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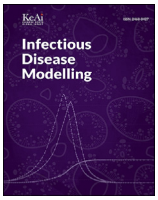

Estimating cumulative infection rate of COVID-19 after adjusting the dynamic zero-COVID policy in China

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ABSTRACT

Background: At the end of 2022, China adjusted its coronavirus disease 2019 (COVID-19) prevention and control strategy. How this adjustment affected the cumulative infection rate is debated, and how second booster dose vaccination affected the pandemic remains unclear.

Methods: We collected COVID-19 case data for China's mainland from December 7, 2022, to January 7, 2023, reported by the World Health Organization. We also collected cumulative infection rate data from five large-scale population-based surveys. Next, we developed a dynamic transmission compartment model to characterize the COVID-19 pandemic and to estimate the cumulative infection rate. In addition, we estimated the impact of second booster vaccination on the pandemic by examining nine scenarios with different vaccination coverages (0%, 20%, and 40%) and vaccine effectiveness (30%, 50%, and 70%).

Results: By January 7, 2023, when COVID-19 was classified as a Class B infectious disease, the cumulative infection rate of the Omicron variant nationwide had reached 84.11% (95% confidence interval [CI]: 78.13%–90.08%). We estimated that the cumulative infection rates reached 50.50% (95% CI: 39.58%–61.43%), 56.15% (95% CI: 49.05%–67.22%), 73.82% (95% CI: 64.63%–83.02%), 75.76% (95% CI: 67.02%–84.50%), and 84.99% (95% CI: 79.45%–90.53%) on December 19, 20, 25, and 26, 2022, and on January 15, 2023, respectively. These results are similar to those of the population survey conducted on the corresponding dates, that is 46.93%, 61%, 63.52%, 74%, and 84.7%, respectively. In addition, we estimated that by January 7, 2023, the cumulative infection rate decreased to 29.55% (64.25%) if vaccination coverage and the effectiveness of second booster vaccination were 40% (20%) and 70% (30%), respectively.

Conclusion: We estimate that, in late 2022, the cumulative infection rate was approximately 84% and that second booster vaccination before the policy adjustment was effective in reducing this rate.

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1. Introduction

Coronavirus disease 2019 (COVID-19) is an acute respiratory disease caused by infection with severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), a pathogen known for its high transmissibility and pathogenicity (Yang et al., 2022). Thus, the global COVID-19 pandemic has imposed tremendous social, economic, and medical burdens on countries. According to the World Health Organization (WHO), as of January 7, 2023, 94,449,740 confirmed cases of COVID-19 had been reported in China (WHO, 2023). The Omicron variant of SARS-CoV-2 was initially found in China at the end of 2021 and became dominant in early 2022, due to its having a shorter generation interval, increased infectivity, enhanced ability to evade neutralizing antibodies, and more covert transmission process than other variants (Feng et al., 2022; Kwon, 2022; Li et al., 2022; National Health Commission of the People's Republic of China, 2023a; Park et al., 2023; Schmidt et al., 2021).

From the beginning of the pandemic, China implemented stringent non-pharmaceutical interventions, such as travel restrictions, nucleic acid testing, and tracing and isolation of cases and close contacts and conducted large-scale SARS-CoV-2 vaccination campaigns when vaccines became available (Chinese Center for Disease Control and Prevention, 2023; Wilder-Smith & Freedman, 2020; Yao et al., 2021). These measures effectively controlled the pandemic in China. On November 11, 2022, China announced 20 measures to further promote COVID-19 prevention and control and on December 7, 2022, released an optimized “Ten New Measures” policy (National Health Commission of the People's Republic of China, 2022a; Xinhua, 2022). The 20 measures reduced the rigor of prevention and control measures, such as by decreasing coverage for SARS-CoV-2 testing, decreasing the required isolation time for close contacts or people entering China, and ceasing tracing of secondary close contacts. The “Ten New Measures” allowed home isolation and further reduced the scope of nucleic acid testing, such that except for high-risk populations, SARS-CoV-2 testing was conducted according to individual needs. On January 8, 2023, China downgraded the management of COVID-19 to that of a Class B disease (National Health Commission of the People's Republic of China, 2023c). In addition, after the adjustment of the COVID-19 prevention and control policy in December 2022, China issued recommendations and plans for second booster vaccination (National Health Commission of the People's Republic of China, 2022b). Compared with three doses of a SARS-CoV-2 vaccine, second booster vaccination was found to be more effective at preventing SARS-CoV-2 infection and severe COVID-19, but the impact of second booster vaccination on the increase in COVID-19 cases in late 2022 in China is unclear (Bar-On et al., 2022; Cohen, Oster, Moses, Spitzer, & Benenson, 2022; Regev-Yochay et al., 2022). This impact was examined in the present study.

