Simulation Prediction and Control Strategy of COVID-19 Dynamic Contact Network in USA and Various States -- Based on Effective Regeneration Number and Improved Discrete SEIQDHR Model

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Abstract. Purpose: Based on the latest characteristics of the transmission mechanism of the COVID-19 epidemic in the United States, this article improves the classic dynamics model of the spread of infectious diseases, simulates and predicts the future trend of the COVID-19 epidemic in the United States and various states. According to the computer program of COVID-19 dynamic contact network, the results provide effective control strategies for the future epidemic prevention work of the United States. Method: The SEIR model is improved by the latest effective reproduction number of the COVID-19 epidemic in the United States, and an improved discrete SEIQDHR model is established for the spread of the COVID-19 epidemic in the United States and various states. MATLAB software is used to perform least square fitting of key parameters, and the computer simulation process of COVID-19 dynamic contact network is solved dynamically. Results: The improved discrete SEIQDHR model is reliable in the analysis of the spread of infectious diseases. The model well simulates the current dynamic contact network of the COVID-19 epidemic in the United States. The results of computer program show that mid-to-late November 2020 is the period with the largest number of new diagnoses before the end of the epidemic in the United States. In a long period of time in the future, the cumulative number of confirmed cases in the United States and states will continue to show a clear upward trend. The cumulative number of confirmed cases of the COVID-19 epidemic in the United States will reach its peak in early December 2021, which is about 37.11 million; the cumulative number of confirmed cases in Texas will reach its peak on March 15, 2021, about 3.21 million. Controlling the source of infection, blocking the route of transmission and strengthening the tracking and isolation are still effective measures to prevent and control the epidemic.
Keywords: SEIR, dynamic contact network, COVID-19 in USA, simulation and control

1. Introduction
In December 2019, a novel coronavirus pneumonia broke out in Wuhan, Hubei Province, China. On January 12, 2020, the World Health Organization officially named the new coronavirus that caused the Wuhan pneumonia epidemic as 2019-nCoV, and named the symptoms caused by the virus as COVID-19 the following month [1-6]. 2019-nCoV spreads to the world in a short period of time, characterized by its extremely high transmission efficiency, severe infection consequences and hidden latency [7-10].

Due to the insufficient attention paid to the prevention and control of new coronary pneumonia in the United States, the cumulative number of confirmed cases and deaths of the COVID-19 epidemic has continued to increase since December 2019 [11][12]. In March 2020, the President of the United States announced a state of emergency in response to the new crown epidemic [13-17]. At this time, the cumulative number of confirmed cases of the COVID-19 epidemic has reached nearly 100,000, ranking first in the world [18][19]. The general election in November 2020 has made the United States more chaotic [20-25]. At this time, the cumulative number of confirmed cases in the United States has exceeded 3 million, and the death toll is nearly 37,000; by January 2021, the cumulative number of confirmed cases in the United States has exceeded 25 million. The death toll has exceeded 420,000 [26-30]. When will the US epidemic reach its peak and when will it be brought under control? Many scholars are concerned about it [31][32].

2. Improved seiqdhr model and its dynamic contact network

2.1. Data
First, The data used in this paper are from Johns Hopkins University, covering the number of newly diagnosed cases, cumulative confirmed cases, cumulative cured cases, cumulative deaths and cumulative number of close contacts in the United States from November 1, 2020 to January 16, 2021 [33-38]. First of all, we use a computer program to implement specific HTML codes to draw a new crown epidemic US population density map based on US population data, as shown in Figure 1.

![State epidemic situation map](image)

**Figure 1.** State epidemic situation map.

As shown in Figure 1, from April 2020 to January 2021, the overall development of the COVID-19 epidemic in the United States has become more and more severe [39][40]. The density of 2019-nCoV infections in all states in the United States is increasing, and the COVID-19 epidemic situation in the eastern U.S. urban agglomeration is the most serious [41][42]. The cumulative number of confirmed diagnoses in the eastern states of the United States has already exceeded 200,000 [43]. Therefore, based...
on the latest characteristics of the transmission mechanism of the COVID-19 epidemic in the United States, the classical dynamics model of infectious disease transmission will be improved, and the SEIQDHR model will be established for the dynamic contact network of the United States epidemic.

