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Received: 17 March 2020 | Accepted: 31 March 2020

DOI: 10.1002/jmv.25827

RESEARCH ARTICLE

JOURNAL OF MEDICAL VIROLOGY WILEY

The effectiveness of quarantine of Wuhan city against the Corona Virus Disease 2019 (COVID-19): A well-mixed SEIR model analysis

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Funding information
National Natural Science Foundation of China, Grant/Award Numbers: 30400173, 30971257, 81170180, 81970302; Priority Academic Program Development of Jiangsu Higher Education Institutions

Abstract

A novel coronavirus pneumonia, first identified in Wuhan City and referred to as COVID-19 by the World Health Organization, has been quickly spreading to other cities and countries. To control the epidemic, the Chinese government mandated a quarantine of the Wuhan city on January 23, 2020. To explore the effectiveness of the quarantine of the Wuhan city against this epidemic, transmission dynamics of COVID-19 have been estimated. A well-mixed "susceptible exposed infectious recovered" (SEIR) compartmental model was employed to describe the dynamics of the COVID-19 epidemic based on epidemiological characteristics of individuals, clinical progression of COVID-19, and quarantine intervention measures of the authority. Considering infected individuals as contagious during the latency period, the well-mixed SEIR model fitting results based on the assumed contact rate of latent individuals are within 6–18, which represented the possible impact of quarantine and isolation interventions on disease infections, whereas other parameter were suppose as unchanged under the current intervention. The present study shows that, by reducing the contact rate of latent individuals, interventions such as quarantine and isolation can effectively reduce the potential peak number of COVID-19 infections and delay the time of peak infection.

KEYWORDS

contact rate, COVID-19, latent individuals, SEIR compartmental model

1 | INTRODUCTION

On 11 February 2020, the COVID-19 virus was identified by the International Committee on Taxonomy of Viruses (ICTV) as a "severe acute respiratory syndrome coronavirus 2" (SARS-CoV-2), and a report from the ICTV Coronaviridae Study Group determined the virus belongs to the existing species of severe acute respiratory syndrome-related coronavirus.[1] The novel coronavirus has been named as COVID-19 by the director-general of the World Health Organization (WHO).[2] The pneumonia outbreak became a worldwide concern when the Wuhan Municipal Health Commission reported 27 cases of viral pneumonia, including seven critically ill cases on 31 December 2019. The WHO reported that a novel coronavirus (2019-nCoV) was identified as the causative virus by Chinese authorities on 7 January 2020.[3]

Can Hou and Jiaxin Chen contributed equally to the study.

As of 14 February 2020, 66 492 accumulative laboratory-confirmed cases and 1523 deaths have been reported in China, and 505 accumulative laboratory-confirmed cases and 2 deaths in 24 countries other than China.[4] To control the epidemic, the Chinese government mandated a quarantine of Wuhan city on 23 January 2020. The international community has paid close attention to the effectiveness of the quarantine.[5,6] Here, transmission dynamics of COVID-19 were performed, based on currently available epidemiological information to explore the effectiveness of the quarantine of Wuhan city against this epidemic.

2 | METHODS

2.1 | Data collection

The data of confirmed and suspected cases of COVID-19 acute respiratory disease reported by cities and provinces in mainland China were obtained from the following: The Health Commission of Wuhan City, the Health Commission of Hubei Province, the National Health Commission of the People's Republic of China, and the World Health Organization situation reports.[7-10]

2.2 | The well-mixed SEIR compartmental model

A well-mixed susceptible-exposed-infectious-recovered (SEIR) compartmental model was applied to describe the dynamics of the COVID-19 epidemic process, based on the epidemiological characteristics of individuals, clinical progression of COVID-19, and quarantine intervention measures of the authority. The model was parameterized by the data obtained from confirmed and suspected cases of COVID-19 reported by regions and provinces in China. This model was used to estimate the dynamics of COVID-19 in Wuhan city.

