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Evaluation of Intervention Policies for the COVID-19 Epidemic in the Seoul/Gyeonggi Region through a Model Simulation

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Purpose: To evaluate the efficacy of intervention policies on coronavirus disease-19 (COVID-19) dissemination.
Materials and Methods: An age-structured compartmental model for the COVID-19 outbreak was proposed to predict the impact of control measures in the Seoul/Gyeonggi region. The model was calibrated based on actual data and realistic situations, including daily vaccine doses, proportion of delta variant cases, and confirmed cases by age. We simulated different scenarios for non-pharmaceutical interventions by varying social distancing and school attendance strategies.
Results: Two-step mitigation of social distancing without in-person classes would result in a rapid increase in confirmed cases up to 10000 but would keep severe cases within the manageable range of the health care system. The overall impact of taking down the distancing level by one step with twice the increase in contacts at school was comparable to the above scenario. Implementation of two-step mitigation of social distancing along with a two-fold increase in contacts among the school-age group would dramatically increase confirmed and severe cases by over 80000 and 100, respectively, as early as the beginning of December. This policy would cause the situation to spiral out of control, considering the scale of the response and time to prepare. On the other hand, the burden on the current healthcare system caused by two-step mitigation of social distancing and 40% increased contacts in the school-age group was manageable if prepared.
Conclusion: A compromise between social distancing and school attendance policy and timely preparations for the spread of COVID-19 are required.

Key Words: COVID-19, simulation model, infection control

INTRODUCTION

After the first case of coronavirus disease-19 (COVID-19) on January 20, 2020, 642207 confirmed COVID-19 cases and 5730 deaths due to COVID-19 have been reported as of January 3, 2022 in South Korea. The Korean government has implemented social distancing measures since February 23, 2020 in an attempt to mitigate the COVID-19 pandemic.[1] At the beginning of the Spring semester, education in all institutes was delayed until online classes started on April 9, 2020.[2,3] These nonpharmacological interventions have substantially reduced contact levels and, therefore, led to a substantial decline in incidence. However, maintaining the current restrictions would incur great social costs, such as accumulated fatigue, loss of business for the self-employed, and academic loss for students.[4]

Along with non-pharmaceutical interventions, vaccination

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started on February 26, 2021;[5] 83% of total population had completed the first dose, and 80% were fully vaccinated as of December 7, 2021.[6] The priority of vaccination was given to older adults and those at high risk of infection.[7] Vaccination is effective in preventing both infection and progression to serious conditions.[8] To this end, the Korean government has attempted to gradually recover daily life by relaxing distancing measures and expanding vaccination.

Before doing so, it would be essential to analyze the impact of response strategies on the spread of the epidemic. More than 60% of confirmed cases occur in the Seoul metropolitan area, and different policies have been applied to this area and other regions. In this study, we assessed the effects of intervention measures on COVID-19 transmission in the Seoul/Gyeonggi region to help policymakers of the Seoul Metropolitan Government and other areas prepare guidelines. An age-structured compartmental model for the COVID-19 outbreak was developed to predict the impact of control measures. The model was calibrated using daily confirmed cases, and an effective reproduction number was estimated. We simulated different scenarios for non-pharmaceutical interventions by varying social distancing and school attendance strategies. The output in terms of incidence, severe cases, and deaths was obtained to better prepare the health system for similar occurrences and allocate resources optimally.

MATERIALS AND METHODS

Data sources

The study participants comprised the population of the Seoul/Gyeonggi region, and the information used for model calibration included daily incidence data and stages of social distancing. Age-specific daily confirmed cases of Seoul were provided by one of the authors from the Infectious Disease Research Center, Citizen's Health Bureau, Seoul Metropolitan Government. Data for the Gyeonggi region were obtained from the website of the Gyeonggi Infectious Disease Control Center.[9]

We referred to the Korea Disease Control and Prevention Center to determine the stages of social distancing in Seoul and Gyeonggi. The system of social distancing was reorganized from three levels to five levels on November 7, 2020 and to four levels on July 1, 2021.[10] We approximated the social distancing stage for each period under the four-tier system by comparing the implemented policies, including quarantine measures. The maximum number of people at private gatherings and the business hours of multi-use facilities are key differentiating factors for social distancing steps. Relaxing social distancing steps allows more people and longer periods of time, which leads to increased contact between people [refer to the website, Coronavirus (COVID-19), Republic of Korea[11] for more information]. The effects of vaccination and the proportion of delta variants were considered in this study. The daily vaccine dose by age group was obtained from the public data portal (Fig. 1).[12] The proportion of delta variants was extracted from press releases from the Korea Disease Control and Prevention Agency,[13] as shown in Table 1.