2.2. Theory and Establishment of SEIQDHR Model

The establishment of the COVID-19 epidemic dynamic model needs to focus on three aspects:

2.2.1. The propagation mechanism of 2019-nCoV. This is closely related to disease transmission parameters such as effective contact rate and basic reproduction number [44].

2.2.2. The characteristics of 2019-nCoV itself. 2019-nCoV has the characteristics of extremely high transmission efficiency, serious infection consequences and hidden latent methods [45].

2.2.3. The impact of government intervention on the spread of 2019-nCoV. The government often takes different measures to interfere with the spread of the epidemic at different stages of the development of the epidemic [46][47].

Combining the above three points, we establish a schematic diagram of the spread of the new crown epidemic in the United States, as shown in Figure 2. And the various parameters in the figure and their corresponding meanings are shown in Table 1.

![Figure 2. Schematic diagram of the spread of COVID-19 among People.](image)

| Sign    | Illustration                                       | Value  |
|---------|----------------------------------------------------|--------|
| \( f(t) \) | S to E incidence                                    | fixed  |
| \( g(t) \) | H to D incidence                                    | fixed  |
| \( \varepsilon \) | Proportion of E converted to I                     | fixed  |
| \( d_{id} \) | Rate of I transferred to D                         | 0.3333 |
| \( \delta_1 \) | Proportion of deaths among I                       | 0.0046 |
| \( d_{eq} \) | The rate of E converted to Q                        | fixed  |
| \( d_{qd} \) | The rate of Q diagnosed with D                      | 0.2210 |
| \( d_{qu} \) | The proportion of Q converted to S                  | 0.0337 |
| \( \delta \) | Probability of death of D due to treatment failure | 0.0046 |
| \( \gamma \) | The rate of recovery among D                        | 1/30   |
| \( C \)    | Contact rate                                        | fixed  |
| \( \beta(t) \) | Infections rate of the group I at time t            | 0.1    |
It can be seen from Figure 2 that the improved SEIQDHR infectious disease dynamic model based on the SEIR model we established divides the population into seven different parts, specifically $S(t)$—the general susceptible population in a free environment; $E(t)$—latent people who have been infected but have not developed the disease; $Q(t)$—suspected cases under isolation and observation; $D(t)$—people who have been diagnosed by observing the glassy shadows in the lungs; $I(t)$—have been infected and sick but have not been isolated and treated with highly infectious; $H(t)$—medical staff who take care of the confirmed patients, these people are very vulnerable to infection; $R(t)$—cured and discharged with antibodies to the new coronavirus[48][49]. The population imported from the outside world is denoted as $A_i$, which is transformed into the corresponding $S$, $E$, $I$, and $H$ groups in the proportion of $a_i$.

2019-nCoV is an infectious virus that can maintain a strong immunity for a long time after the infected person is cured [50]. Therefore, the choice is based on the classic SIR model of KM, combined with 2019-nCoV itself, which has extremely high transmission efficiency and serious infection consequences and hidden latent mode, and the 2019-nCoV transmission data after November 2020 in the United States, to establish the SEIQDHR infectious disease dynamic model, as follows:

$$\begin{align*}
\frac{dS}{dt} &= a_iA_i + d_qQ(t) - f(t) - d_qS(t), \\
\frac{dE}{dt} &= a_eE + f(t) - \epsilon E(t) - d_qE(t), \\
\frac{dI}{dt} &= a_hI - d_sI(t) - \delta I(t), \\
\frac{dQ}{dt} &= g(t) + s_qS(t) - d_qQ(t) - d_qQ(t), \\
\frac{dD}{dt} &= d_qQ(t) + d_sI(t) - (\gamma + \delta)D(t), \\
\frac{dH}{dt} &= A_h - g(t), \\
\frac{dR}{dt} &= \gamma D(t).
\end{align*}$$

