Shortages of hospital beds exacerbate severity of COVID-19 outbreaks

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RESEARCH

Shortages of hospital beds exacerbate severity of COVID-19 outbreaks

Weike Zhou¹, Aili Wang², Xia Wang¹, Robert A Cheke³ and Sanyi Tang^{1*}

Abstract

Background: The global outbreak of COVID-19 has caused worrying concern amongst the public and health authorities. The first and foremost problem that many countries face is a shortage of medical resources. The experience of Wuhan, China, in fighting against COVID-19 provides a model for other countries to learn from.

Methods: We formulated a piecewise smooth model to describe the limitation of hospital beds, based on the transmission progression of COVID-19, and the strengthening prevention and control strategies implemented in Wuhan, China. We used data of the cumulative numbers of confirmed cases, cured cases and deaths in Wuhan city from 10 January to 20 March, 2020 to estimate unknown parameters and the effective reproduction number. Sensitivity analysis was conducted to investigate the impact of a shortage of hospital beds on the COVID-19 outbreak.

Results: Even with strong prevention and control measures in Wuhan, slowing down of the supply rate, reducing the maximum capacity and delaying the intervention time of supplementing hospital beds aggravated the outbreak severity by magnifying the cumulative numbers of confirmed cases and deaths, prolonging the period of the outbreak in Wuhan, enlarging the value of the effective reproduction number during the outbreak and postponing the time when the threshold value is reduced to 1.

Conclusions: The quick establishment of the Huoshenshan and Leishenshan Hospitals in a short time and the deployment of mobile cabin hospitals played important roles in containing the COVID-19 outbreak in Wuhan, providing a model for other countries to provide more hospital beds for COVID-19 patients faster and earlier.

Keywords: COVID-19 outbreak; Transmission model; Medical resources; Effective reproduction number

Background

A severe outbreak of coronavirus disease (COVID-19) is spreading rapidly across the world, with major impacts on global public health. The virus responsible for COVID-19 is a new strain of coronaviruses that has not been previously identified in humans, and was named severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) [1, 2, 3]. The rapidly increasing number of infected cases reveals that the novel virus is more contagious than both MERS-CoV and SARS-CoV [4, 5]. The World Health Organization (WHO) announced on 11 March 2020 that the COVID-19 outbreak as a 'pandemic' as the virus spreads increasingly worldwide [3].

The current situation in China is showing an encouraging sign of improvement. In particular, Wuhan, where the most severe outbreak of COVID-19 appeared, has apparently achieved significant progress with daily new confirmed lo-

cal cases declining from thousands to zero or close to zero [6, 7]. At the same time, many other countries, including Italy, Sweden, Germany, Iran, etc., are undergoing similar or even more severe situations than the increasing phase of the COVID-19 outbreak in Wuhan. The alarming levels of spread and severity of the disease pose a burden on the development of nations' economies and societies and have led to aggressive actions by governments to control the pandemic. Lessons learnt from China's experience will be helpful for other countries' efforts to contain it. Thus it is essential to study the control procedure and control measures adopted in Wuhan to help in estimating the outbreak risks in other countries.

Since 23 January 2020, a series of prompt public health measures, including contact tracing, quarantine, travel restrictions, lock-down of cities, etc., have been strictly carried out to prevent the spread of the disease [8]. To meet an urgent need of medical resources, the public health authorities mobilized health-care workers from other provinces of China to give assistance, and medical resources were de-

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livered from various regions to Wuhan to relieve the burden of medical-resource constraints. However, it was still far from sufficient for Wuhan under such a severe situation. Further, to make sure medical facilities for COVID-19 available to all people needing medical assistance [9], a number of hospitals were successively requisitioned as designated hospitals and Huoshenshan and Leishenshan hospitals and mobile cabin hospitals were built for treatment of confirmed patients. Meanwhile, many quarantine centers were also established to quarantine suspected cases. As a result, a total of more than 51,000 hospital beds were provided to accommodate more patients and suspicious cases and all people needing medical assistance were admitted to medical facilities at middle February [10]. With sufficient medical resources and strict control measures, the outbreak of COVID-19 in Wuhan, the epicenter of the outbreak, was contained.

