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Coronavirus Pandemic

Long-term predictions of COVID-19 waves in China based on an improved SEIRS-Q model of antibody failure

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Abstract

Introduction: China had already experienced two COVID-19 epidemics since the promulgation of 10 new prevention and control measures in December 2022.

Methodology: In response to the current frequent epidemics of severe acute respiratory syndrome coronavirus 2 variants in China and the gradual relaxation of prevention and control policies, we built and ran a susceptible-exposed-infective-removed-susceptible-quarantined model incorporating self-isolation to predict future cases of COVID-19.

Results: Four waves of outbreaks were predicted to occur in November 2023, and in April, July, and November 2024. The first two waves were predicted to be more severe, with the maximum number of infected cases reaching 18.97% (269 million) and 8.77% (124 million) of the country's population, respectively, while the rest were predicted to affect a maximum of < 3%.

Conclusions: Future outbreaks are expected to occur at shorter intervals but last for longer durations. COVID-19 epidemics in China are expected to subside after November 2024.

Key words: Antibody failure; China; COVID-19; fluctuating epidemic; SEIR model.

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Introduction

Despite the promulgation of 10 new measures, China is likely to experience several waves of coronavirus disease 2019 (COVID-19) infections that will affect the healthcare systems in every city nationwide. In this context, conducting a predictive analysis of possible epidemics is important to ensure timely and effective responses to these waves.

On 7 December 2022, China's State Council issued a notice on further optimising the implementation of prevention and control measures for COVID-19, namely, the '10 new measures' [1], signalling a shift in policy direction to gradually lift travel restrictions [2]. Subsequently, the number of COVID-19 cases owing to the BA.5.2 strain and its sub-branches increased dramatically in many cities across China, with daily numbers reaching a peak around 21 December 2022. Within 6 months, the XBB strain and its sub-branches replaced BA5.2 as the main strain in China, with the peak of infection occurring around 28 May 2023 [3]. Given the increasing mutant rate of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), the general susceptibility of the population to new strains, abolishment of mandatory quarantine and nucleic acid testing, and a large number of people not wearing masks and having contact with each other in a short period, these new mutated strains are expected to cause more rapid infection waves in the future.

The antibodies produced in response to COVID-19 last for only 4–6 months; therefore, an epidemic infecting millions of people could theoretically arise in China every 6 months [4]. However, the 6-month infection cycle is an estimation based on expert opinion only. Despite the declining virulence of SARS-CoV-2 variants and with decreasing infectiousness and pathogenicity [5], modelling the prevalence and trend of COVID-19 in China over the near future is worthwhile. Therefore, we used an improved susceptible-exposed-infective-removed-susceptible-quarantined (SEIRS-Q) model incorporating antibody failure to predict the prevalence of COVID-19 within 3 years of the promulgation of the 10 new measures, aiming to provide public health policymakers with a reference for implementing prevention and control counterstrategies.

Methodology

The study model

The SEIR-Q model for infectious disease dynamics has been widely used for predicting COVID-19 outbreaks, with its scientific validity and feasibility having been confirmed [6,7]. Considering the negligible rate of severe illness in relation to the current prevalent strain in China and that mandatory quarantine and nucleic acid testing has been lifted, an improved SEIRS-Q model was used to divide the Chinese population into susceptible (S), exposed (E), symptomatic (I_s), asymptomatic (I_a), self-quarantined (Q), and removed (R) categories (Figure 1). The disease model is presented using seven equations related to the course of the pandemic as follows:

$$\frac{dS}{dt} = -\frac{r_{Is}\beta_{Is}SI_s}{N} - \frac{r_{Ia}\beta_{Ia}SI_a}{N} + fR$$

$$\frac{dE}{dt} = \frac{r_{Is}\beta_{Is}SI_s}{N} + \frac{r_{Ia}\beta_{Ia}SI_a}{N} - \frac{1}{\alpha}CE - \frac{1}{\alpha}(1-C)E$$