The influences of dynamically adjusted COVID-19 prevention and control policies on the pandemic have been explored previously using a modified susceptible—exposed—infected—removed (SEIR) model with vaccination, isolation, and severe illness compartments (Cai et al., 2022; Liu et al., 2021). In addition, in the early stages of the pandemic, the effectiveness of lockdown and isolation polices was assessed using the susceptible—exposed—infected—quarantined—recovered model, among others, and how to adjust intervention measures to improve control of the pandemic was examined (Shen, Peng, Guo, et al., 2020; Shen, Peng, Xiao, & Zhang, 2020). After the introduction of SARS-CoV-2 vaccines, dynamic models with vaccination compartments were developed to investigate the effectiveness of vaccines and to optimize the allocation of vaccine resources (Shen, Xiao, Zhuang, Li, & Zhang, 2021; Shen, Zu, et al., 2021). Moreover, dynamic modeling has been performed to investigate the status of the COVID-19 pandemic after policy optimization at the end of 2022. For example, Goldberg, Lin, Romero-Severson, and Ke (2023) developed an SEIR-type model for the pandemic at the end of 2022 and estimated that the China-wide SARS-CoV-2 infection rate reached 97% (95% confidence interval [CI]: 95%—99%) in December 2022. However, the results of two national online surveys (Chinese Ministry of Human Resources and Social Security, 2023a, 2023b), suggest that the infection rate estimated by Goldberg et al. (2023) may be an overestimate of the true size of the pandemic, because they used an online self-reported survey. Similarly, Leung, Lau, Wong, Leung, and Wu (2023) estimated that the cumulative infection rate of COVID-19 in Beijing reached 75.7% two weeks after the policy adjustment. However, their model assumed a linear increase in the scaling factor for mobility data in mid-November, so their estimates suggest that the effective reproduction number peaked during this period and that many infections had already accumulated. This is inconsistent with the reality that a large number of interventions remained implemented at this time. Thus, they may have estimated a larger number of infected individuals, which would have further impacted the transmission of SARS-CoV-2 in December, leading to their obtaining an inaccurate final cumulative infection rate. In addition, neither of these studies accounted for changes in detection rates under the new policy.

Accordingly, in the present study, we developed a model that integrates the previously discussed factors. Specifically, we used data from the WHO to construct a susceptible—exposed—asymptomatic—symptomatic—tested—recovered (SEAITR) model to estimate the SARS-CoV-2 Omicron variant infection rate in China during the implementation of the “Ten New Measures.” Moreover, we incorporated multi-source survey data to improve the accuracy and reliability of the model-simulated results. We also investigated the impact of early second booster vaccination on the pandemic. Our results provided theoretical evidence that allowed estimation of cumulative infection rates and the impact of second booster vaccination, which can provide guidance for future infectious disease prevention and control measures.

2. Methods

2.1. Data source

Reported COVID-19 cases were collected from WHO region-specific dashboards and/or aggregated counts reported to WHO Headquarters (WHO, 2023). The date represented the date of reporting, rather than the date of symptom onset. In addition, all data were verified and updated retrospectively. Data were collected on the reported daily numbers of new cases of COVID-19 in China's mainland from December 7, 2022, to January 7, 2023.

Cumulative infection rates obtained from two large-scale national surveys (Chinese Ministry of Human Resources and Social Security, 2023a, 2023b), two surveys in Sichuan Province (Sichuan Center for Disease Control and Prevention, 2023), and one survey in Shaanxi Province (Zhang et al., 2023) were used to calibrate the model.

The period for which COVID-19 data were collected was when policies implemented in response to the pandemic in China were changed. COVID-19 prevention and control measures were derived from the official notices and announcements of the National Health Commission of the People's Republic of China.

