SIR model for novel coronavirus-infected transmission process and its application

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Research article

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Abstract

Background: To establish a novel coronavirus-infection transmission process model in Wuhan, and to provide a decision support for epidemic prediction and prevention.

Methods: SIR model for novel coronavirus-infection transmission process was built based on the data of the infected persons, discharged patients and discharged patients during the period of isolation and control in Wuhan. Least squares estimation method was used to estimate the key parameters of the model.

Results: The changing trend of the predicted value of SIR model was basically consistent with the actual value, and fitting effect was well. Based on the prediction results of model, future development trend of the epidemic showed that the inflection point of the epidemic was the 38th day, namely at the end of February, the peak number of infected persons was about 22000 (excluding clinical diagnosis cases); Different infection intensity and removal intensity had an impact on the development of the epidemic.

Conclusion: The SIR model for novel coronavirus-infection transmission process in Wuhan has high veracity. Through the prediction and application of the model, it can provide guidance and advice for the actual epidemic prevention and control, and take effective measures to control the epidemic situation in time.

Keywords

Novel coronavirus; SIR model; Least squares estimation; Model prediction

Background

Novel coronavirus-infection pneumonia originated in Wuhan has spread throughout the country since the end of 2019. The new coronavirus ［1］ can cause respiratory, digestive and neurological diseases in humans and animals, meanwhile, it can infect vertebrates. The spread of virus not only causes social panic and social panic, but also endangers people's life and health seriously.

Susceptible Infected Recovered (SIR for short) Model［2］is a classical mathematical model of dynamic epidemical. It was first proposed by Kermack and McKendrick in 1927, and has been widely used and promoted as yet [3-7]. In recent years, the research on infectious diseases based on SIR model has developed rapidly. Tang et al. ［4］ applied SIR model to the evaluation of infectious source management effect of HFMD, aimed to simulate the trend of epidemic change under different control effects; Based on SIR model and finite difference idea, Ehrhardt et al. ［5］

described the process of immunity weakening after vaccination, and proposed a novel simplified model for solving the problem. The above application of SIR model shows the good stability and applicability in simulating the epidemic process of infectious diseases.

A novel coronavirus-infected transmission process model based on the theory of SIR is proposed in this paper. The proposed model is designed to analyze the epidemic regularity of virus transmission by combining mathematical models with real data. It has great significance in the prevention and control of the epidemic, and provides important guidance for prevention and control of infectious diseases in the future.

2. Methods

2.1 Data

An outbreak of novel coronavirus-infection pneumonia occurred in Wuhan since the end of 2019. As of February 11, 2020, 19558 cumulative confirmed cases and 810 cumulative deaths were reported in Wuhan. Since the outbreak originated, and the number of patients is the largest and the most representative in Wuhan, so the epidemic data of Wuhan were used to establish the model. The data were obtained from the official data released by the WHO [8] and Health Commission of Hubei Province [9]. Since the isolation, closure and other measures were started to implement since January 23 in Wuhan, it can be considered that the total population change of Wuhan is ignored in this stage. Meanwhile, in order to avoid the problems caused by the lagging and incomplete data statistics in the early stage of epidemic, we selected the data selection from January 23 to February 11, 2020, mainly including the daily total number of confirmed cases, death cases, cure cases and the number of newly cases.

2.2 SIR model for novel coronavirus-infected transmission process

SIR is a classical mathematical model of dynamic epidemical, driven by the solution of differential equations. During the transmission of novel coronavirus. In outbreak areas, the whole population were divided into three categories and defines and propositions［10］as follows:

- **Definition1 (Susceptibles):** The susceptibles refers to a group of people who are not yet infected but may be infected with the virus at any time. The number of susceptibles is recorded as S_t at time *t.*
- **Definition2 (Infectives):** The infectives refers to a group of people who have been infected and have infectivity. The number of infectives is recorded as I_t at time *t*.
- **Definition3(Removals):** The removed refers to a group of people who have been removed from the infected people, such as died, isolated or recovered and are immune to the virus. The number of removed is recorded as R_t at time *t*.
- **Definition4(Intensity of removal):** The intensity of removal refers to the proportion of people cured or died from infectives at time t, denoted

as γ_t: $\gamma_t = \frac{R_t - R_{(t-1)}}{I_{(t-1)}}$.

