow decline. The possible explanations are that these areas have taken active measures after the COVID-19 epidemic in Wuhan, and the spread of COVID-19 was well controlled from the beginning. The initial $R_0$ value in class 2 was relatively high and was even higher than that of Hubei Province. However, $R_0$ declined rapidly, and the decline rate was the fastest among the three latent classes. The possible reason is that the measures adopted at the beginning of the epidemic of COVID-19 were not effective. Then, the epidemic was effectively controlled after quickly adjusting the measures in these areas, thus the infection capacity of COVID-19 decreased rapidly. The initial $R_0$ value in class 3 (Hubei Province) was observed to be between that of types 1 and 2, but this higher $R_0$ level lasted longer and decreased slowly. Wuhan city, Hubei Province, is the first area in China where COVID-19 was found to be endemic. Due to the lack of understanding of the emerging infectious disease pathogens, transmission routes, susceptible populations, disease characteristics, epidemic characteristics, and other unknown reasons, the $R_0$ of COVID-19 lasted longer at higher levels in Hubei Province. In other words, before January 31, 2020, Hubei Province COVID-19 was strongly infective. Therefore, our findings agree that the adoption of active prevention and control measures at the beginning of the epidemic can effectively control the spread of COVID-19.

What is more, the $R_0$ of COVID-19 in Hubei Province and Shandong Province were approximately 1.2 by February 18, 2020, presenting that there is still a certain risk of transmission within these provinces. The $R_0$ (1.01–1.06) in other provinces were approximately equal to 1 or greater than 1. It is widely recognized that $R_0$ can reflect the endemic trend of infectious diseases. When $R_0 > 1$, the greater the $R_0$, the greater the infectious ability of these diseases, and the greater the number of cases. When $R_0 < 1$, it means that the epidemic of infectious diseases will gradually come to an end. The optimal target of effective interventions is to control the $R_0$ at a value $< 1$ (41). At present, because the population of China has gradually resumed work and school, population movement and crowd accumulation make it difficult to properly implement prevention and control measures, which ultimately increase the risks of COVID-19 transmissions within the country and also the difficulty of prevention and control. Furthermore, COVID-19 is an epidemic that has spread to many countries around the world, with international import cases giving rise to the possibility of a secondary epidemic (42, 43). Consequently, China also needs to continue to strengthen its prevention and control for COVID-19.

In this study, the $R_0$ of COVID-19 was simulated by searching the confirmed cases and objective case data from the provinces closely related to Hubei Province (such as provinces with major transportation hubs and provinces with migrant workers moving within them) and to combine the methods mentioned in previous studies with the latent category method. The results of the three categories also show that the population distribution and economic conditions of different cities (20) also determine the infection rate and transmission rate of COVID-19. Despite the identification of human-to-human transmission and the reporting of exponential increases in the number of cases, forecasting is critical for national and international public health planning and control. At present, there is no good treatment available, however, timely understanding of the prevalence of COVID-19 with public awareness on preventative measures will help. Our study can provide the government with a more comprehensive chart of the epidemic trend and corresponding measures, and also provide side information for the storage of medical resources and clinical diagnosis and treatment. In China, COVID-19 in the regions other than Hubei Province showed a substantial control of the virus transmission rates. However, the possibility of imported infection and transmission was higher than before, in addition, because, at the time of this work, there was neither a vaccine nor a specific drug treatment for COVID-19, a range of public health (non-pharmaceutical) interventions has been used to control the epidemic (44).

| $R_0$ from SARS parameters | Model | AIC | BIC | aBIC | Entropy | Class probability (%) |
|---------------------------|-------|-----|-----|------|---------|------------------------|
| 1                         | 317.51| 341.38| 160.72| -     | 1         |
| 2                         | 72.44 | 106.65| -165.35| 1.00  | 18.2/81.8 |
| 3                         | -92.09| -43.55| -410.89| 1.00  | 27.3/63.9/9.1 |
| 4                         | -30.09| 30.79 | -429.90| 1.00  | 27.3/31.8/31.8/9.1 |
| 5                         | -83.25| -10.04| -664.06| 1.00  | 18.2/27.3/36.4/9.1/9.1 |