$$\frac{dI_s}{dt} = \frac{1}{\alpha}CE - \frac{1}{\gamma_s}I_s - qI_s$$

$$\frac{dI_a}{dt} = \frac{1}{\alpha}(1-C)E - \frac{1}{\gamma_a}I_a$$

$$\frac{dQ}{dt} = qI_s - \frac{1}{\gamma_s}Q$$

$$\frac{dR}{dt} = \frac{1}{\gamma_s}I_s + \frac{1}{\gamma_a}I_a + \frac{1}{\gamma_s}Q - fR$$

$$N(t) = S(t) + E(t) + I_s(t) + I_a(t) + Q(t) + R(t)$$

where α represents the disease incubation period, C represents the proportion of exposed individuals who become symptomatic patients, and Q represents the proportion of symptomatic patients who self-quarantined. It is important to note that Q in our model refers to self-quarantined people because the quarantine policy has changed from mandatory to voluntary quarantine subsequent to the implementation of the '10 new measures', resulting in the quarantine rate reducing from 100% to a very low level. γ_s and γ_a represent the average recovery times of symptomatic and asymptomatic patients, respectively, where symptomatic, asymptomatic, and self-quarantined patient data cannot be converted back during an infection process. f represents the antibody failure rate of removed patients, mainly reflecting that after a set period, f of removed people will be converted back into that of susceptible people. In addition, over the predicted time, f will gradually decrease with each antibody failure period. Definitions and assumptions of all other parameters are consistent with the basic SEIR model, and parameter settings are shown in Table 1.

We started running the model on 7 December 2022, simulating an epidemic of COVID-19 cases in China within 3 years following the 10 new measures. Data were obtained from China's National Health Commission and Center for Disease Control and Prevention (CDC) reports using web crawlers. A comparison set before 3 July 2023 was used to validate our model, including two reported spikes in December 2022 and June 2023, with subsequent times used as a prediction set. The comparison and prediction set proportions were 25% and 75%, respectively.

In the comparison set, the fitting results of our model were consistent with positivity rates of SARS-CoV-2 surveillance in sentinel hospitals deployed by the Chinese CDC and predicted two epidemics of the BA5.2 and XBB strains within the correct timeframe (root mean square error [RMSE] = 288.10, r = 0.79, $p < 0.05$; Figure 2).

Results

Our model predicted that there would be six waves of COVID-19 in China between 18 December 2022 and 16 November 2024 (Table 2). The percentages of infected cases at the peaks of these six waves were

Figure 1. Schematic presentation of the improved susceptible-exposed-infective-removed-susceptible-quarantined (SEIRS-Q) model.

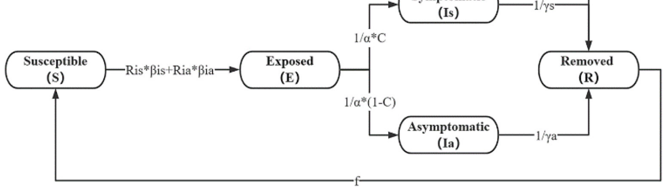


Table 1. Parameters of an improved susceptible-exposed-infective-recovered-susceptible-quarantined (SEIRS-Q) model with the addition of antibody failure.

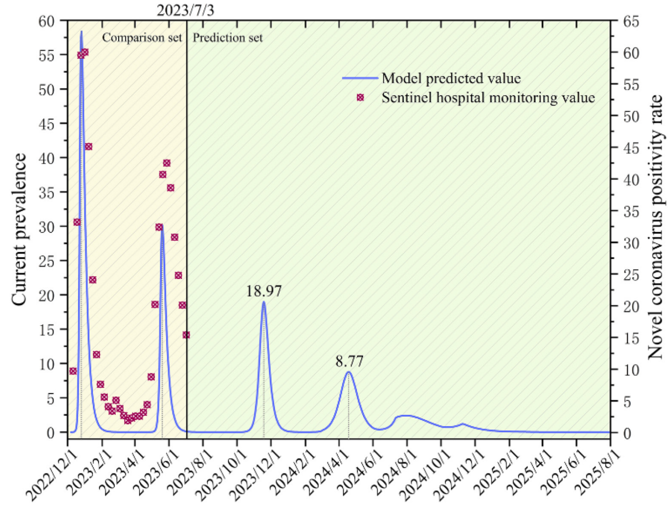
Parameter	Value
$r_{Is}r_{Ia}$	10
$\beta_{Is}\beta_{Ia}$	8
α	3
C	0.7
q	0.5
γ_s	10
γ_a	7
f (After 120–160 days of recovery)	0.9