- **Proposition 1:** During the period of virus transmission, the influence of population dynamics, such as birth, death, migration and migration of population in this period is ignored. Therefore, the total population of epidemic area in Wuhan can be regarded as a constant, denoted as N, namely $N=S_t+I_t+R_t$.
- **Proposition 2:** The number of new virus infector person is directly proportional to the number of susceptible at time t, denoted as $\beta S_t I_t$, where β indicates the intensity of infection.
- **Proposition 3:** The number of new removal, due to death, isolation or cure, is directly proportional to the number of infected, denoted as γI_t, where γ indicates the intensity of removal.

By the way, we present the novel coronavirus-infected transmission process based on SIR model in Wuhan, as shown in the following figure 1.

The differential equation is expressed as:

$$\begin{cases} \frac{dS_t}{dt} = -\beta S_t I_t \\ \frac{dI_t}{dt} = \beta S_t I_t - \gamma I_t \\ \frac{dR_t}{dt} = \gamma I_t \end{cases} \tag{2}$$

2.3 Least Square Estimation

The least square estimation method ［11］［12］is aimed to find the optimal solution of parameter estimation by solving the sum of the squares of the minimum residuals. In the SIR model, namely minimize the sum of squared error between the value of model prediction and the real data, so the value of the unknown parameters (β, γ) can be estimated optimally.

2.4 Statistical analysis

Considering the high complexity of calculation process and the convenience of data display, in this paper, the programs by Python for data processing, parameter value estimation, and model prediction are applied in subsequent experiments.

3 Results

3.1 Descriptive statistics

The data of novel coronavirus-infection transmission process from January 23rd to February 11th were selected in this paper. According to definition 4, the intensity of removal (γ), as one of the important parameters of SIR model represents the proportion of patients cured and died every single day (see table 1).

3.2 Parameters of model

The arithmetic mean value is selected as the estimation value of the intensity of removal in SIR model, that is, $\hat{\gamma}=0.0238$. In least square estimation, the initial value of (S_0,β) is respectively set as [500,10000] and $[1\times10^{-5},5\times10^{-2}]$. Furthermore, we obtain the estimation values as $\hat{S}_0\approx5,\hat{\beta}\approx0.38$ (see figure 2).

3.3 Model evaluation

Figure 3 and 4 describe the prediction for SIR model, and the comparison between the predicted and observed values of the infectives and the removals. Predicted values of the model are consistent with the actual observed, and the numerical difference is small. The fitting correlation coefficient [13] is calculated, $R^2(Infectives) = 0.8765$ and $R^2(Removals) = 0.8319$ respectively, the model fitting effect is well.

3.4 Model prediction

According to the prediction results of SIR model in Wuhan, the number of infectives has risen sharply since the 20th day of the epidemic, peaked on the 38th day, becoming the turning point, about the end of February; the maximum number of infectives is about 22000 (excluding clinical diagnosis cases), and then the infectives gradually decreases. The number of removals rise slightly from the 25th day of the epidemic, and rise steadily after that.

3.5 Influence of different (β, γ) on the development of epidemic in SIR model

As shown in Figure 6, compared with the original model, with the decrease of β by 10%, 20%, 30%, 40% and 50%, the model curve shows the trend of downward displacement to the right, and the number of infectives at the peak shows the trend of downward gradient, and the date to reach the peak also moves backward in turn; as shown in Figure 7, compared with the original model, with the increase of γ by 10%, 20%, 30%, 40% and 50%, the model curve shows a downward displacement trend, the number of infectives at the peak shows a downward gradient trend, and the date to reach the peak keep almost the same.

4 Discussion

In this paper, we put forward the SIR model for novel coronavirus-infection transmission process based on the epidemic data during the period of epidemic control and isolation in Wuhan. The proposed model illustrated the propagation rule and development process, and predicted the future development trend of the epidemic. Meanwhile, the influences of different model parameters on the epidemic situation were discussed. The above mentioned have direct reference value and play a positive guidance role in the actual work of epidemic prevention and treatment. There are four main conclusions in this study.

First, the novel coronavirus is well consistent in the SIR model and the accuracy of the new model is well. **Second**, the model predicts the turning point of the outbreak on the thirty-eighth day, that is the end of February. The number of removals rise slightly from the 25th day of the outbreak, and then rise steadily. Therefore, it can provide reasonable guidance for prevention and control preparations before the peak of the epidemic, such as increasing or allocating medical materials, personnel and other resources, strengthening isolation and control measures. **Third**, different parameters will lead to the development of the epidemic in different directions, such as reducing the intensity of infection and increasing the intensity of removal, will reduce the scale of the development of the epidemic and slow down the trend of the development of the epidemic. Therefore, we believe that following measures should be taken: Effective measures to reduce the intensity of infection and improve the intensity of removal, such as early detection, early isolation and early treatment of cases, minimize the close contact between people, strictly control the internal infection of the hospital, do a good job in disinfection and sanitation, constantly optimize and improve the diagnosis and treatment plan of patients with new coronary pneumonia, shorten the diagnosis and treatment cycle, etc. **Fourth**, the existing SIR model can be used to test the exist of singular value data, to be used for determining whether there is any concealment or omission of the epidemic situation.