Mathematical model and parameters

The standard SEIR model was modified to include hospitalizations, which classified the total population of the Seoul/Gyeonggi region into five groups (Fig. 2). The state variables S, E, I, H, R, V_1 and V_2 denote the number of susceptible individuals, exposed, infected, hospitalized, recovered, the first dose vacci-

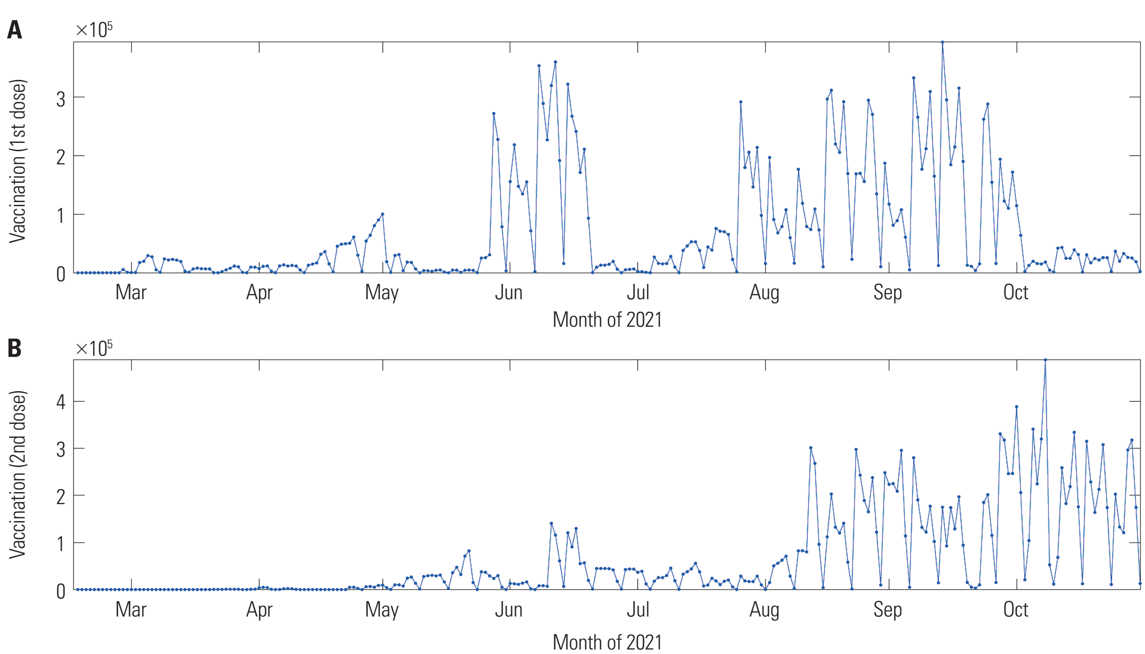

Fig. 1. The daily numbers of first (A) and second (B) doses of vaccines.

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nated, and the second dose vaccinated, respectively. Each compartment was further divided into nine age groups of 10 years, from 0 to 79 years and older than 80 years, with different transmission dynamics. Refer to Supplementary Table 1 (only online) for the sizes and proportions of the population by age in the Seoul and Gyeonggi regions.