COVID-19 has an incubation period and exposed people with no symptoms can carry SARS-CoV-2,[11] unlike SARSr-CoV. COVID-19 is contagious during the incubation period[12]; therefore, the SEIR compartmental model was modified in the present study. For the well-mixed SEIRS model, the population under consideration is represented by four groups of individuals: susceptible (S) (vulnerable to SARS-CoV-2 infection), exposed (E) (latent individuals and those capable of spreading SARS-CoV-2), infectious (I) (symptomatic, capable of spreading SARS-CoV-2), and recovered (R) (immune to the SARS-CoV-2). The contact rates, r1 and r2, which represent the probability of susceptible persons coming into contact with an infected individual and latent individuals being infected, respectively. The infectious rates, $\beta 1$ and $\beta 2$, control the rate of spread. In this situation, $\beta 1$ represents the probability of infection per exposure when a susceptible individual (S) has contacted an infected patient (I) and becomes a latent exposed individual (E). While $\beta 2$ represents the potential rate per exposure when a susceptible individual (S) has mutual contact with an exposed individual (E), and transmits it to another exposed individual (E). Since there were controversies about the transmissibility of latent infection, we assumed that half of these asymptomatic latent infections were infectious, similar to influenza.[13] So, we set $\beta 2 = 1/2 \times \beta 1$. The incubation rate, α, is the rate of latent individuals becoming infectious (average duration of incubation is $1/\alpha$). The recovery rate, $\gamma = 1/D$, is determined by the average duration time (day). The following system of equations summarizes the transmission dynamics model (Figure 1).

2.3 | Parameter estimations for COVID-19

As previously mentioned, the key parameters involved in this model include the initial values of the susceptible population, the exposed population, the symptomatic infected population, and the recovered population. These parameters are described in Table 1.

The parameters included in the model were transition probabilities from one state to another on any given day. Referring to the SARS epidemic data, the contact rate of infected individuals after quarantine and isolation is set to 6.[18] In addition, the contact rate of latent individuals was measured as follows: the number of cumulative close contacts (739) divided by the number of confirmed cases (41), based on the report from the Health Commission of Wuhan City on 11 January 2020.[16] A contact rate ranging from 6 to 18 was applied to analyze the spread of COVID-19 and the effectiveness of quarantine in Wuhan.

The probability of infection of susceptible individuals, which were infected by symptomatic exposed groups, could be estimated as the number of newly confirmed cases divided by the number of closed contacts, based on the report from the National Health Commission of the People's Republic of China from 21 January 2020, to 19 February 2020.[17] The average number, 4%, was set as the parameter in the model. The reciprocal value of the incubation period was set as the transition rate of latent individuals becoming infected

$$dS/d\,t=-r_1\beta_1 IS/N-r_2\beta_2 ES/N$$

$$dE/dt=r_1\beta IS/N-\alpha E+r_2\beta_2 ES/N$$

$$dI/dt=\alpha E-\gamma I$$

$$dR/dt=\gamma I$$

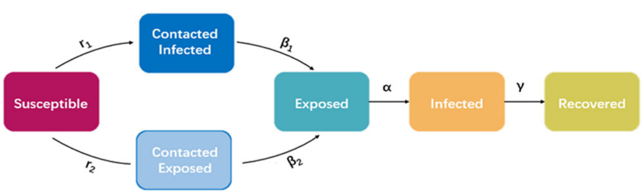

FIGURE 1 Diagram of the well-mixed susceptible-exposed-infectious-recovered (SEI) model adopted in the present study for simulating the COVID-19

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TABLE 1 Parameter estimates for COVID-19 in Wuhan City since 31 December 2019

Parameter	Model input	Equation	References
N	11081000	N = S + E + I + R	7 and 14
S	11080778	S = N−E−I−R	15
E	193	E = I/α	15
I	27	NA	15
R	2	NA	15
r1	6	NA	13
r2	18	739/41 = 18	16
β1	0.4	Newly confirmed cases/ cumulative tracking of close contact	17
β2	0.2		17
α	0.14	1/7 = 0.14	17
γ	0.048	1/21 = 0.048	17