In summary, this study has positive reference significance for the actual epidemic prevention and control work, but there is still room for improvement. In this paper, for the purpose of model simplification, the parameter values of infection intensity and removal intensity are set as constants. Although the current data can be used to better fit the development law of the epidemic as a whole, with the long-term development of the epidemic. Therefore, we should consider the change function of the key parameters of SIR model with the development of the epidemic, constantly adjust the parameter values and optimize the model.

This work is complex and will be carried out in the follow-on study.

Abbreviation

SIR: Susceptible Infected Recovered.

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Availability of data and materials

Data used for analysis is available from the first author on reasonable request.

Authors' contributions

TT conceived the study, participated in its design, drafted the manuscript, and revised the manuscript. CaoLei collected data and helped to draft the manuscript. TT and CaoLi and LCY participated in its design and intellectual input. CaoLi coordinated the research groups. TT performed the statistical analysis. All authors read and approved the final manuscript.

Ethics approval and consent to participate

An approval for this study was established, and approved by the First Affiliated Hospital of Nanchang University. Written informed consent was obtained from individual or guardian participants.

Consent for publication

Written informed consent for publication of clinical images and details was obtained. A copy of the consent form is available for review by the Editor of this journal.

Competing interests

All authors declare that they have no competing interests.

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Figures

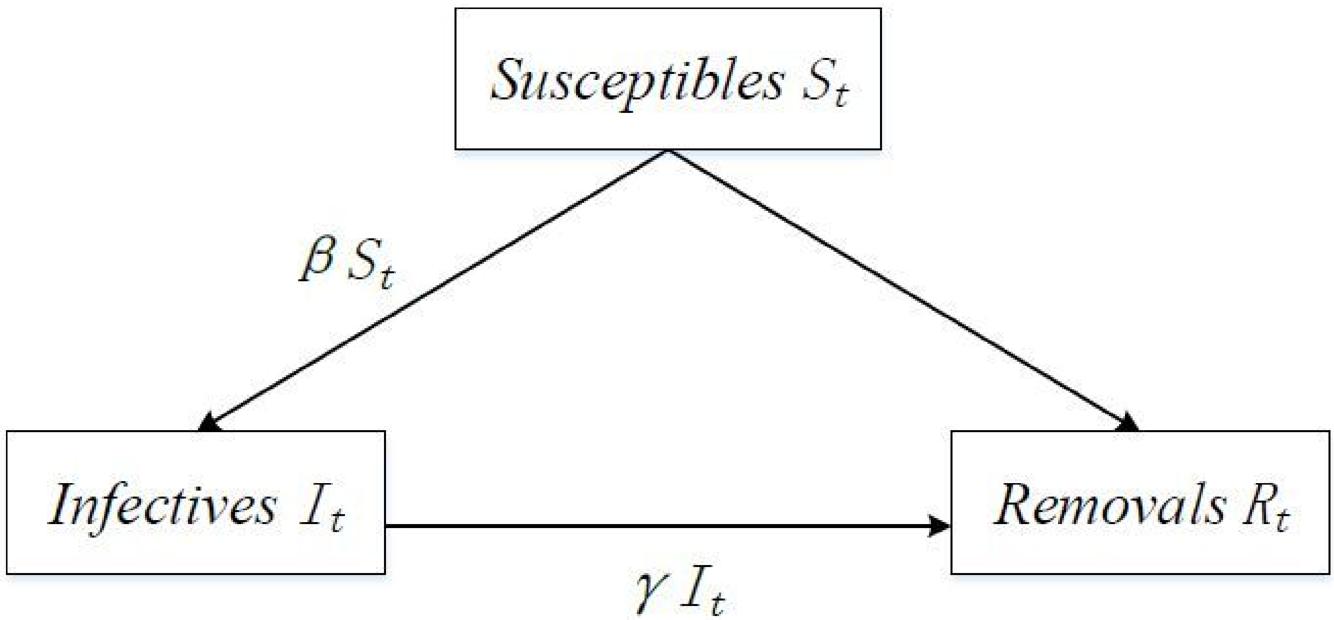

Figure 2

Novel coronavirus-infected transmission process based on SIR model Fig.