2.2. SEAITR model

An SEAITR model was developed to describe the pandemic during the implementation of the “Ten New Measures” (see Fig. 1). People infected with SARS-CoV-2 variants were classified as asymptomatic cases (A) or symptomatic cases (I). SARS-CoV-2 testing was mandatory for residents of high-risk areas and workers in high-risk positions, such as service workers in crowded working environments, medical personnel in fever clinics, and workers in direct contact with inbound persons, objects, and the environment, but voluntary for others (National Health Commission of the People's Republic of China, 2022c). Therefore, cases of COVID-19 confirmed by nucleic acid or antigen testing were defined as the tested population (T). As mandatory isolation measures were cancelled during this period, the exposed population (E), A, I, and T could transmit SARS-CoV-2. It was assumed that all people infected with SARS-CoV-2 variants spontaneously recovered.

The following model equation was derived based on the SEAITR model. Detailed descriptions and values of parameters and compartments are listed in Table 1.

$$\begin{cases}
\dfrac{dS}{dt} = -\beta S(E+A+I+T)\Big/N \\
\dfrac{dE}{dt} = \beta S(E+A+I+T)\Big/N - \omega E \\
\dfrac{dA}{dt} = (1-\rho)\omega E - \delta_1 A - \gamma_1 A \\
\dfrac{dI}{dt} = \rho\omega E - \delta_2 I - \gamma_2 I \\
\dfrac{dT}{dt} = \delta_1 A + \delta_2 I - \gamma_3 T \\
\dfrac{dR}{dt} = \gamma_1 A + \gamma_2 I + \gamma_3 T
\end{cases} \tag{1}$$

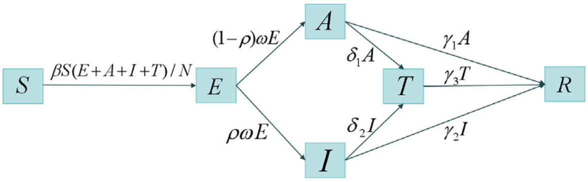

Fig. 1. Schematic representation of the SEAITR model. Here, S denotes susceptible individuals, E denotes exposed individuals, A denotes asymptomatic individuals, I denotes symptomatic individuals, T denotes tested individuals, R denotes recovered individuals.

Table 1
Definitions and values of parameters and compartments in the susceptible–exposed–asymptomatic–symptomatic–tested–recovered model.

Parameter/ compartment	Definition	Value	Source
β	Transmission rate	–	Calculated
c_0	Minimum transmission rate	0.085 (0.079–0.091)	Estimated
c_1	Adjustment coefficient	0.730 (0.673–0.787)	Estimated
c_2	Exponential decline rate of transmission rate	0.090 (0.084–0.096)	Estimated
δ_1	Detection rate of asymptomatic cases	0.010 (0.005–0.015)	Estimated
δ_2	Detection rate of symptomatic cases	0.016 (0.012–0.021)	Estimated
ρ	Proportion of symptomatic cases	97%	(Goldberg et al., 2023; Liu et al., 2023)
ω	Transition rate from exposed to infectious	1/3.4	Wu et al. (2022)
γ_1	Recovery rate of asymptomatic cases	1/5.7	Goldberg et al. (2023)
γ_2	Recovery rate of symptomatic cases	1/5.7	Goldberg et al. (2023)
γ_3	Recovery rate of tested individuals	1/5.7	Goldberg et al. (2023)
$N(0)$	Total population	1,411,750,000	National Bureau of Statistics (2023)
$S(0)$	Initial susceptible population	$N(0)$- $E(0)$- $A(0)$- $I(0)$- $T(0)$- $R(0)$	Calculated
$E(0)$	Initial exposed population	1,300,038 (1,072,244 –1,527,831)	Estimated
$A(0)$	Initial asymptomatic cases	1,069,136 (841,658 –1,296,615)	Estimated
$I(0)$	Initial symptomatic cases	1,288,468 (1,060,839 –1,516,097)	Estimated
$T(0)$	Initial tested population	400,000	(National Health Commission of the People's Republic of China, 2023b)
$R(0)$	Initial recovered population	0.1% × $N(0)$	Assumed

where β is the transmission rate and is a time-dependent function that is simultaneously influenced by c_0, c_1, and c_2, which are the minimum transmission rate, adjustment coefficient, and exponential decline rate of β, respectively. The expression for β is as follows:

$$\beta = c_0 + c_1 e^{-c_2 t} \tag{2}$$

2.3. Parameter estimation and model calibration

A nonlinear least-squares method was applied to obtain the optimal values of parameters such as c_0, c_1, c_2, and the detection rate. This method minimizes the sum of squared residuals between model-fitted diagnosed cases ($\delta_1 A + \delta_2 I$) and reported cases and between model-fitted cumulative infection rates and reported cumulative infection rates obtained from the five large-scale surveys. The remaining model parameters were obtained from the literature and official reports. Latin hypercube sampling (LHS) was repeated 100 times to obtain 95% CIs for the parameters. All analyses and simulations were performed in MATLAB R2019b.