Abbreviation: NA, not available.

individuals, and the reciprocal value of the duration of disease was estimated as the probability of recovering from an infection. According to the report, 7 and 21 days were set as the incubation period and duration of disease, respectively.[19]

2.4 | Simulation

According to the report from the Health Commission of Wuhan City on 31 December 2019,[15] 27 cases of COVID-19 were confirmed, 2 patients had recovered, and latent individuals were estimated as 193, based on the 7-day incubation period of COVID-19. The population of Wuhan is about 11 081 000[14]; therefore, we set S (0) = 11,081,000 to 27–2 to 193 = 11 080 778.

2.5 | Statistical analyses

R software (version 3.6.1) was used for well-mixed SEIR compartmental model analysis, with "deSolve" and "ggplot2" packages for calculating predicted parameters and plotting peak values. Curve estimation was analyzed by using Statistics Package for Social Sciences (ver. 16.0; SPSS Incorporated, Chicago, IL). Significance was identified if the null hypothesis could be rejected with more than 95% confidence. All P values are two-tailed.

3 | RESULTS

3.1 | Well-mixed SEIR model fitting

The well-mixed SEIR model fitting results are presented in Figure 2 and Table 2. Noted that the model estimations are based on the assumed contact rate of latent individuals (6-18), which represent the possible impact of quarantine and isolation interventions on disease infections. We assumed the other parameters were constant under the current intervention.

The trend of the COVID-19 epidemic in Wuhan city was predicted by the estimated parameter values. To explore the possible impact of quarantine and isolation interventions on COVID-19 spread, we plotted the number of exposed individuals, the number of infected individuals, the number of removed individuals, and the number of susceptible individuals and contact rates of latent individuals. As shown in Figure 2 and Table 2, the results suggest that lowering the contact rate of latent individuals consistently reduces the number of infected individuals but may delay the peak in infections.

3.2 | Curve estimation of predicted and actual values of infected individuals

Curve estimation was applied to investigate the relationship between the predicted cases of COVID-19, based on the well-mixed SEIR model, and reported cases of COVID-19, based on the report from the National Health Commission of the People's Republic of China. The curve estimation procedure produces curve estimation regression statistics and related plots to 11 different curve estimation regression models. A separate model is produced for each dependent variable. In the analysis model of curve estimation, the number of actual reported cases of COVID-19 from 10 January 2020 to 29 February 2020, was set as the dependent variable. And the number of predicted cases of COVID-19 based on the well-mixed SEIR model, in which the contact rate of latent individuals is set as 18 from 10 January 2020 to 29 February 2020, was set as the independent variable. The R^2 values of the linear, logarithmic, inverse, quadratic, cubic, power, compound, S-curve, growth, and exponential models were 0.938, 0.603, 0.132, 0.977, 0.981, 0.816, 0.975, 0.402, 0.816, 0.816, and 0.816, respectively (all $P < .01$) (Table 3 and Figure 3). The most suitable description for the relationship between the predicted and actual values of the infected individuals' curve was the cubic model. Therefore, the cubic model was used to estimate the relationship between the predicted and actual values of infected individuals in the present study.

When the contact rate of latent individuals varied from 6 to 18, R^2 was 0.954, 0.945, 0.943, 0.952, 0.970, 0.985, 0.992, 0.992, 0.989, 0.980, 0.932, 0.990, and 0.981 (all $P < .01$) (Table 4). The curve estimation of the cubic model results with varying contact rates of latent individuals is shown in Figure 4. Therefore, predicted cases of COVID-19 based on the well-mixed SEIR model are in good agreement with the reported cases of COVID-19 based on the report.