| $R_0$ from COVID-19 parameters | Model | AIC | BIC | aBIC | Entropy | Class probability (%) |
|-------------------------------|-------|-----|-----|------|---------|------------------------|
| 1                             | 229.47| 253.35| 72.69| -     | 1         |
| 2                             | -16.12| 20.09 | -253.91| 1.00  | 18.2/81.8 |
| 3                             | -181.98| -133.43| -500.78| 1.00  | 27.3/63.9/9.1 |
| 4                             | -119.98| -59.10| -519.78| 1.00  | 27.3/63.6/4.5/4.5 |
| 5                             | -149.15| -75.9 | -629.96| 1.00  | 0/27.3/36.4/27.3/9.1 |
FIGURE 4 | The latent class of $R_0$ from COVID-19 and SARS parameters. (A) $R_0$ from COVID-19 parameters everyday; (B) $R_0$ from SARS parameters everyday.
The present study has several strengths and limitations. The main strength of this work was to calculate the $R_0$ based on the epidemic data of major endemic areas of China as of February 18, 2020. However, previous research on $R_0$ was mostly predicted and estimated based on the limited epidemiological data of COVID-19 in Wuhan in the early days. Another strength was an analysis of the latent class of $R_0$ and explored the regional differences in prevention and control effects. The findings presented in this study have implications for the preliminary evaluation of the effectiveness of prevention and control measures for COVID-19 adopted in China. In addition, the research results can provide knowledge for other countries on how to respond to COVID-19, and also provide a support for previous prediction studies. There are several limitations to our study. Firstly, the calculation of $R_0$ was affected by multiple parameters and various factors (41). And yet, the factors considered are relatively single in this study. Additional research is necessary to confirm the accuracy of $R_0$, considering the large uncertainties around the estimates of $R_0$ and the duration of infectiousness (45, 46). Secondly, there are many methods for calculating $R_0$ in the world (18), but this study did not use multiple methods to compare the results. In the susceptible-exposed-infected-removed model, the $R_0$ of COVID-19 was a little higher than that of SARS (23). Wang et al. (37) used the exponential growth method to estimate $R_0$, the results showed that the $R_0$ of COVID-19 was 2.95 (95% CI: 2.86–3.03) after taking control measures. One study used a susceptible-exposed-infected-removed metapopulation model to simulate the $R_0$ for COVID-19, which was 2.68 (95% CI: 2.47–2.86) (20). In our study, we choose a new-structure gray Verhulst model that has a better structure and stronger modeling ability; overcoming the shortcomings of traditional Verhulst model, including parameter dislocation and unreasonable selection of initial values. We used another method to supplement the previous study, which laterally validated and supplemented the previous results. However, it should be noted that if other methods are used to calculate $R_0$ in this study, the results may be different. Thirdly, although this study discusses the prevention and control measures for COVID-19 in the major endemic areas of China, it is difficult to quantitatively evaluate the effects of various measures.

**CONCLUSION**

Overall, we found that the $R_0$ of COVID-19 shows a downward trend in the major endemic areas of China, and there are regional differences (three latent classes). Actively adoption of combined prevention and control measures in the early stages of the epidemic can effectively control COVID-19.

**DATA AVAILABILITY STATEMENT**

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/Supplementary Material.

**ETHICS STATEMENT**

Ethical approval was not required as this study is an analysis of public case data. The patients/participants provided their written informed consent to participate in this study.

**AUTHOR CONTRIBUTIONS**

FT designed the study. HX took primary responsibility for writing the manuscript, managed the literature searches and analyses, and undertook the statistical analysis. MY, LM, ML, YZ, WL, and HG undertook the acquisition of the data. YZ revised the manuscript. GL edited the English Version of this manuscript. All authors contributed to and approved the final manuscript.

**FUNDING**

This work was supported by the Anhui Medical University Emergency Key Research Project for Novel Coronavirus Pneumonia (YJGG2020001) and Emergency Research Project, Anhui Provincial Department of Science and Technology, Anhui Provincial Health Commission (202004a07020002).

**ACKNOWLEDGMENTS**

This manuscript has been released as a pre-print at medRxiv (https://doi.org/10.1101/2020.04.13.20060228).