2.4. Estimation of basic and effective reproduction numbers

The basic reproduction number (R_0) was obtained by determining the spectral radius of the matrix $\tilde{F}\tilde{V}^{-1}$ via the next-generation operator method (Wang, Cai, & wang, 2021), as follows.

$$R_0 = \rho\left(\tilde{F}\tilde{V}^{-1}\right) = \left(\frac{\beta}{\omega} + \frac{\beta(1-\rho)}{\delta_1+\gamma_1} + \frac{\beta\rho}{\delta_2+\gamma_2} + \frac{\beta\rho\delta_2}{(\delta_2+\gamma_2)\gamma_3} + \frac{\beta(1-\rho)\delta_1}{(\delta_1+\gamma_1)\gamma_3}\right) = R_{0E} + R_{0A} + R_{0I} + R_{0T} \tag{3}$$

where ρ denotes the spectral radius, and the matrices $\tilde{F}$ and $\tilde{V}$ are as follows:

$$\tilde{F} = \begin{pmatrix} \beta & \beta & \beta & \beta \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}, \tilde{V} = \begin{pmatrix} \omega & 0 & 0 & 0 \\ \omega\ (\rho-1) & \delta_1+\gamma_1 & 0 & 0 \\ -\omega\ \ \rho & 0 & \delta_2+\gamma_2 & 0 \\ 0 & -\delta_1 & -\delta_2 & \gamma_3 \end{pmatrix} \tag{4}$$

Each term in the expression for R_0 has a clear epidemiological interpretation: $1/\omega$ is the SARS-CoV-2 incubation period; $1/(\delta_1+\gamma_1)$ is the average infectious period of asymptomatic cases; $1/(\delta_2+\gamma_2)$ is the average infectious period of symptomatic cases; $\delta_1/(\delta_1+\gamma_1)$ and $\delta_2/(\delta_2+\gamma_2)$ are the proportions of asymptomatic and symptomatic cases tested, respectively; and R_{0E}, R_{0A}, R_{0I}, and R_{0T} are the contribution of E, A, I, and T to newly confirmed infections, respectively.

The effective reproduction number (R_{eff}) reflects the effectiveness of prevention and control measures and is determined using the following formula:

$$R_{eff} = \frac{S(t)}{N}\left(\frac{\beta}{\omega} + \frac{\beta(1-\rho)}{\delta_1+\gamma_1} + \frac{\beta\rho}{\delta_2+\gamma_2} + \frac{\beta\rho\delta_2}{(\delta_2+\gamma_2)\gamma_3} + \frac{\beta(1-\rho)\delta_1}{(\delta_1+\gamma_1)\gamma_3}\right) \tag{5}$$

2.5. Sensitivity analysis

LHS was performed to obtain partial rank correlation coefficients (PRCCs) to determine the independent effects of each parameter in the SEAITR model on R_{eff} on day 1 and day 16, respectively. Day 1 marked the beginning of the pandemic period under study, and at this point, the new policy was implemented, providing the conditions for the rapid transmission of SARS-CoV-2. Day 16 was the first day when R_{eff} was less than 1. We conducted LHS 100 times to obtain a set of PRCCs for each parameter with R_{eff} and repeated the above operation 1000 times to ensure the reliability of the results.