Currently, shortage of medical resources, especially hospital beds, is also a problem confronting many other countries. Examining the impact of medical resources is therefore an important issue for the control of COVID-19 outbreaks, with Wuhan's example in its fight against COVID-19 being a model for other countries to follow. Quantifying the variation of medical resources and their influence on the control of COVID-19 outbreaks falls within the scope of this study. We then proposed a deterministic mathematical model to examine explicitly the effect of hospital beds on the containment of COVID-19. Time-dependent parameters are adopted to describe the strengthening of control measures and improvements in detection technology, together with an implicit function in terms of the number of hospital beds is introduced to our targeted model to describe the number of newly hospitalized cases in relation to medical-resources constraints.

Methods

Data source and analysis

We obtained the data of COVID-19 cases of Wuhan city from 10 January to 20 March 2020, from the National Health Commission of the People's Republic of China [11], Health Commission of Hubei Province [6] and Wuhan Municipal Health Commission [7]. The data information includes the number of cumulative confirmed cases (Figure 1(a)), the number of cumulative deaths (Figure 1(b)) and the number of cumulative cured cases (Figure 1(c)). Note that the data reported was adjusted on February 12, some COVID-19 induced death cases reported before were cancelled after verification, causing that the number of cumulative deaths reported on February 13 (1,016 cases) is smaller than that on February 12 (1,036 cases). Thus, we regenerate the number of cumulative deaths on February 12 by averaging the numbers reported on February 11 and February 13.

We also collected information on the number of hospital beds in Wuhan. There were two designated hospitals with

about 800 hospital beds for the COVID-19 patients before 23 January 2020, and hospital beds were gradually being expropriated for COVID-19 patients and there were enough hospital beds (about 51,000) as of 2 March [10]. Thus, we assumed that the number of hospital beds $H_c(t)$ at time t is a constant H_{c0} before 23 January, and it is an increasing function which satisfies the following logistic model (1) from then on. r is the net increasing rate of the hospital beds and M is the maximum number of hospital beds in Wuhan during the COVID-19 outbreak. The estimated number of hospital beds everyday is shown in Figure 1(d).

$$\frac{dH_c(t)}{dt} = rH_c(t) \left(1 - \frac{H_c(t)}{M}\right). \quad (1)$$

The model

Based on the disease progression and the intervention measures, we extended the basic *SEIR* model [12, 13] by considering contact tracing followed by quarantine and hospitalization strategies. The total population N is divided into eight compartments, including susceptible (S), quarantined susceptible (S_q), exposed (E), quarantined exposed (E_q), infected (I), confirmed but not hospitalized (P), confirmed and hospitalized (H), recovered (R). Then we have the following model according to the policy of one patient one bed. See the flow diagram of the model in Figure 2.

$$\begin{cases} S' = -\frac{(c(t)\beta + q(t)c(t)(1-\beta))S(I + \theta P)}{N} + \lambda S_q, \\ E' = \frac{(1-q(t))c(t)\beta S(I + \theta P)}{N} - \sigma E, \\ I' = \sigma E - \alpha_I I - \delta_I(t)I, \\ S_q' = \frac{q(t)c(t)(1-\beta)S(I + \theta P)}{N} - \lambda S_q, \\ E_q' = \frac{q(t)c(t)\beta S(I + \theta P)}{N} - \delta_q(t)E_q, \\ P' = \delta_I(t)I + \delta_q(t)E_q - \min\{\eta P, H_c(t) - H\} - \gamma_P P - \alpha_P P, \\ H' = \min\{\eta P, H_c(t) - H\} - \gamma_H(t)H - \alpha_H(t)H, \\ R' = \gamma_P P + \gamma_H(t)H, \end{cases} \quad (2)$$

In model (2), the contact rate is denoted by c and the transmission probability per contact is β . Then a proportion of q of individuals exposed to the virus is quarantined by implementing the contact tracing, and according to whether those people are effectively infected, they can either move to the quarantined exposed compartment E_q with transmission probability β , or move to the quarantined susceptible compartment S_q with a probability of $1 - \beta$. While the other proportion, $1 - q$, missed from the contact tracing, will similarly move to the exposed compartment E with effective transmission probability β , or just stay in