This article adopts the standard incidence rate. Since newly infected patients in a free environment are infected by $E$ and $I$ populations. New medical patients in high-risk environments are infected by $Q$ and $D$ populations. The infection rate of $E$ populations is $\beta_E$. The infection rate of category I population is $\beta_I$. The infection rate of category Q population is $\beta_Q$. The infection rate of category D population is $\beta_D$, and the contact rate is $C$. Combined with the new crown schematic diagram of the spread of the epidemic in the population (Figure 2) and the SEIQDHR infectious disease dynamic model, the incidence rate $f(t)$ in the free environment and the incidence rate $g(t)$ in the high-risk environment can be described as follows:

$$g(t) = \frac{H(t)}{H(t) + Q(t) + D(t)} \times (\beta_Q CQ(t) + \beta_D CD(t))$$

$$f(t) = \frac{S(t)}{S(t) + E(t) + I(t) + R(t)} \times (\beta_E CE(t) + \beta_I CI(t))$$

3. Simulation prediction and control strategy

3.1. Simulation and prediction of COVID-19 in USA and Various States
Taking into account the availability of COVID-19 epidemic data in the United States, in order to use MATLAB software better for dynamic simulation during computer simulation, and to reduce the time complexity and space complexity of the dynamics transmission model of the epidemic in the computer
program implementation process, we will simplify the dynamics model and delete warehouse \( H \), ignoring the inflow and outflow of American people from abroad during the epidemic [51]. At the same time, because the time span of the epidemic dynamic contact network realized by the computer program is limited, and the transmission route of 2019-nCoV does not include vertical transmission, the impact of factors such as birth rate on the spread of the epidemic can be ignored, and the discrete form of SEIQDHR is finally established. The model is shown below:

\[
\begin{align*}
S(t+1) &= S(t) + d_w Q(t) - f(t) - d_d D(t) \\
E(t+1) &= E(t) + f(t) - eE(t) - d_d E(t) \\
D(t+1) &= D(t) + d_w Q(t) + d_d I(t) - (\gamma + \delta) D(t) \\
Q(t+1) &= Q(t) + d_w E(t) + d_w S(t) - d_w Q(t) - d_d Q(t) \\
I(t+1) &= I(t) + eE(t) - d_d I(t) - \delta I(t) \\
R(t+1) &= R(t) + \gamma D(t) \\
E(0) > 0, D(0) > 0, Q(0) > 0, R(0) > 0
\end{align*}
\]

Among them, using the ratio of the infection rate of the \( E \) patients and the \( I \) patients to convert the \( E \) group into the \( I \) group calculation, the expression of \( k \) is as follows:

\[
k = \frac{\beta_E}{\beta_I}
\]

The expression of incidence is as follows:

\[
f(t) = \frac{S(t)}{S(t) + E(t) + I(t) + R(t)} \times (\beta_E E(t) + \beta_I I(t))
= \frac{\beta_E C(t)}{S(t) + E(t) + I(t) + R(t)} (kE(t) + I(t))
\]

The infection rate of each type \( I \) patient can be expressed as:

\[
\beta(t) = \frac{\beta_E C(t)}{S(t) + E(t) + I(t) + R(t)} = \frac{f(t)}{I(t) + kE(t)}
\]

The infection rate of each type \( I \) patient can be expressed as:

\[
f(t) = \beta(t)[kE(t) + I(t)]
\]

Assuming that the cumulative number of confirmed diagnoses on day \( t \) is \( A(t) \), the relevant data show that the newly infected person will stay in a normal environment for eight days before isolation. At this time, the infection rate can be expressed as [52]:

\[
\beta(t) = \frac{f(t)}{I(t) + kE(t)} = \frac{A(t+8)}{A(t) + \sum_{i=1}^{8} A(t)}
\]