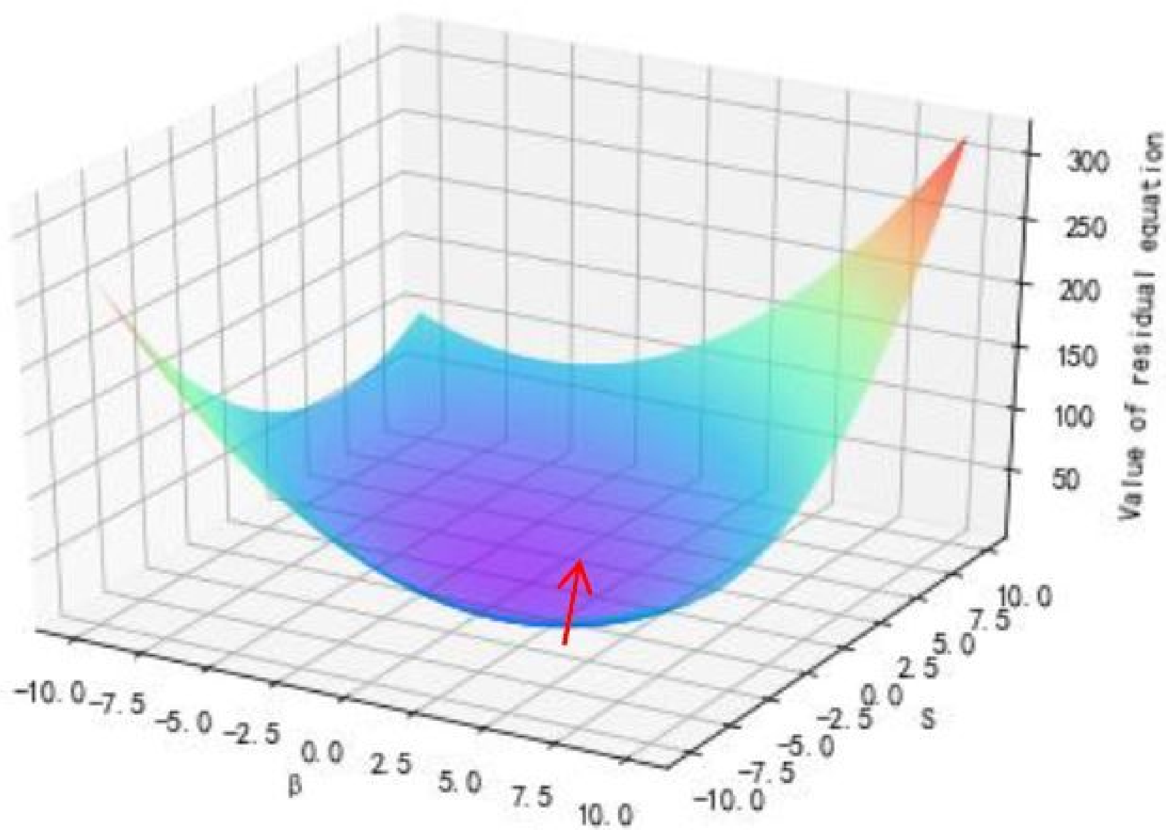

Figure 4

The least square estimation method for parameteres estimation

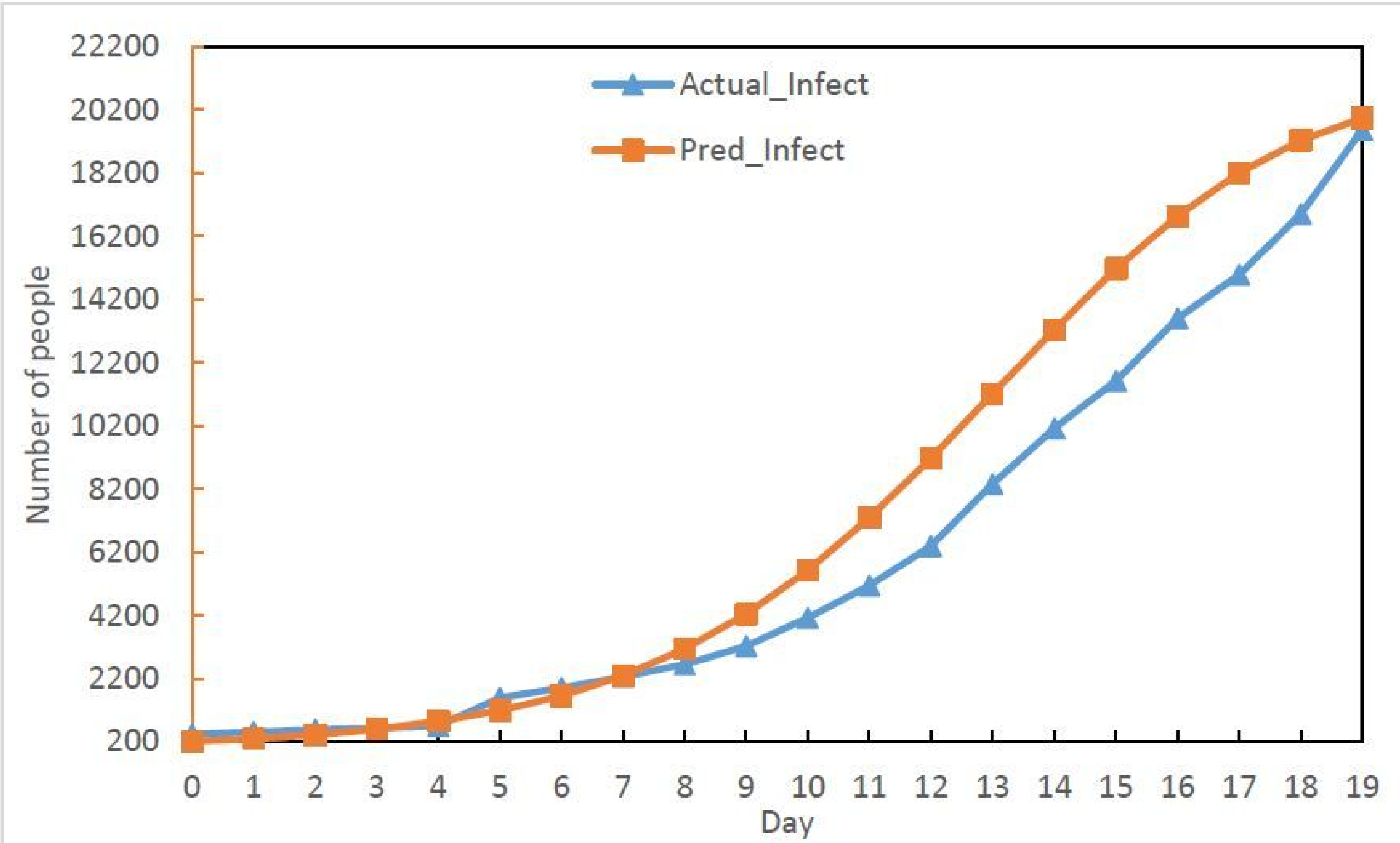