The age-structured SEIHR model can be expressed as:
for i=1, ..., 9,

$$
\begin{aligned}
&S_i(t_{j+1})=S_i(t_j)+\Delta t[-\lambda_i(t_j)S_i(t_j)-Nv_{1,i}(t_j)]\\
&E_i(t_{j+1})=E_i(t_j)+\Delta t\{\lambda_i(t_j)[S_i(t_j)+(1-e_1)V_{1,i}(t_j)+(1-e_2)V_{2,i}(t_j)]-\kappa E_i(t_j)\}\\
&I_i(t_{j+1})=I_i(t_j)+\Delta t[\kappa E_i(t_j)-\alpha I_i(t_j)]\\
&H_i(t_{j+1})=H_i(t_j)+\Delta t[\alpha I_i(t_j)-\gamma H_i(t_j)]\\
&R_i(t_{j+1})=R_i(t_j)+\Delta t[\gamma H_i(t_j)]\\
&V_{1,i}(t_{j+1})=V_{1,i}(t_j)+\Delta t[Nv_{1,i}(t_j)-(1-e_1)\lambda_i(t_j)V_{1,i}(t_j)-Nv_{2,i}(t_j)]\\
&V_{2,i}(t_{j+1})=V_{2,i}(t_j)+\Delta t[Nv_{2,i}(t_j)-(1-e_2)\lambda_i(t_j)V_{2,i}(t_j)],
\end{aligned}
$$

Table 1. Proportions of the Delta Variant

	Week 1	Week 2	Week 3	Week 4	Week 5
Jun	2.4	1.4	2.5	3.3	9.9
July	23.3	33.9	48.0	61.5	
August	73.1	85.3	89.6	94.3	
September	97.0	98.5	98.2	99.5	99.5
October	99.8	100.0	99.8	99.9	

Data are presented as %.

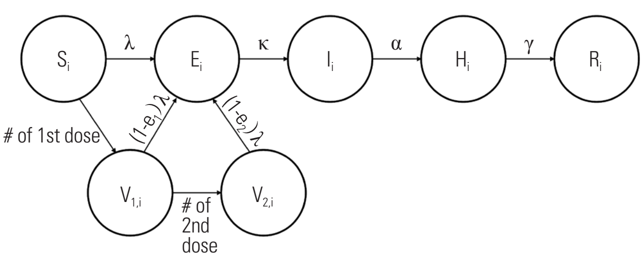

Fig. 2. Diagram of the SEIHR model for COVID-19 dynamics incorporating vaccination.

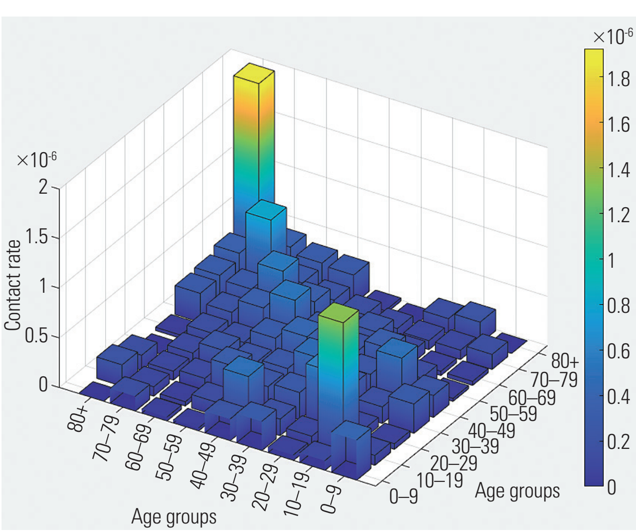

Fig. 3. Contract rates among different age groups estimated from a contact survey conducted in Korea during 2020.

where Δt is the unit time interval, the subscript i denotes the i^{th} age group, and $Nv_{k,i}$ is the number of people who received the k^{th} dose in the i^{th} age group.

The force of infection λ was modeled by incorporating the effects of social distancing and the delta variant:

$$\lambda(t)=\{[(1-p(t))+p(t)\times\delta]\times\beta\times SD(t)\times C\}\times I(t).$$

We assumed that the transmission rates were proportional to social contacts C, which were estimated from contact surveys conducted in 2020 (Fig. 3). p(t) is the proportion of delta variants, and δ is the adjusting factor for the transmission rate of delta variants relative to the alpha variant. Scalar β is the proportionality to calibrate social contacts to transmission rates. SD(t) represents the quantified impact of social distancing measures on pathogen transmission. κ is the progression rate from exposure to infection, where $1/\kappa$ represents the pre-infectious period of COVID-19. α is the isolation rate, and $1/\alpha$ represents the time taken from infection to confirmation and isolation. Isolated patients leave the compartment at recovery γ, thereby acquiring immunity against the disease. e_1 and e_2 denote the effectiveness of the primary and secondary vaccination against SARS-CoV-2 infection, respectively.