the susceptible compartment S with probability $1 - \beta$. $1/\sigma$ is the incubation period, λ is the releasing rate of quarantined susceptible individuals, δ_I and δ_q are the diagnose rate for infected and quarantined exposed individuals, respectively, α_I , α_P , α_H are the disease-induced death rate for I , P and H , respectively, η is the hospitalization rate, γ_P and γ_H are the recovery rate for P and H , respectively. Note that, people confirmed with COVID-19 may not be hospitalized due to the limitation of hospital beds, thus the term $\min\{\eta P, H_c(t) - H\}$ is used to describe the maximum number of newly hospitalized per day to maximize the hospital utilization, which is a piecewise function according to the relationship between ηP and $H_c(t) - H$, where $H_c(t)$ is the number of hospital beds at time t in Wuhan, taking the form derived from the logistic model (1), as shown in equation (3). Meanwhile, those confirmed but not hospitalized have the transmissibility due to contacting with others during their hospital visiting or contacting with their family members during their home quarantine without absolute protective measures, θ is the relative transmissibility of P to I . See more detailed definitions of variables and parameters listed in Table 1.

$$H_c(t) = \begin{cases} H_{c_0}, & t \leq \bar{t}, \\ \frac{H_{c_0}M}{H_{c_0} + (M - H_{c_0})e^{-r(t-t_0)}}, & t > \bar{t}, \end{cases} \quad (3)$$

where $\bar{t} = 13$, representing that hospital beds were offered from 23 January.

Since the medical levels, public awareness as well as the prevention and control measures were improved and strengthened gradually after 23 January, here we assumed that the contact rate c , the quarantine rate q , the diagnose rates δ_I , δ_q , the recovery rate γ_H and disease-induced death rate α_H of hospitalized individuals are time-dependent functions [14]. The contact rate $c(t)$ is assumed to be a constant before 23 January and a decreasing function with respect to time t after 23 January due to the lockdown strategies and raising of public awareness, which takes the following form

$$c(t) = \begin{cases} c_0, & t \leq t_0, \\ (c_0 - c_1)e^{-r_c(t-t_0)} + c_1, & t > t_0, \end{cases} \quad (4)$$

where c_0 is the contact rate without control measures or awareness of the disease, c_1 ($c_1 < c_0$) is the minimum contact rate with the unprecedented intervention measures and self-isolation, r_c is the corresponding decreasing rate of the contact rate. Here $t_0 = 13$ since the data we used for model fitting starts at January 10, 2020.

The quarantined proportion $q(t)$ is assumed to be a constant before 23 January and an increasing function with re-

spect to time t due to contact tracing, which is given by

$$q(t) = \begin{cases} q_0, & t \leq t_0, \\ (q_0 - q_1)e^{-r_q(t-t_0)} + q_1, & t > t_0, \end{cases} \quad (5)$$

where q_0 denotes the initial quarantine rate of individuals exposed to the virus and q_1 ($q_1 > q_0$) is the maximum quarantine rate under the control measures, r_q is the corresponding increasing rate of the quarantine rate.

The period from illness onset to be diagnosed $\frac{1}{\delta_I}$ was gradually shortened due to the rising of public awareness and the developing of detection technology. Thus the diagnose rate is a non-increasing function with respect to t according to the control measures implemented in Wuhan. Furthermore, the confirmed cases were sharply increased on February 12, since the CT diagnose method was implemented despite of the nucleic acid test method, thus we assume that the diagnosed rate reached and kept the maximum from February 12. Hence the diagnosed period is described by the following piecewise function

$$\frac{1}{\delta_I(t)} = \begin{cases} \frac{1}{\delta_{I_0}}, & t \leq t_0, \\ (\frac{1}{\delta_{I_0}} - \frac{1}{\delta_{I_1}})e^{-r_{\delta_I}(t-t_0)} + \frac{1}{\delta_{I_1}}, & t_0 < t \leq t_1, \\ \frac{1}{\delta_{I_1}}, & t > t_1, \end{cases} \quad (6)$$

where $t_1 = 33$, δ_{I_0} is the initial diagnose rate of infected individuals, δ_{I_1} ($\delta_{I_1} > \delta_{I_0}$) is the maximum diagnose rate of individuals and r_{δ_I} is the decreasing rate of the diagnose period from symptom onset to be diagnosed.