Figure 5

The predicted vs. Observed values for the SIR model for the infectives

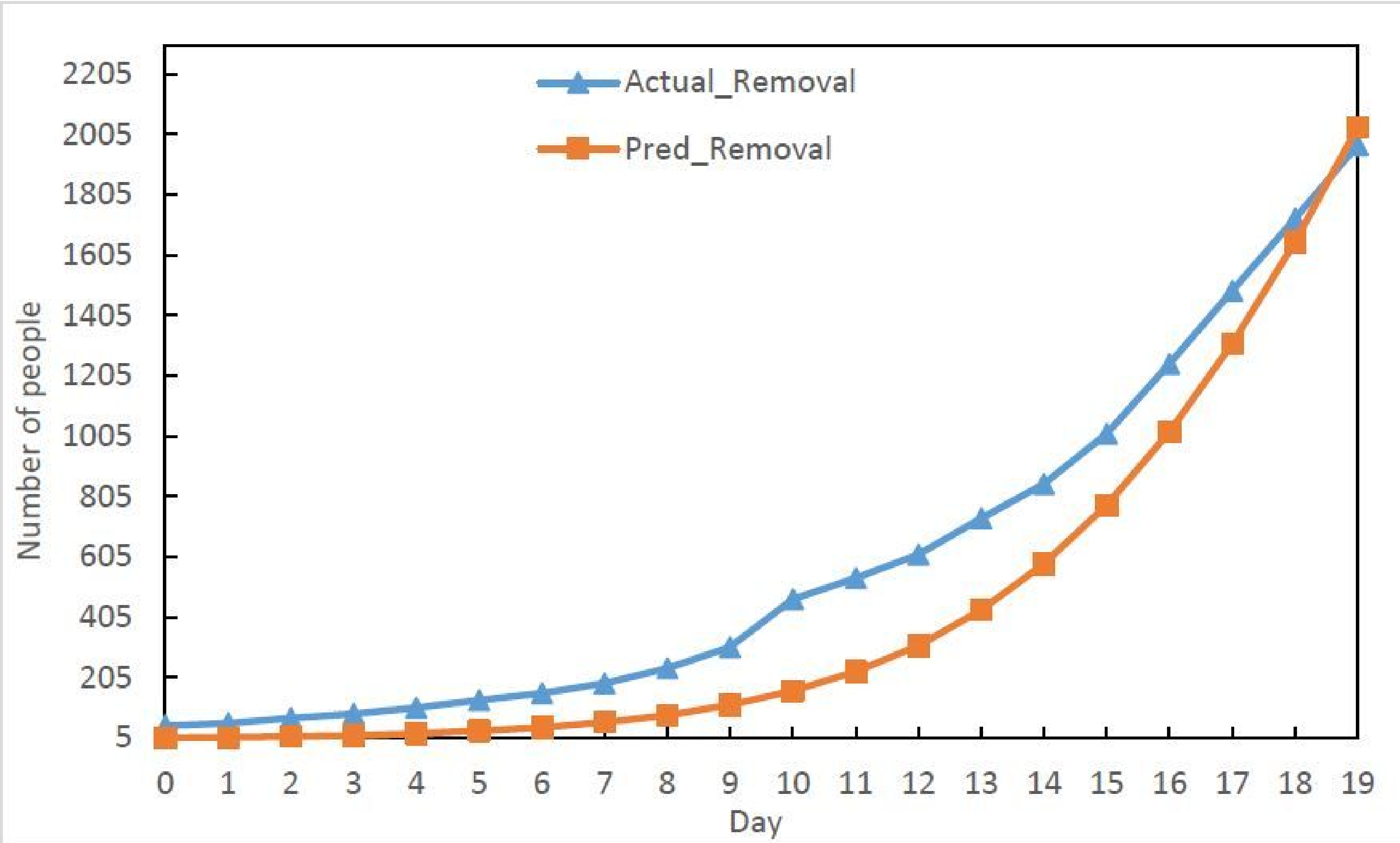

Figure 7