2.6. Scenarios considered in simulations of second booster vaccination coverage

The National Health Commission of the People's Republic of China issued guidelines regarding second booster vaccination, but actual coverage of second booster vaccination remains unclear. We hypothesized several coverage scenarios: 0%, 20%, and 40%. Several Israeli studies have shown that compared with the third dose of an mRNA vaccine, a second booster dose of the vaccine increases prevention against infection (Bar-On et al., 2022; Cohen et al., 2022; Regev-Yochay et al., 2022). However, in China, inactivated vaccines were mainly administered in the early stages of the pandemic, and thus, the effectiveness of second booster vaccination against infection is not clear. Therefore, we assumed vaccine effectiveness of 30%, 50%, and 70% in numerical simulations. Vaccination coverage and vaccine effectiveness are represented as n and θ, respectively. The SEAITRV model, i.e., the SEIATR model with a vaccination (V) compartment, is schematically represented in Appendix Fi gure S1 and Equation S(1). The reported daily numbers of new cases of COVID-19 and cumulative infection rates with various vaccination coverages (0%, 20%, and 40%) and vaccine effectiveness (30%, 50%, and 70%) are shown in Fig. 4.

3. Results

3.1. Cumulative infection rate

The reported daily numbers of new cases of COVID-19 estimated by the SEIATR model are consistent with the actual trends during this period of the pandemic (see Fig. 2a). According to the model, the peak occurred on day 18 (December 24, 2022), when the reported daily number of new cases of COVID-19 reached a maximum of 5,224,683 (95% CI: 3,707,657–6,741,710). This is consistent with the actual peak during this period, which occurred on day 17 (December 23, 2022), when the reported daily number of new cases of COVID-19 reached a maximum of 6,966,046.

The model estimated that the cumulative infection rates of COVID-19 reached 50.50% (95% CI: 39.58%–61.43%), 56.15% (95% CI: 49.05%–67.22%), 73.82% (95% CI: 64.63%–83.02%), and 75.76% (95% CI: 67.02%–84.50%) on December 19, 20, 25, and 26, 2022, respectively, and 84.99% (95% CI: 79.45%–90.53%) on January 15, 2023. These results are highly consistent with the cumulative SARS-CoV-2 infection rates reported in two national surveys conducted on December 20 (61%) and December 26 (74%), 2022; in two Sichuan provincial surveys conducted on December 19 (46.93%) and December 25 (63.52%), 2022; and in the provincial surveys conducted in Shaanxi province on January 15, 2023 (84.7%) (Fig. 2b). In addition, the model estimated that as of January 7, 2023, the cumulative infection rate of COVID-19 in China's Mainland was 84.11% (95% CI: 78.13%–90.08%).

Furthermore, it was estimated that at the beginning of the epidemic, R_{eff} was 7.388 (95% CI: 6.868–7.907), and that it subsequently gradually decreased over time. For example, on January 7, 2023, R_{eff} was 0.185 (95% CI: 0.125–0.245).

3.2. Sensitivity analysis of R_{eff}

Fig. 3 shows the PRCCs of each parameter with R_{eff} on day 1 and day 16. To ensure the reliability of the results, we summarized the PRCCs from 1000 LHS results. On day 1, β exhibited a strong positive correlation with R_{eff} ($r = 0.996$, $P < 0.0001$), while γ_2, γ_3, and ω showed negative correlations with R_{eff}, i.e., γ_2 ($r = -0.943$, $P < 0.0001$), γ_3 ($r = -0.258$, $P = 0.0843$), and ω ($r = -0.752$, $P < 0.0001$). In summary, a reduction in the infection rate and an increase in the recovery rate both effectively decreased R_{eff} and controlled the spread of the pandemic. The nucleic acid testing rates (δ_1 and δ_2) and the recovery rate of asymptomatic cases (γ_1) did not have a significant effect on R_{eff}, likely due to the lack of appropriate quarantine control after testing in the late stage of the pandemic. Finally, the PRCCs on day 16 are consistent with those on day 1.

3.3. Effectiveness of second booster vaccination

Fig. 4 displays the reported daily numbers of new cases of COVID-19 and cumulative infection rates of COVID-19 with various vaccination coverages (0%, 20%, and 40%) and vaccine effectiveness (30%, 50%, and 70%). Second booster vaccination