**SUPPLEMENTARY MATERIAL**

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpubh.2021.575315/full#supplementary-material

**REFERENCES**

1. Liu K, Fang YY, Deng Y, Liu W, Wang MF, Ma JP, et al. Clinical characteristics of novel coronavirus cases in tertiary hospitals in Hubei Province. Chin Med J. (2020) 133:1025-31. doi: 10.1097/CM9.0000000000007744

2. Lu R, Zhao X, Li J, Niu P, Yang B, Wu H, et al. Genomic characterisation and epidemiology of 2019 novel coronavirus: implications for virus origins and receptor binding. Lancet. (2020) 395:565-74. doi: 10.1016/S0140-6736(20)30251-8

3. Chen N, Zhou M, Dong X, Qu J, Gong F, Han Y, et al. Epidemiological and clinical characteristics of 99 cases of 2019 novel coronavirus pneumonia in Wuhan, China: a descriptive study. Lancet. (2020) 395:507–13. doi: 10.1016/S0140-6736(20)30211-7

4. Li YI, You Z, Wang Q, Zhou ZJ, Qiu Y, Luo R, et al. The epidemic of 2019-novel coronavirus (2019-nCoV) pneumonia and insights for emerging infectious diseases in the future. Microbes Infect. (2020) 22:80-8. doi: 10.1016/j.micinf.2020.02.002
5. Guo YR, Cao QD, Hong ZS, Tan Y, Chen SD, Jin HJ, et al. The origin, transmission and clinical therapies on coronavirus disease 2019 (COVID-19) outbreak - an update on the status. Mil Med Res. (2020) 7:11. doi: 10.1186/s40779-020-00240-0

6. Huang C, Wang Y, Li X, Ren L, Zhao J, Hu Y, et al. Clinical features of patients infected with 2019 novel coronavirus in Wuhu, China. Lancet. (2020) 395:497–506. doi: 10.1016/S0140-6736(20)30183-5

7. Nishiura H, Linton NM, Akhmetzhanov AR. Serial interval of novel coronavirus (COVID-19) infections. Int J Infect Dis. (2020) 93:284–6. doi: 10.10110/2020.02.03.20019497

8. Thompson RN. Novel coronavirus outbreak in Wuhan, China, 2020: intense surveillance is vital for preventing sustained transmission in new locations. J Clin Med. (2020) 9:498. doi: 10.3390/jcm9020498

9. Yang S, Cao P, Du P, Wu Z, Zhuang Z, Yang L, et al. Early estimation of the case fatality rate of COVID-19 in mainland China: a data-driven analysis. Ann Transl Med. (2020) 8:128. doi: 10.21037/atm.2020.02.66

10. Wiersinga WI, Rhodes A, Cheng AC, Peacock SJ, Prescott HC. Pathophysiology, transmission, diagnosis, and treatment of coronavirus disease 2019 (COVID-19): a review. JAMA. (2020) 324:782–93. doi: 10.001/jama.2020.12839

11. Bulut C, Kato Y. Epidemiology of COVID-19. Turkish J Med Sci. (2020) 50:56–70. doi: 10.3906/sag-2004-172

12. Sommer P, Lukovic E, Fagley E, Long D, Sobol J, Heller K, et al. Epidemiology of COVID-19. Turkish J Med Sci. (2020) 50:563–70. doi: 10.3906/sag-2004-172

13. Ganyani T, Faes C, Chowell G, Hens N. Assessing inference of the basic reproduction number in an SIR model incorporating a growth-scaling parameter. Stat Med. (2018) 37:4490–506. doi: 10.1002/sim.7935

14. Sato K. Basic reproduction number of SEIRS model on regular lattice. Math Biosci Eng. (2019) 16:6708–27. doi: 10.3934/mbe.2019335

15. Chang HJ. Estimation of basic reproduction number of the Middle East respiratory syndrome coronavirus (MERS-CoV) during the outbreak in South Korea, (2015). Biomed Eng Online. (2017) 16:79. doi: 10.1186/s12938-017-0370-7

16. Chowell G, Nishiura H, Bettencourt LM. Comparative estimation of the reproduction number for pandemic influenza from daily case notification data. Eur Rev Med Pharmacol Sci. (2020) 24:2006–11. doi: 10.26355/eurrev_202002_20378

17. Delameter PL, Street EJ, Leslie TF, Yang YT, Jacobsen KH. Complexity and interventions to mitigate early spread of SARS-CoV-2 in Singapore: a modelling study. Interventions to mitigate early spread of SARS-CoV-2 in Singapore: a modelling study. Lancet Infect Dis. (2020) 20:678-88. doi: 10.1016/S1473-3099(20)30129-8