4 | DISCUSSION

Given the scenarios of different public health intervention efficacy, we applied the well-mixed SEIR compartmental model to predict the

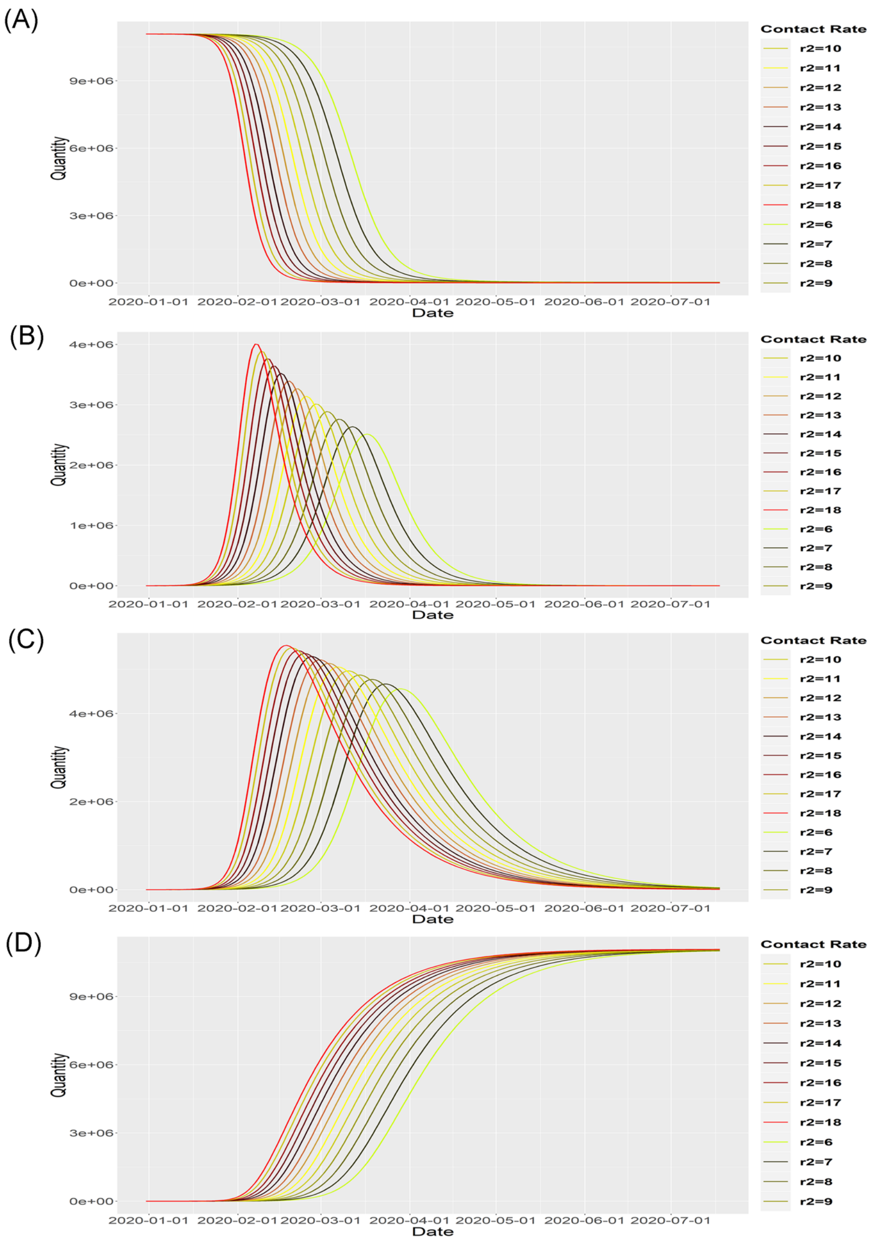

FIGURE 2 The well-mixed susceptible-exposed-infectious-recovered (SEIR) model fitting results. A, The well-mixed SEIR model estimated the number of susceptible individuals based on the supposition that the contact rate of latent individuals is 6 to 18. B, The well-mixed SEIR model estimated the number of exposed individuals based on the suppose that the contact rate of latent individuals is 6 to 18. C, The well-mixed SEIR model estimated the number of infected individuals based on the suppose that the contact rate of latent individuals is 6 to 18. D, The well-mixed SEIR model estimated the number of removed individuals based on the suppose that the contact rate of latent individuals is 6 to 18