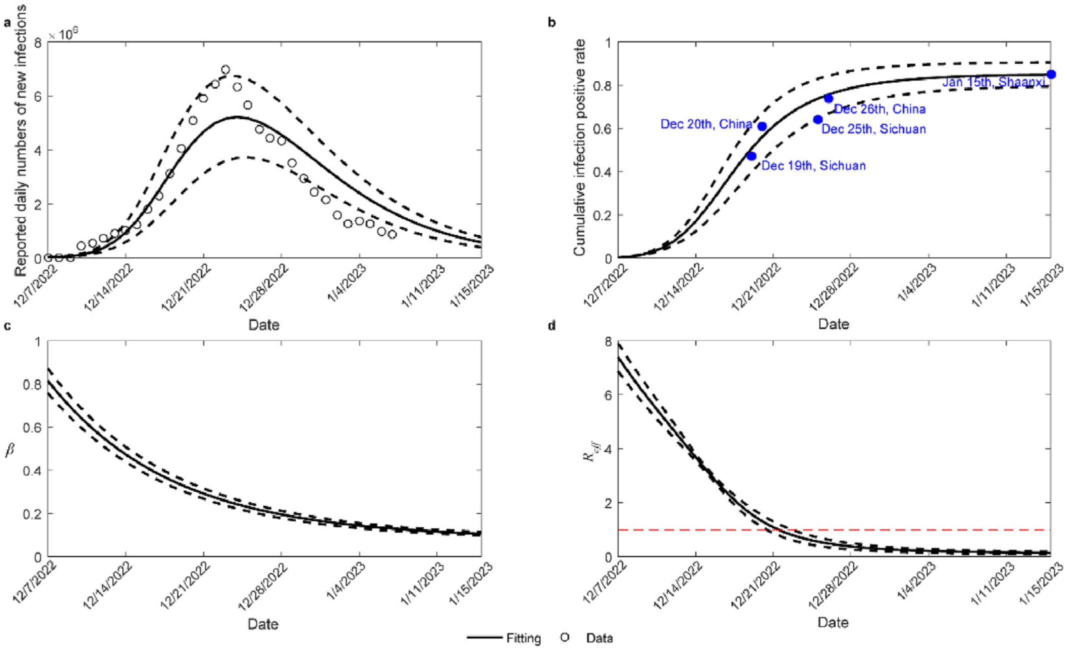

Fig. 2. Estimated reported daily numbers of new cases of coronavirus disease 2019 (a), cumulative infection rates of COVID-19 (b), transmission rates (β) (c), and effective reproduction numbers (R_{eff}) (d) from December 7, 2022, to January 15, 2023.

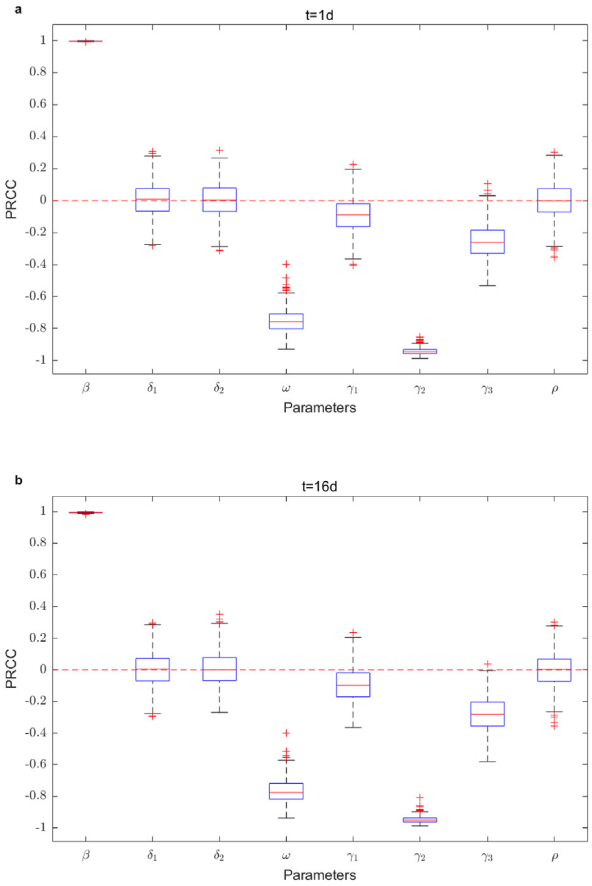

Fig. 3. Partial rank correlation coefficients (PRCCs) of parameters with effective reproduction numbers on day 1 (t = 1, a) and day 16 (t = 16, b).