$r_{Is}r_{Ia}$, $\beta_{Is}\beta_{Ia}$ and f decreases for each wave, decreasing to 90% of the original value.

predicted to be 8.38%, 30.15%, 18.97%, 8.77%, 2.41%, and 1.19% of the total population of China, respectively. COVID-19 is not expected to cause large-scale epidemics after November 2024 in China. The duration of the six waves of infection was predicted to be 31, 46, 45, 61, 73, and 13 days, respectively.

China experienced a surge of SARS-CoV-2 infections within 20 days of lifting restrictions on movement and travel. At the peak of the first wave, approximately 55% of the national population was infected, with a cumulative infection rate exceeding 80%. At the peak of the second wave, the infection rate was 30%, indicating an approximately 25% reduction from the first wave. Infection rates in the third and fourth waves are expected to continue to decrease, with each wave showing a linear reduction of approximately 60% from the previous wave. While the time interval between each wave is predicted to shorten, which could lead to the merging of the last two waves, the duration of infection can be expected to gradually increase with each wave of the epidemic owing to future mutant strains. One possible reason for this is that the infectiousness and pathogenicity of the SARS-CoV-2 variants decline over time, resulting in shorter recovery times for each wave [8].

Figure 2. Simulation of the prevalence of COVID-19 in China after the promulgation of the '10 new measures'.



The x-axis is the date. The model prediction values correspond to the left y-axis, and the sentinel hospital monitoring values correspond to the right y-axis. The yellow area represents the comparison set and the green area represents the prediction set.

Discussion

China has accumulated considerable experience in the prevention and control of COVID-19 [9,10]. In future COVID-19 epidemics, the government and public health departments should formulate corresponding response and control measures for different scenarios before the onset of each future wave, including stockpiling of vaccines and drugs, management of hospital beds, and ensuring the availability of emergency medical personnel.

This study had some limitations. Following promulgation of the 10 new measures, the number of daily new cases has no longer been officially counted and published. Thus, data can only be obtained through monthly reports from the Chinese CDC. Moreover, in this study period, only approximate estimates were provided through news reports; therefore, the accuracy of the model could only be verified according to trend, not exact values.

Conclusions

This study simulated the overall epidemic trend of COVID-19 in China after the 10 new measures were promulgated on 7 December 2022, using an improved SEIR-Q model of antibody failure. Our results predicted that China would experience four more waves of COVID-19 after December 2022, lasting until November 2024, after which the outbreaks would gradually subside. Our findings may help government and public health departments in decision-making and information support in preparation of future epidemics.

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Table 2. The two waves of outbreaks that have already occurred and the future outbreaks predicted by the model.

Wave	Start date	Peak date	End date	Time interval between waves (days)
Comparison set				
1	2022/12/18	2022/12/26	2023/1/18	-
2	2023/5/10	2023/5/20	2023/6/15	112
Prediction set				
3	2023/11/2	2023/11/18	2023/12/17	140
4	2024/3/17	2024/4/18	2024/5/17	91
5	2024/7/9	2024/7/30	2024/9/20	53
6	2024/11/3	2024/11/9	2024/11/16	44

Time to last wave refers to the time difference between the end time and the start time.

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Conflict of interests

No conflict of interests is declared.

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