actual number of infected cases and latent individuals. Using existing data and incorporating these data with the well-mixed SEIR compartmental model, our results suggest that reducing the contact rate of latent individuals after quarantine and isolation can effectively reduce the number of individuals infected with COVID-19 and delay the peak time. Prevention and control of COVID-2019 epidemics require a better understanding of its mode of geographical dissemination. Different from the coronavirus diseases we have experienced, such as SARS and Middle East Respiratory Syndrome are not contagious during asymptomatic infection, the incubation period of asymptomatic patients with COVID-19 is extremely contagious to close contacts.[20] Although measures such as quarantine and isolation were taken early in the outbreak to reduce the contact rate of infected individuals, it is crucial to reduce the contact rate of latent individuals. By decreasing the contact rate to latent individuals, the number of infections decreases and the peak time is delayed, which is shown in Table 2 and Figure 2. Therefore, movement restriction and community containment measures, such as quarantine and isolation, are essential to control the spread of COVID-19.

The models were used to fit the actual reported cases in Wuhan City from the National Health Commission of the People's Republic of China. The curve estimation program generates curve estimation regression statistics and correlation graphs for 11 different curve estimation regression models. R^2 of the cubic model is 0.981, which is the highest in 11 different curve estimation regression models and this indicated that using the cubic model to estimate the relationship between the predicted

TABLE 2 The effects of contact rate of latent individuals' restrictions at the peak spread of COVID-19 in Wuhan city since 31 December 2019

Contact rate of latent individuals	Peak time
6	3/29/2020
7	3/24/2020
8	3/19/2020
9	3/14/2020
10	3/11/2020
11	3/7/2020
12	3/4/2020
13	3/1/2020
14	2/27/2020
15	2/24/2020
16	2/22/2020
17	2/20/2020
18	2/18/2020

value and the actual value of infected individuals is more accurate than the other curve estimation regression models. As indicated by Table 3 and Figure 3, combined with actual reported cases, the contact rate of latent individuals in the well-mixed SEIR model is set to 18, which can accurately simulate the trend of infected individuals. As mentioned above, the curve estimation of the cubic model results, with different contact rates of latent individuals from 6 to 18, gave R^2 values of 0.954, 0.945, 0.943, 0.952, 0.970, 0.985, 0.992, 0.992, 0.989, 0.980, 0.932, 0.990, and 0.981 (all $P < .01$). Thus, the well-mixed SEIR

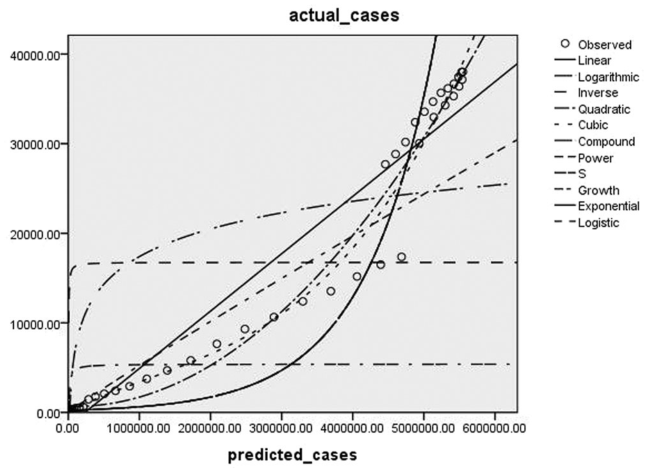

FIGURE 3 The curve estimation model plot based on the contact rate of latent individuals is set as 18

model-based prediction of COVID-19 cases is consistent with the reported data.