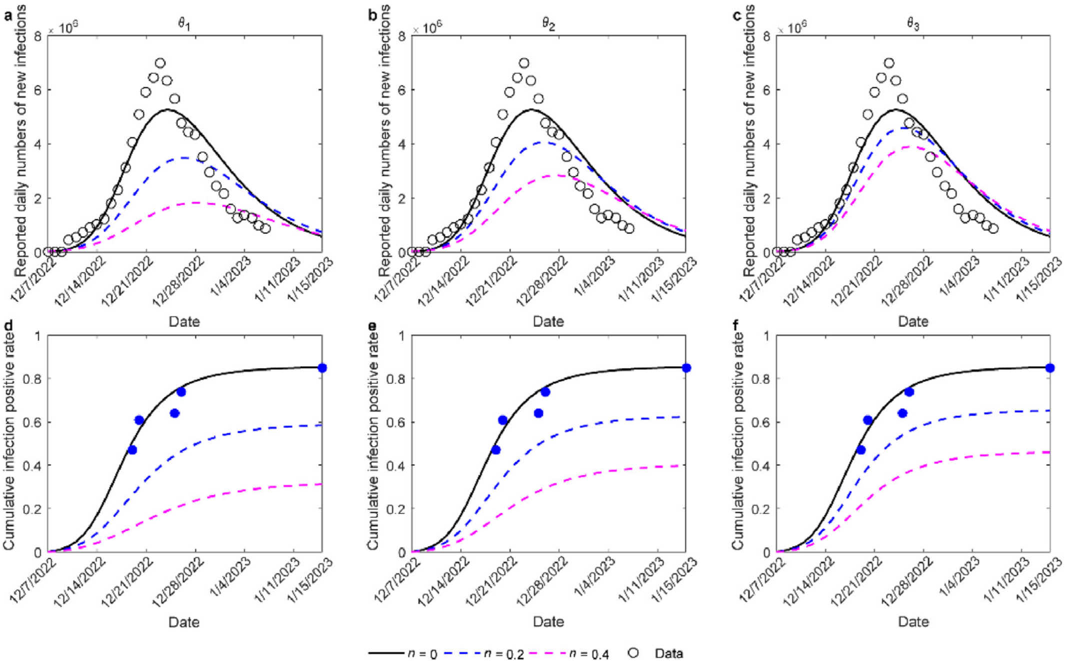

Fig. 4. Estimated reported daily numbers of new cases of COVID-19 when second booster SARS-CoV-2 vaccination effectiveness was 70% (a), 50% (b), and 30% (c). Estimated cumulative infection rates of COVID-19 when second booster SARS-CoV-2 vaccination effectiveness was 70% (d), 50% (e), and 30% (f).

effectively delayed the peak of this period of the pandemic by 2–4 days when both vaccine coverage and effectiveness were high. Moreover, increased coverage of second booster vaccination and increased vaccine effectiveness caused decreases in the reported daily numbers of new cases of COVID-19, particularly during peak times. When the vaccine coverage was 40% and the vaccine effectiveness was 70% or 30%, the peak reported daily numbers of new cases decreased from 5,263,082 to 1,826,378 and 3,891,359, respectively. Moreover, even when the vaccine coverage was 20% and its effectiveness was 30%, the peak reported daily number of new cases decreased to 4,596,297, reducing the number of infections by 666,785.

Additionally, second dose vaccination contributed to a decrease in the cumulative infection rate of COVID-19. It was estimated that as of January 7, 2023, the cumulative infection rate of COVID-19 decreased from 84.37% to 29.55% in the scenario in which there was high vaccination coverage and high vaccine effectiveness. Moreover, even in the scenario in which there was low vaccination coverage (20%), the cumulative infection rate decreased to 64.25%, 61.12%, and 57.00% when the vaccine effectiveness was 30%, 50%, and 70% respectively. This effectively controlled this period of the pandemic.

4. Discussion

We developed an SEAITR model to simulate the prevalence of the SARS-CoV-2 Omicron variant in China during the implementation of the “Ten New Measures” between December 7, 2022, and January 7, 2023. According to the model, the national cumulative infection rate of COVID-19 reached 84.11% on January 7, 2023, and 84.99% on January 15, 2023. In addition, the model estimated that R_{eff} decreased from 7.388 at the beginning of the pandemic to 0.185 by January 7, 2023. Simulations of second booster vaccination scenarios revealed that as of January 7, 2023, the cumulative infection rate decreased significantly, from 84.37% to 29.55%, in the scenario in which there was high vaccine coverage (40%) and high effectiveness (70%). This effectively suppressed this period of the pandemic. Moreover, even with low vaccination coverage (20%) and low vaccine effectiveness (30%), the nationwide proportion of infected individuals was greatly reduced, reaching 64.25%.