Considering that large-scale crowd movements such as demonstrations and rallies in the US presidential election in November 2020 will affect the number of patients with new coronary pneumonia, and make the prediction results fluctuate, we adopt the COVID-19 epidemic data from the beginning of November 1, 2020 to January 16, 2021 in the United States to carry out simulation [53] [54].
According to data released by Hopkins University, the initial value on November 1st is:

\[ P(0) = 19292 \quad Q(0) = 5185757 \quad R(0) = 115676 \]  

(10)

Through the formula (8) combined with the least square method, use MATLAB fitting to get \( \beta(t) \) expression as follow:

\[ \beta(t) = 0.9318 e^{0.0039 t} \]  

(11)

Use MATLAB to implement a computer program to perform least squares fitting on the data of the new crown epidemic in the United States from November 1 to January 26 to minimize the error between the fitted value and the true value, and solve the \( k \) value; use \( D(t) \) represents the true value at time \( t \), \( D_c(k, \beta(t, k)) \) represents the fitted value at time \( t \), and the expression of the error SSE is as follows:

\[ SSE = \min \sum_{i=1}^{77} \left\| D_c(k, \beta(t, k)) - D(t) \right\| \]  

(12)

In summary, we use MATLAB to perform computer simulation solutions, and use computer programs to implement dynamic simulations of the discrete format SEIQDHR model, and solve the cumulative number of diagnoses in the United States and the five most severe states of the new crown epidemic and the prediction results of the number of newly diagnosed people. As shown in Figure 3.

Figure 3. Forecast chart of confirmed cases in USA and some states.

It can be seen from Figure 3 that the dynamic simulation results of the computer program show that the COVID-19 epidemic in the United States will continue to show a clear upward trend for a long period of time in the future, and the current and future growth will be relatively rapid, and then gradually flatten out. The total number of confirmed diagnoses in the United States will reach a peak in early December 2021, reaching about 37.11 million. For some specific states, the timetable for the peak number of COVID-19 confirmed cases is shown in Table 2.
Table 2. Summaries of Cumulative Confirmed Cases

| Area   | Peak Time | Peak Value         |
|--------|-----------|--------------------|
| USA    | 2021/12/01| 37.11million       |
| California | 2021/3/30| 2.22 million       |
| Florida | 2021/8/27 | 1.86 million       |
| Illinois| 2021/5/19 | 1.38 million       |
| Ohio   | 2021/12/05| 1.51 million       |
| Texas  | 2021/3/15 | 3.21 million       |

Figure 4. People. Forecast chart of new confirmed cases in USA and some states.

It can be seen from Figure 4 that mid-to-late November 2020 is the period when the number of newly diagnosed COVID-19 epidemic in the United States has increased the fastest. On November 22, 2020, the overall number of newly confirmed diagnoses in the United States reached a peak of 211,183. Although the period of the fastest increase in the number of newly diagnosed people in the United States has passed, the number of people infected with 2019-nCoV is still increasing at a rapid rate and will continue for some time. The overall situation of the COVID-19 epidemic in the United States is still not optimistic. The government needs to attach great importance to this epidemic and gives full play to its prevention and control functions.

3.2. Control strategy for COVID-19 dynamic contact network

In infectious diseases, the basic reproduction number R0 can reflect the control of the epidemic, if $R_0 > 1$, it indicates that the epidemic is still increasing and the difficulty of prevention and control is increasing. If $R_0 < 1$, it means that the epidemic situation is getting better. Combined with the equations [55], the average incubation period of the new coronavirus pneumonia is $\frac{1}{\varepsilon + d_{eq}}$. The ratio of latent persons to diseased persons is $\frac{\varepsilon}{\varepsilon + d_{eq}}$. The average time for a virus carrier to be diagnosed is $\frac{1}{d_{iq} + d_{eq}}$.