The predicted vs. Observed values of SIR model for the removals

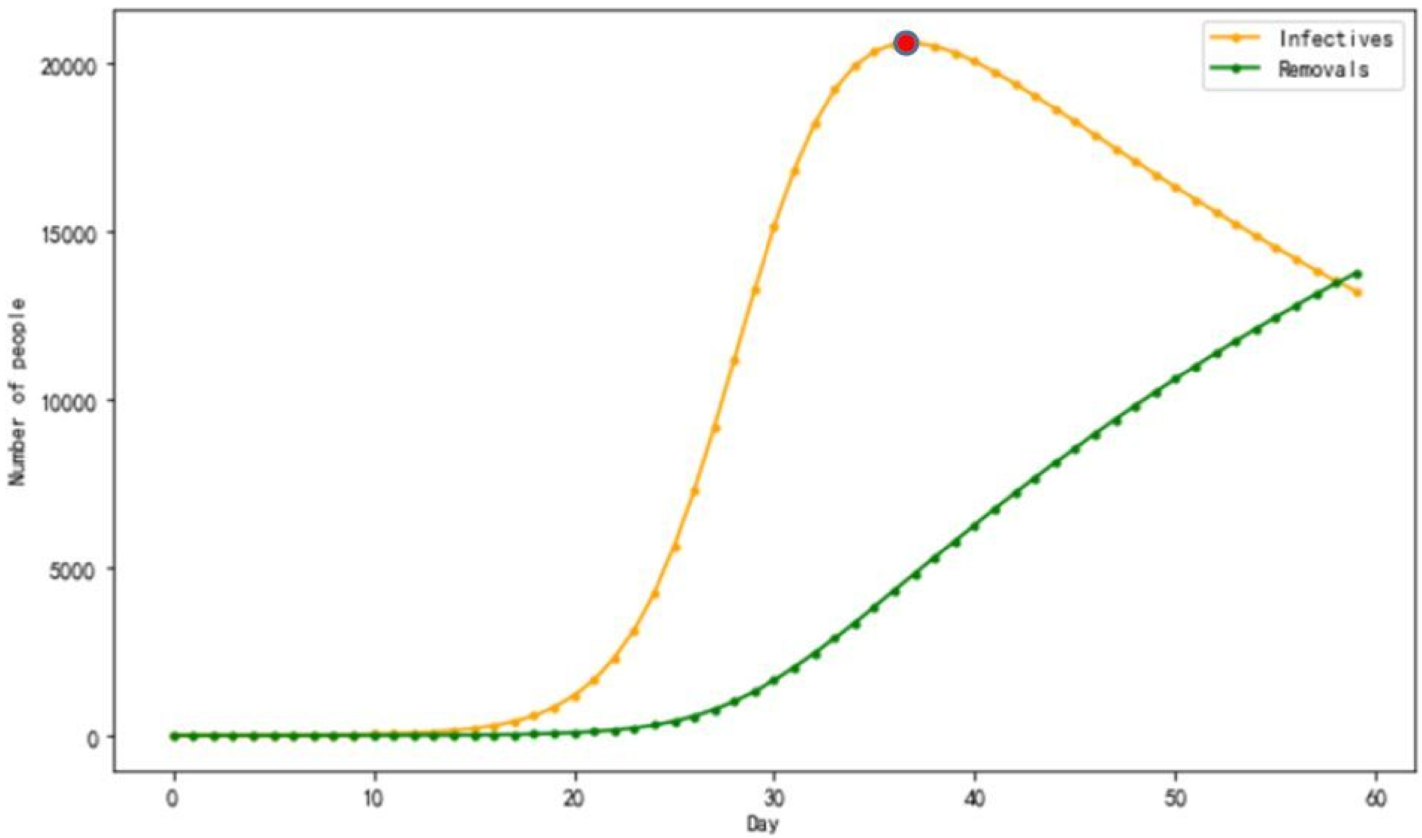

Figure 9

The prediction of SIR model for the