Accurately identifying the epidemic trend in advance is critical for infectious disease prevention and control.[21] The well-mixed SEIR model can provide a reference for evaluating the effects of intervention measures. While the basic assumptions are established, especially in the absence of external intervention, the establishment of a dynamic model based on early epidemic data, or model prediction based on prior parameters, can clearly predict the development of the epidemic without intervention. The traditional public health measures of quarantine and isolation are the most effective measures to control the novel coronavirus outbreak, for which we currently have no specific therapeutics or vaccines. However, quarantining and isolating infected individuals

TABLE 3 The curve estimation model summary and parameter estimates based on the contact rate of latent individuals is set as 18

	Model summary					Parameter estimates			
Equation	R^2	*F*	*df*1	*df*2	Significance	Constant	b1	b2	b3
Linear	0.938	743.067	1	49	.000	−1.499E3	0.006		
Logarithmic	0.603	74.341	1	49	.000	−4.414E4	4.452E3		
Inverse	0.132	7.480	1	49	.009	1.675E4	−4.273E7		
Quadratic	0.977	1.035E3	2	48	.000	673.025	0.000	1.244E−9	
Cubic	0.981	799.295	3	47	.000	89.162	0.004	−8.65E−10	2.56E−16
Compound	0.816	217.856	1	49	.000	228.570	1.000		
Power	0.975	1.876E3	1	49	.000	0.010	0.955		
S	0.402	32.884	1	49	.000	8.592	−1.256E4		
Growth	0.816	217.856	1	49	.000	5.432	1.008E−6		
Exponential	0.816	217.856	1	49	.000	228.570	1.008E−6		
Logistic[a]	0.816	217.856	1	49	.000	0.004	1.000		

Note: Dependent variable: actual reported cases of COVID-19; independent variable: the predicted cases of COVID-19.

and latent individuals at the beginning of the outbreak period would have been a strategic preventative measure.

However, there are several limitations to this study that must be discussed, namely, too many parameters and nonconstant parameters. Before the mandated quarantine of Wuhan city on 23 January 2020, the population of Wuhan fluctuated; thus, the exact population of Wuhan cannot be determined. In addition, the parameters of the population contact rate were not from an accurate data set. Due to quarantine and isolation measures, the contact rate is constantly changing. Furthermore, we did not consider the rate of change in personal activity, such as wearing masks, increasing social distance, and ceasing travel to Wuhan. Thus, the estimates of virus imports may not be totally accurate. Finally, our models are based on human-to-human transmission. The possibility of outbreaks caused by fomites or contamination of the water system by infected feces was not taken into account. Therefore, if reported data on population