Similarly, the detection rate $\delta_q(t)$ of quarantined individuals, those have been contacted with infected individuals and have been traced, is an increasing function from January 23 with more detection reagents being supplied and improved detection technology. The detection rate reached the maximum on February 12 with CT diagnosis. Thus the period from quarantine to detection is described by

$$\frac{1}{\delta_q(t)} = \begin{cases} \frac{1}{\delta_{q_0}}, & t \leq t_0, \\ (\frac{1}{\delta_{q_0}} - \frac{1}{\delta_{q_1}})e^{-r_{\delta_q}(t-t_0)} + \frac{1}{\delta_{q_1}}, & t_0 < t \leq t_1, \\ \frac{1}{\delta_{q_1}}, & t > t_1, \end{cases} \quad (7)$$

where δ_{q_0} is the diagnose rate of quarantined individuals before January 23, δ_{q_1} ($\delta_{q_1} > \delta_{q_0}$) is the maximum diagnose rate of quarantined individuals and r_{δ_q} is the decreasing rate of the period from quarantine to diagnosis.

For hospitalized confirmed cases, the recovery rate $\gamma_H(t)$ increases and the disease-induced death rate $\alpha_H(t)$ decreases by receiving treatment and health-care measures, with

more medical supplies. Thus $\gamma_H(t)$ and $\alpha_H(t)$ take the following form

$$\gamma_H(t) = \begin{cases} \gamma_P, & t \leq t_0, \\ (\gamma_P - \gamma_{H_1})e^{-r_{\gamma_H}(t-t_0)} + \gamma_{H_1}, & t > t_0, \end{cases} \quad (8)$$

$$\alpha_H(t) = \begin{cases} \alpha_P, & t \leq t_0, \\ (\alpha_P - \alpha_{H_1})e^{-r_{\alpha_H}(t-t_0)} + \alpha_{H_1}, & t > t_0, \end{cases} \quad (9)$$

where γ_P and α_P are the recovery rate and disease-induced death rate of hospitalized individuals before January 23, which are the same as the recovery rate and disease-induced death rate of confirmed but not hospitalized patients, γ_{H_1} ($\gamma_{H_1} > \gamma_P$) and α_{H_1} ($\alpha_{H_1} < \alpha_P$) are the maximum recovery rate and minimum disease-induced death rate of hospitalized individuals under treatment, r_{γ_H} and r_{α_H} are the corresponding increasing rate of the recovery rate and the corresponding decreasing rate of the disease-induced death rate.

The effective reproduction number is defined as

$$R_e(t) = \frac{(1-q(t))c(t)\beta}{\alpha_I + \delta_I(t)} \left(1 + \frac{\theta \delta_I(t)}{\min\left\{\eta, \frac{H_C(t)-H(t)}{P(t)}\right\} + \gamma_P + \alpha_P} \right) + \frac{\theta q(t)c(t)\beta}{\min\left\{\eta, \frac{H_C(t)-H(t)}{P(t)}\right\} + \gamma_P + \alpha_P}.$$

Results

By using the Least Square Method we fitted model (1) to the cumulative number of hospital beds, and fitted model (2) to the cumulative number of confirmed cases, cumulative number of cured cases and cumulative number of deaths (shown in Figure 1) to estimate unknown parameters and listed in Table 1. Note that in our model, we fixed $\eta = 1$ in agreement with the policy 'Receive all patients' implemented in China. The good fits are shown in Figure 3, in which the red circles are the data from 10 January - 20 March and the black curves are the fitted curves. The estimated number of hospital beds everyday is shown in Figure 1(d), which simulates the growth pattern of the hospital beds with the estimated parameters r and M .

To examine the impact of medical resources on COVID-19 outbreak, we investigated the impact of hospital beds on the number of cumulative confirmed cases and the number of cumulative deaths. By decreasing the net increasing rate of hospital beds (r), which means that new hospitals were not established or designated rapidly, the number of cumulative confirmed deaths increase significantly and delay the end of the outbreak. In particular, the simulation results showed that by reducing the increasing rate of hospital beds by 50%, the cumulative number of confirmed cases increases about 3 times (to about 150,000 confirmed cases),

and the cumulative number of deaths increases 20 times (to more than 50,000 deaths), compared with the actual situation in Wuhan (50,006 confirmed cases and 2,538 deaths reported as of 27 March), even with the unprecedented strong control measures and use of the maximum number of hospital beds, as shown in Figure 4(a) and 4(d).

We also conducted a sensitivity analysis of the cumulative numbers of confirmed cases and deaths by decreasing the maximum number of hospital beds M . Similarly, the results showed that if decreasing the capacity of hospital beds would increase the cumulative numbers of confirmed cases and deaths and delay the outbreak. In particular, if the maximum number of hospital beds supplied is not enough, for example if 20,724 hospital beds were supplied in total (reduced by 60%), the cumulative number of confirmed cases would be increased to 84,000 cases and the cumulative number of deaths would be increased to about 15,000 cases, as shown in Figure 4(b) and 4(e).