infectives and removals

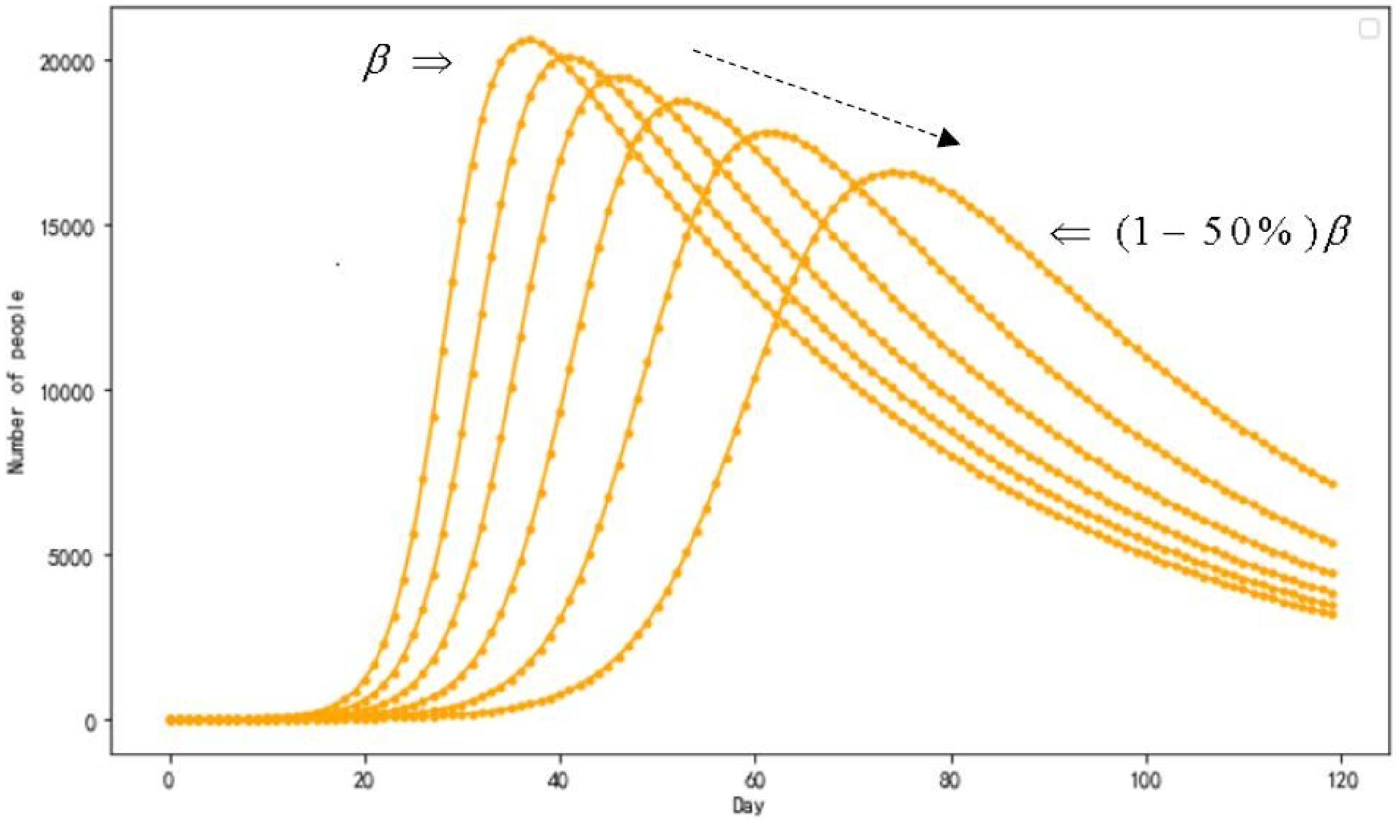

Figure 12

The influence of β on the development of epidemic in SIR model Fig.7.