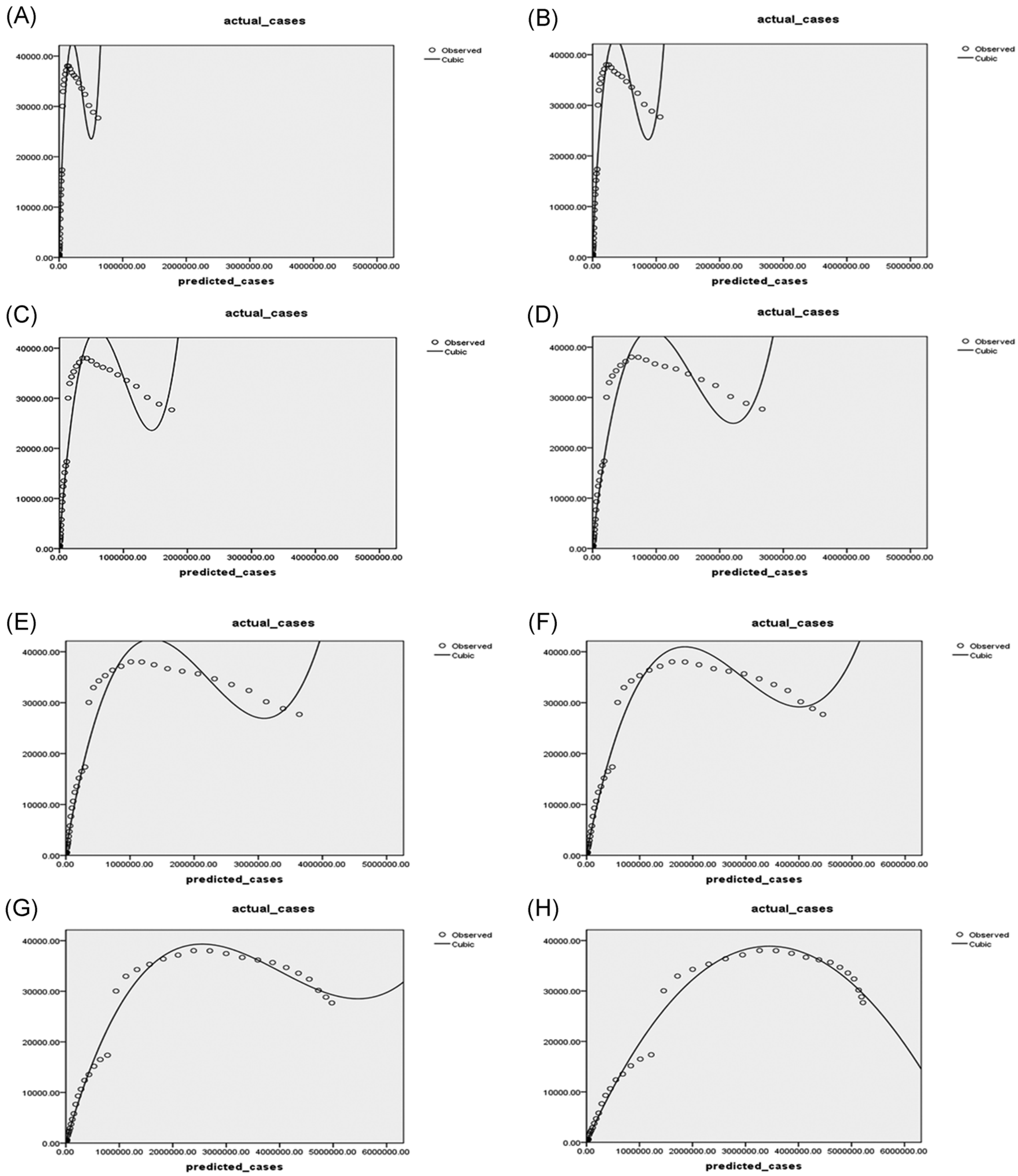

FIGURE 4 The curve estimation of the cubic model plot with varying contact rates of latent individuals: (A) 6, (B) 7, (C) 8, (D) 9, (E) 10, (F) 11, (G) 12, (H) 13, (I) 14, (J) 15, (K) 16, (L) 17, and (M) 18

TABLE 4 The cure estimation of cubic model results with varying contact rate of latent individuals

Contact rate of latent individuals	R^2	*P* value	Constant	b1	b2	b3
6	0.954	.000	206.139	0.473	−1.600E−6	1.49E−12
7	0.945	.000	831.711	0.276	−5.462E−7	2.96E−13
8	0.943	.000	1.181E3	0.166	−1.983E−7	6.50E−14
9	0.952	.000	1.186E3	0.106	−3.871E−8	5.81E−15
10	0.970	.000	877.386	0.072	.000	1.793E−9
11	0.985	.000	434.200	0.052	−2.046E−8	2.32E−15
12	0.992	.000	124.662	0.036	−1.048E−8	8.71E−16
13	0.992	.000	140.919	0.023	−3.584E−9	4.72E−17
14	0.989	.000	408.813	0.012	1.144E−9	−4.30E−16
15	0.980	.000	568.785	0.005	2.766E−9	−4.91E−16
16	0.932	.000	9.289E3	−2.712E3	157.900	−1.888
17	0.990	.000	117.991	0.005	−6.92E−10	1.85E−16
18	0.981	.000	89.162	0.004	−8.65E−10	2.56E−16

mobility, epidemiological characteristics, and viral transmission mechanisms were considered by the models, the accuracy and validity of the estimates would improve.