In summary, the basic regeneration number obtained by the definition can be expressed as:

$$R_0 = \frac{k\beta}{\varepsilon + d_{eq}} + \frac{\beta\varepsilon}{(\varepsilon + d_{eq})(d_{eq} + d_{iq})}$$  (13)
Since the government will improve relevant measures during the epidemic, we use the effective reproduction number $R(t)$ to reflect the number of people infected during the infection process at time $t$ as follow:

$$R(t) = R_e \frac{S(t)}{S + E + I + R}$$

(14)

To control the epidemic, it is necessary to control the effective reproduction number $R<1$ [56]. Through the relevant data of the COVID-19 epidemic in the United States from November 1, 2020 to January 16, 2021, the effective reproduction number over time can be described as shown in Figure 5.

Figure 5. Sequence diagram of effective reproducing number.

It can be seen from Figure 5 that although the value of the effective reproduction number has two major fluctuations in the next 7 months, the overall trend is gradually decreasing. The current effective reproduction number of the new crown pneumonia virus in the United States has gradually decreased to less than 1, and has stabilized at about 0.8, indicating that the United States is still controllable. Based on the actual situation, the current isolation policy and the requirement to wear masks in the United States have played a certain role in slowing down the surge in the cumulative number of confirmed cases.

The cumulative number of confirmed diagnoses in the United States reflects the overall situation of the epidemic, and the ratio of the infection rate of the 2019-nCoV incubation period to the patient's infection rate (Referred to the infection ratio, denoted as $k$) and the mortality rate of 2019-nCoV infection are controlled and analyzed, and the cumulative diagnosis has been obtained [57]. Figure 6 shows the relationship between the number of cumulative confirmed cases and the infection ratio and mortality rate.
Figure 6. Control strategy simulation of infection ratio (top) and mortality (bottom).

The dynamic simulation results in Figure 6 show that the infection ratio has a great influence on the overall situation of the US epidemic. The peak of the cumulative number of diagnoses fluctuates in the upper and lower range of $k=1$, and the peak of the cumulative number of diagnoses is the lowest when the infection ratio $k$ is 0.75. This shows that the ratio of the infection rate of the latent population to the infection rate of the unisolated sick population should be controlled in an appropriate range to effectively control the spread of the epidemic. In this regard, the United States should increase the scope of nucleic acid testing, shorten the time to screen for people who may be carrying the virus, and take timely isolation measures to reduce the probability of infection among latent populations. On the other hand, people who have developed the disease should also be isolated and treated in time. This is necessary for the prevention and control of the US epidemic.

As you can see from the picture on the bottom, the change in mortality has little effect on the cumulative number of confirmed cases, indicating that the virus in the body of the 2019-nCoV infected person is low after death. As long as it is handled in a timely manner, it will not have much impact on the COVID-19 epidemic in the United States.

4. Conclusion

This article collects and collates data on various indicators of the new crown pneumonia epidemic in the United States from January 2020 to January 2021. Through the establishment of an improved discretized SEIQDHR model, the current dynamic contact network of the COVID-19 epidemic in the United States is simulated by computer, and the development law of the epidemic in the United States is analyzed and predicted, and effective control strategies are given for epidemic prevention. The research results show
that the established SEIQDHR model can provide reliable theoretical support for the formulation of future epidemic intervention decisions. For a long period of time in the future, the COVID-19 epidemic in the United States will generally show a clear upward trend, and the number of 2019-nCoV infections will continue to increase rapidly at present and in the future. From the perspective of the government, restraining the source of infection, blocking the route of transmission, strengthening tracking and quarantine and other ways to reduce the infection rate are still effective measures to prevent and control the epidemic. The US government needs to attach great importance to this epidemic and give full play to the government's prevention and control of the epidemic functions.

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