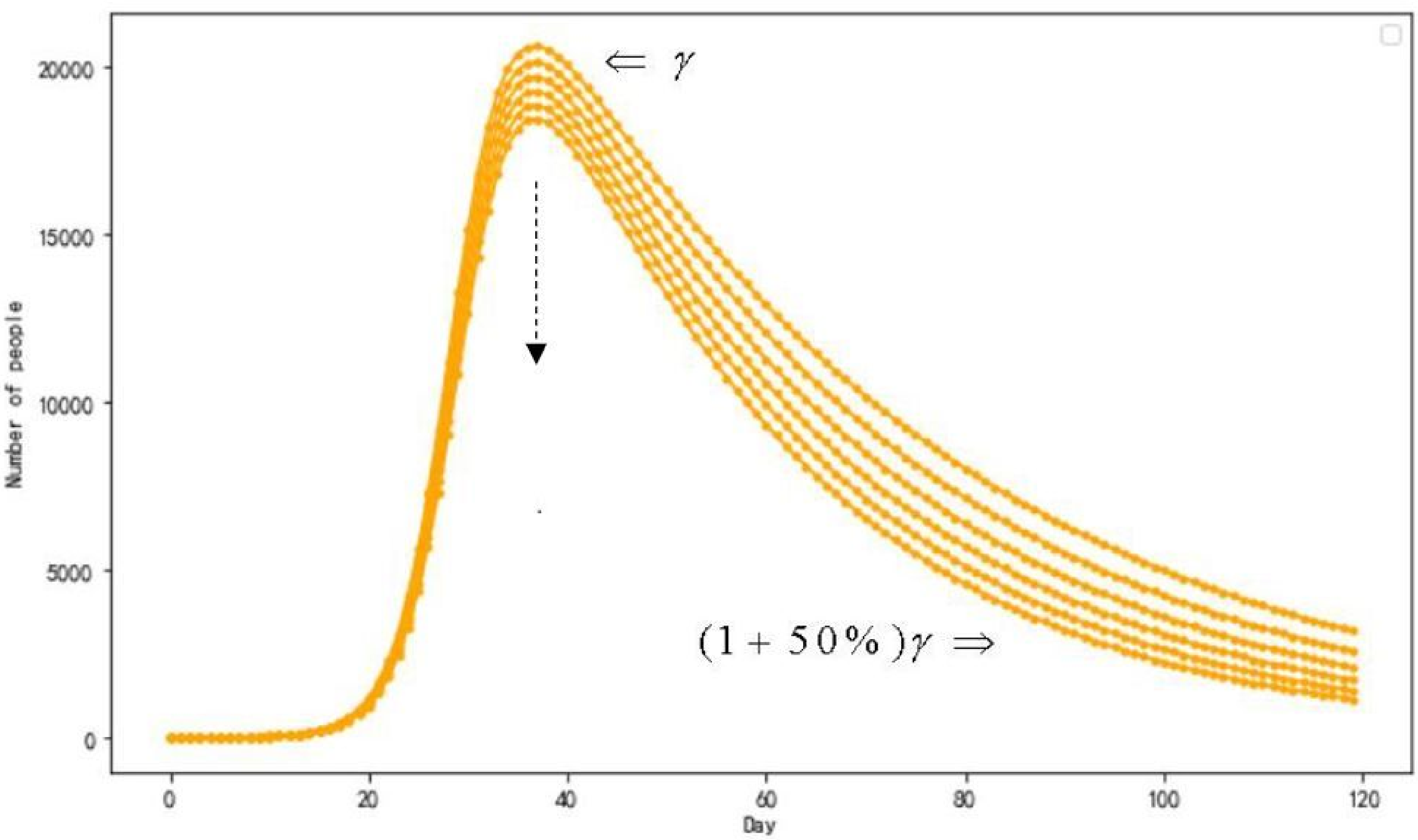

Figure 14

The influence of γ on the development of epidemic in SIR model

Supplementary Files

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