In conclusion, we developed a well-mixed SEIR compartmental model to describe the dynamics of the COVID-19 epidemic process. The fitting results of the well-mixed SEIR model assumed that the contact rate of latent individuals is between 6 and 18, representing the possible impact of isolation and quarantine measures on the disease infection rate. The results suggest that interventions, by reducing the contact rate, such as isolation and quarantine, can effectively reduce the peak number of COVID-19 infections and delay the peak time of infections.

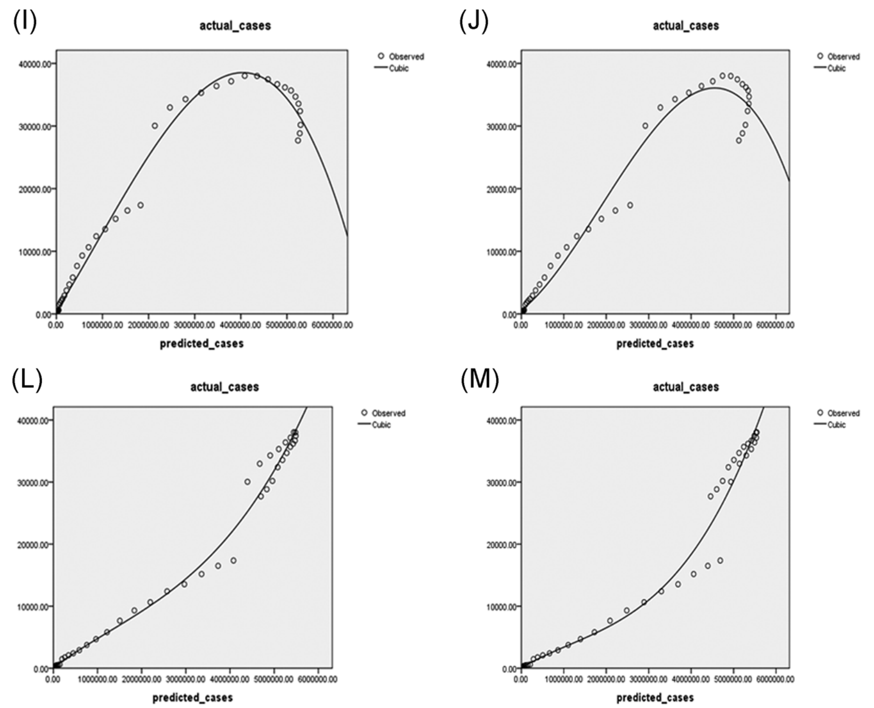

FIGURE 4 (Continued)

ACKNOWLEDGMENTS

We would like to acknowledge colleagues for helpful comments. This study was supported by the National Natural Science Foundation of China (Nos. 81170180, 30400173, 30971257, and 81970302). A project funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions.

CONFLICT OF INTERESTS

The authors declare that there are no conflict of interests.

AUTHOR CONTRIBUTIONS

As the guarantor, EJ conceived the study. CH and JC initially drafted the manuscript. YZ, LH, JY, SH, YG enrolled participants and collected data under the supervision of QJ and SZ. CZ, JZ and GX coordinated the study.

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How to cite this article: Hou C, Chen J, Zhou Y, et al. The effectiveness of quarantine of Wuhan city against the Corona Virus Disease 2019 (COVID-19): A well-mixed SEIR model analysis. *J Med Virol*. 2020;92:841–848. https://doi.org/10.1002/jmv.25827