18. Koo JR, Cook AR, Park M, Sun Y, Sun H, Lim JT, et al. Analysis of the role of current prevention and control measures in the epidemic of new coronavirus based on the SEIR model. J Int J Infect Dis. (2020) 92:214–7. doi: 10.1093/aje/kwab55

19. Wilder-Smith A, Chiew CJ, Lee VJ. Can we contain the COVID-19 outbreak with the same measures as for SARS? Lancet Infect Dis. (2020) 20:102-7. doi: 10.1016/S1473-3099(20)30129-8

20. Wallinga J, Teunis P. Different epidemic curves for severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) and coronavirus disease-2019 (COVID-19): the epidemic and the challenges. Interventions to mitigate early spread of SARS-CoV-2 in Singapore: a modelling study. Lancet Infect Dis. (2020) 92:214–7. doi: 10.1093/aje/kwab55

21. Majumder MS, Rivers C, Lofgren E, Fisman D. Estimating MERS-corona virus reproductive number and case fatality rate for the spring 2014 Saudi Arabia outbreak: insights from publicly available data. PLoS Curr. (2014) 6:1–11.

22. Geng H, Xu A, Wang X, Zhang Y, Yin X, Ma M, et al. Analysis of the role of current prevention and control measures in the epidemic of new coronavirus based on the SEIR model. J Int J Infect Dis. (2020) 92:214–7. doi: 10.1093/aje/kwab55

23. Kuniya T. Prediction of the epidemic peak of coronavirus disease in Japan, (2020). J Clin Med. (2020) 9:789. doi: 10.3390/jcm9030789

24. Wang Y, You XY, Wang YJ, Peng LP, Du ZC, Gilmour S, et al. Estimating the basic reproduction number of COVID-19 in Wuhan, China. Chin J Epidemiol. (2020) 41:476–9. doi: 10.3760/cma.j.cn112338-20200210-00086

25. Anderson RM, Heesterbeek H, Klinkenberg D, Hollingsworth TD. How will country-based mitigation measures influence the course of the COVID-19 epidemic? Lancet. (2020) 395:931–4. doi: 10.1016/S0140-6736(20)30567-5

26. Koo JR, Cook AR, Park M, Sun Y, Sun H, Lim JT, et al. Interventions to mitigate early spread of SARS-CoV-2 in Singapore: a modelling study. Lancet Infect Dis. (2020) 20:678-88. doi: 10.1016/S1473-3099(20)30126-2

27. Hellewell J, Abbott S, Gimma A, Bosse NI, Jarvis C, Russell TW, et al. Feasibility of controlling COVID-19 outbreaks by isolation of cases and contacts. Lancet Glob Health. (2020) 8:e488–96. doi: 10.1016/S2214-093X(20)30074-7

28. Delamater PL, Street EJ, Leslie TF, Yang YT, Jacobsen KH. Complexity of the basic reproduction number (R0). Emerg Infect Dis. (2019) 25:1–4. doi: 10.3201/eid2501.171901

29. Lai CC, Shih TP, Ko WC, Tang HJ, Hsueh PR. Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) and coronavirus disease-2019 (COVID-19): the epidemic and the challenges. Int J Antimicrob Agents. (2020) 55:105924. doi: 10.1016/j.ijantimicag.2020.105924

30. Palacios CM, Santos E, Velazquez CM, Leon JM. COVID-19, a worldwide public health emergency. Rev Clin Esp. (2020) 221:55-61. doi: 10.1016/j.rce.2020.03.001

31. Tian H, Liu Y, Li Y, Wu CH, Chen B, Kraemer M, et al. An investigation of transmission control measures during the first 50 days of the COVID-19 epidemic in China. Science. (2020) 368:638–42. doi: 10.1126/science.abb6105
45. Rebuli NP, Bean NG, Ross JV. Estimating the basic reproductive number during the early stages of an emerging epidemic. *Theor Popul Biol.* (2018) 119:26–36. doi: 10.1016/j.tpb.2017.10.004

46. Prem K, Liu Y, Russell TW, Kucharski AJ, Eggo RM, Davies N, et al. The effect of control strategies to reduce social mixing on outcomes of the COVID-19 epidemic in Wuhan, China: a modelling study. *Lancet Public Health.* (2020) 5:e261-70. doi: 10.1016/S2468-2667(20)30073-6

**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

**Publisher’s Note:** All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

*Copyright © 2021 Xu, Zhang, Yuan, Ma, Liu, Gan, Liu, Lum and Tao. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.*