The time when the supply of hospital beds dedicated to COVID-19 patients was started is also very important. Thus, we investigated how the cumulative numbers of confirmed cases and deaths vary with the intervention timing t . We conducted a sensitivity analysis to show what would happen if the supply of hospital beds was implemented 1 week later (from 30 January), 2 weeks later (from 6 February) and 3 weeks later (from 13 February). It follows from the Figure 4(c) and 4(f) that the later the hospital beds were supplied, the severer the outbreak is. In particular, if the authorities offered hospital beds from 13 February (3 weeks later than Wuhan did in reality), the cumulative numbers of confirmed cases and deaths would be increased dramatically, resulting in more than 218,000 confirmed cases and nearly 10,000 deaths.

It follows from the Figure 4(g-i) that the effective reproduction number is obviously affected by the increasing rate of the availability of hospital beds, the maximum capacity of hospital beds and the time when the hospital beds are supplied. We can observe that reducing the increasing rate of hospital beds, reducing the maximum capacity of hospital beds, may not affect the general trend (i.e., decreasing) of the effective reproduction number. All of them, more or less, could magnify the value of the effective reproduction number in some period and postpone the time when the threshold value is reduced to 1. However, delaying the intervention timing for the hospital beds significantly changes the declining trend and increases the effective reproduction number, and hence may result in a large outbreak.

Discussion

The global outbreak of COVID-19 caused by a new strain of coronavirus has had profound impacts on almost all of the world and is, the most serious respiratory virus since the 1918 H1N1 influenza pandemic. Such a pandemic has put

a very considerable strain on public health organizations and led to significant shortages in health-care resources. Therefore, for preserving public health, it is of major importance to quantify how medical resource availability affects the COVID-19 outbreak and so the experience gained in fighting against COVID-19 in Wuhan, China, provides a model for other countries to learn from.

We proposed a piecewise smooth model based on the transmission progression of COVID-19 and the control policy implemented in Wuhan, China, to describe the limitation of hospital beds and investigated how the increasing rate, the maximum capacity, the timing of the supply of hospital beds affected the COVID-19 outbreak in Wuhan. With the strengthening control measures, we modeled the epidemic system and its parameters by assuming that they are related by a piecewise function with respect to time and that the number of hospital beds followed a logistic growth curve. The results identified the vital role of supply rate, supply capacity and supply timing of hospital beds. The findings demonstrated that slowing down of the supply rate, reducing the maximum capacity and delaying the intervention time of supplementing hospital beds all aggravate the outbreak severity, including magnifying the cumulative numbers of confirmed cases and deaths, and prolonging the period of the outbreak in Wuhan. Meanwhile, lack of urgency in supplying hospital beds also enlarges the value of the effective reproduction number during the outbreak and postpones the time when the threshold value is reduced to 1. These findings suggest that shortage of hospital beds is an important issue that must not be neglected. Even with the prompt and unprecedented strong control measures, such as lockdown of cities, travel restriction, contact tracing, etc., insufficient hospital beds would impede the mitigation of the outbreak and cause a severer situation.

Conclusion

The quick establishment of the Huoshenshan and Leishenshan Hospitals in a short time and the deploying of mobile cabin hospitals contributed to the rapid increase and the increased capacity of the hospital beds in Wuhan, which relieved the medical pressure and curbed the COVID-19 outbreak in Wuhan. Without these hospitals, the maximum capacity and the rate of hospital bed provision in Wuhan would have been insufficient and there would have been more confirmed cases and deaths. Thus it is important for other countries to provide more hospital beds for COVID-19 patients, and the faster and earlier, the better.

Ethical Approval and Consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Author's contributions

WZ, AW, XW, RAC, ST designed the research; WZ collected data; WZ, XW analyzed data; WZ, AW, RAC, ST interpreted the results and wrote the manuscript. All authors read and approved the final manuscript.

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Figures

Figure 1 Data of COVID-19 in Wuhan from January 10 to March 20. (a) Cumulative number of confirmed cases; (b) Cumulative number of cured cases; (c) Cumulative number of deaths; (d) Estimated number of hospital beds.