Furthermore, compared with the national cumulative infection rate reported by Goldberg et al. (2023), the rate estimated by the model is lower and is closer to the rates determined in real-world cross-sectional surveys. In addition, the rate estimated by the model for December 22, 2022, is similar to that reported by Leung et al. (2023). However, in contrast to the present study, Leung et al. (2023) estimated that the cumulative infection rate increased to 92.3% by January 31, 2023. This rate might have been an overestimate, due to an assumption in their model that mobility and population-mixing levels remained unchanged after December 22, 2022. In contrast, a study in Guangzhou based on an age-specific renewal equation determined that 80.7% of people were infected with SARS-CoV-2 within 30 days of the policy change (Huang et al., 2023). This is very close to the cumulative infection rate estimated in the present study. The cumulative infection rate of COVID-19 in China at the end of 2022 had rapidly increased in a very short period. This indicates that preparing healthcare resources such as hospital beds and drugs in advance is needed to decrease the peak of the epidemic, and thus to reduce the number of severe and dead cases.

Expanding the coverage of second booster vaccination in China has a very important role to play in the prevention and control of COVID-19, especially when the overall susceptibility of the population has increased. Moreover, the effectiveness of the third dose of the SARS-CoV-2 vaccine at the end of 2022 has been greatly reduced or even eliminated (Goldberg et al., 2023; Wang et al., 2022), and the zero-COVID policy has been changed. Our estimates showed that even with 20% coverage and 30% vaccine effectiveness, second booster vaccination significantly reduced the cumulative numbers of infections and effectively mitigated this period of the pandemic. This finding is consistent with the results of Li et al. (2024) for the United States, where expanding the second booster vaccination strategy to cover different age groups was not only effective but was also possibly cost-effective. Similarly, Hon et al. developed a stochastic model with an age structure to simulate the effect of second booster vaccination after the policy adjustment in China. They concluded that with 80%–90% coverage, a heterologous booster vaccination reduced the number of daily new emergency department visits by 1.4–1.5 times and shortened the peak visit period by 3 days, thereby helping to mitigate the peak number of infections (Hon et al., 2023). The results of this study suggest that in order to reduce the infection rate of COVID-19 outbreaks, a booster vaccine can be administered to reduce the susceptibility of the population.

The present study has several limitations. First, our estimation of the proportion of symptomatic COVID-19 cases relied on previous national surveys. Because of these surveys' reliance on self-reporting data, they might have been subject to bias due to cognition, recall, and psychological effects, which might have decreased the accuracy of our estimates (Leung et al., 2023; Liu et al., 2023). Second, data on the effectiveness of second booster vaccination in China were unavailable. Thus, we made some reasonable assumptions regarding this aspect, based on the results of previous studies (Cohen et al., 2022; Regev-Yochay et al., 2022; Wang et al., 2024). Third, the SEAITR model does not account for the impact of severe cases and deaths during pandemics. Finally, we included three provincial survey data (two surveys in Sichuan and one survey in Shaanxi) in our model calibration, which may not be as representative as the national survey data.

Overall, this study estimated the cumulative infection rate of COVID-19 after China announced the optimization of its COVID-19 prevention and control measures. These estimates contribute to retrospective predicting the spread of the COVID-19 pandemic. In addition, our findings emphasize the significance of administering second booster vaccination under the current optimized policy in response to COVID-19. This measure can prevent large-scale outbreaks of COVID-19 in the future. We hope that our findings will serve to inform recommendations to policymakers that will encourage them to increase medical resources in a timely manner, expand the scope of second booster vaccination, and protect high-risk populations in China.

4.1. Ethics approval

This study did not require ethical approval because it did not involve human participants and was conducted only using aggregated publicly available data.

CRediT authorship contribution statement

Sijia Zhou: Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation. **Miao Lai:** Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation. **Shuhan Tang:** Methodology, Data curation. **Wen Liu:** Methodology, Data curation. **Mingwang Shen:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Zhihang Peng:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Availability of data

All data used in this study are publicly available and sources are cited in the References section.

Declaration of competing interest

The authors declare that they have no competing interests.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.idm.2024.12.012.

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