Figure 2 Flow diagram. Flow diagram to illustrate the infection dynamics of COVID-19 in Wuhan city. Integrated control measures including intensive contact tracing, quarantine and isolation are illustrated.

Figure 3 Fitted results for the data from 10 January to 20 March, 2020 in Wuhan. The red circles represent the real data. The black curves are the best fitting curves of model (2) to these data.

Figure 4 Impact of hospital beds. Impact of hospital beds on the cumulative number of confirmed cases (a-c), cumulative number of deaths (d-f) and the effective reproduction number (g-i) in Wuhan. Varying parameters are: the increasing rate of hospital beds r (left column), the maximum capacity of hospital beds M (middle column), and the intervention timing of supplying hospital beds (right column).

Tables

Table 1 Definition and values of variables and parameters for system (2)

Variables	Description	initial value	Resource
S	Susceptible population	11081000	[6]
E	Exposed population	46.8732	LS
I	Infected population	94.5778	LS
S_q	Quarantined susceptible population	739	[7]
E_q	Quarantined exposed population	1.0362	LS
P	Confirmed but not hospitalized population	0	data
H	Confirmed and hospitalized population	38	data
R	Recovered population	2	data
Parameters	Description	Value	Resource
$c(t)$	c_0 Contact rate before 23 Jan	12.3905	LS
	c_1 Minimum contact rate with control strategies	0.7035	LS
	r_c Exponential decreasing rate of the contact rate	0.0566	LS
β	Transmission probability from I to S per contact	0.0547	LS
θ	Relative transmissibility of I to H	0.4986	LS
$q(t)$	q_0 Quarantine rate before 23 Jan	1.2187×10^{-7}	LS
	q_1 Maximum quarantine rate with control measures	0.9851	LS
	r_q Exponential increasing rate of quarantine rate	0.0222	LS
λ	Releasing rate of quarantined susceptibles	1/14	
σ	Progression rate of exposed individuals to infectives	1/5	[15, 16, 17]
$\delta_I(t)$	δ_{I_0} Diagnose rate of infected individuals before 23 Jan	0.122	LS
	δ_{I_1} Maximum diagnose rate of infected individuals	0.84	LS
	r_{δ_I} Exponential decreasing rate of diagnose period from symptom onset to detection	0.01	LS
α_I	Disease-induced death rate of I	0.0017	LS
$\delta_q(t)$	δ_{q_0} Diagnose rate of quarantined individuals before 23 Jan	0.0890	LS
	δ_{q_1} Maximum diagnose rate of quarantined individuals	1.0000	LS
	r_{δ_q} Exponential decreasing rate of diagnose period from quarantine to detection	0.2089	LS
η	Hospitalization rate	1	Policy
γ_H	γ_P Recovery rate of confirmed individuals without hospitalization	0.001	LS
	γ_{H_1} Maximum recovery rate of hospitalized individuals with treatment	0.05	LS
	r_{γ_H} Exponential increasing rate of recovery rate	0.2887	LS
α_H	α_P Disease-induced death rate of confirmed individuals without hospitalization	0.0346	LS
	α_{H_1} Minimum disease-induced death rate of hospitalized individuals with treatment	0.0008	LS
	r_{α_H} Exponential decreasing rate of disease-induced death rate	0.2952	LS
$H_c(t)$	H_{c_0} Initial number of hospital beds for COVID-19 in Wuhan	800	data
	r Logistic increasing rate of hospital beds	0.2070	LS
	M Maximum capacity of hospital beds	51806	LS

Figures

Figure 1

Data of COVID-19 in Wuhan from January 10 to March 20. (a) Cumulative number of confirmed cases; (b) Cumulative number of cured cases; (c) Cumulative number of deaths; (d) Estimated number of hospital beds.

Figure 2

Flow diagram. Flow diagram to illustrate the infection dynamics of COVID-19 in Wuhan city. Integrated control measures including intensive contact tracing, quarantine and isolation are illustrated.

Figure 3

Fitted results for the data from 10 January to 20 March, 2020 in Wuhan. The red circles represent the real data. The black curves are the best fitting curves of model (2) to these data.

Figure 4

Impact of hospital beds. Impact of hospital beds on the cumulative number of confirmed cases (a-c), cumulative number of deaths (d-f) and the effective reproduction number (g-i) in Wuhan. Varying parameters are: the increasing rate of hospital beds r (left column), the maximum capacity of hospital beds M (middle column), and the intervention timing of supplying hospital beds (right column).

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