The parameter values were determined using published literature reviews and estimated, derived, or assumed based on the best available local epidemiological data and mathematical formulas as of October 31, 2021. Table 2 summarizes the descriptions and values used in the simulations. In previous research, the time-dependent reproduction number according to the change in the social distancing stage was estimated from April 8, 2020 to March 11, 2021(Supplementary Fig. 1 and Supplementary Fig. 2, only online). Then the median values of contact increases or decreases according to social distancing step changes were derived. Based on this result, it was assumed that adjusting social distancing levels by one step up and down would result in a 32% decrease and a 40% increase in contact, respectively.

The effectiveness of primary and secondary vaccination in preventing infection, severe cases, and death was estimated by

Table 2. Summary of Parameters for the COVID-19 Transmission Model

Parameter	Description	Value	Reference
λ	Force of infection	Formula	
p(t)	Proportion of delta variant	Table 1	20
δ	Relative infectivity of delta variant	3.2568	Estimated
β	Proportionality of transmission rate	0.0426	Estimated
SD(t)	Effect of social distancing	One step 1.40 Two step 1.96	Assumed
C	Contact matrix	Fig. 3	
$1/\kappa$	Average pre-infectious period	4	21
$1/\alpha$	Average infectious period	4	21
γ	Recovery rate	1/14	21
e_j	Vaccine effectiveness of j^{th} dose	Table 4	20,22

considering the proportion of alpha and delta variants, as well as AstraZeneca and Pfizer vaccines, the two most widely used vaccines in Korea (Table 3).[14-17] Then, β and the relative infectivity of delta variant δ were estimated by fitting the model to the age-specific daily confirmed cases from February 15, 2020 to November 1, 2021 in the Seoul/Gyeonggi region (Fig. 4). The maximum likelihood estimation technique was employed, assuming a Poisson distribution for the incidence data in the model calibration.[18]

Intervention scenarios

To investigate the impact of social distancing and school attendance policies on the disease burden of COVID-19 in the Seoul metropolitan area, various scenarios were simulated. As of October 31, 2021, social distancing was at level 4, and schools were implementing all online classes. We considered three policies of easing social distancing, by one level, by two levels, and gradually. It was assumed that if the distancing level was lowered by one or two levels, contacts would increase by 40% and 96%, respectively. Gradual easing of distance lowers one level on November 1, 2021 and another on December 13, 2021. Unlike social distancing, there is no evidence on how much contact increases by going to school. Thus, in-person classes were assumed to increase social contact by 40% and 96% at school age, which corresponds to easing of social distancing by one and two steps. With reference to the literature, a case of full recovery of daily life without taking any measures including a mask was also considered. We assumed in-person classes would increase contact by 607%, comparing the number of school-age contacts in the POLYMOD survey and the 2020 Korean survey.[19] Different scenarios combining social distancing and school attendance policies are summarized in Table 4. Incidence, severe cases, bed utilization rate, and deaths were predicted until January 31, 2022 for each scenario.

Table 3. Effectiveness of Vaccines in Preventing Infection, Severe Cases, and Death

	1st dose of vaccine		2nd dose of vaccine	
Prevention of infection	Alpha variant	48.1	Alpha variant	32.8
	Delta variant	84.1	Delta variant	77.5
Prevention of severe cases	75[14,15]		94[14,15]	
Prevention of death	85[16]		96.1[17]	

Data are presented as %.

Table 4. Intervention Scenarios by Varying Social Distancing and School Attendance Strategies

	Social distancing	Contacts increased in the school-age group owing to in-person classes
Scenario 1	Maintain	None
Scenario 2	One-step mitigation	None
Scenario 3	Two-step mitigation	None
Scenario 4	Gradual mitigation	None
Scenario 5	Maintain	40%
Scenario 6	One-step mitigation	40%
Scenario 7	Two-step mitigation	40%
Scenario 8	Gradual mitigation	40%
Scenario 9	Maintain	96%
Scenario 10	One-step mitigation	96%
Scenario 11	Two-step mitigation	96%
Scenario 12	Gradual mitigation	96%
Scenario 13	Maintain	607%
Scenario 14	One-step mitigation	607%
Scenario 15	Two-step mitigation	607%
Scenario 16	Gradual mitigation	607%

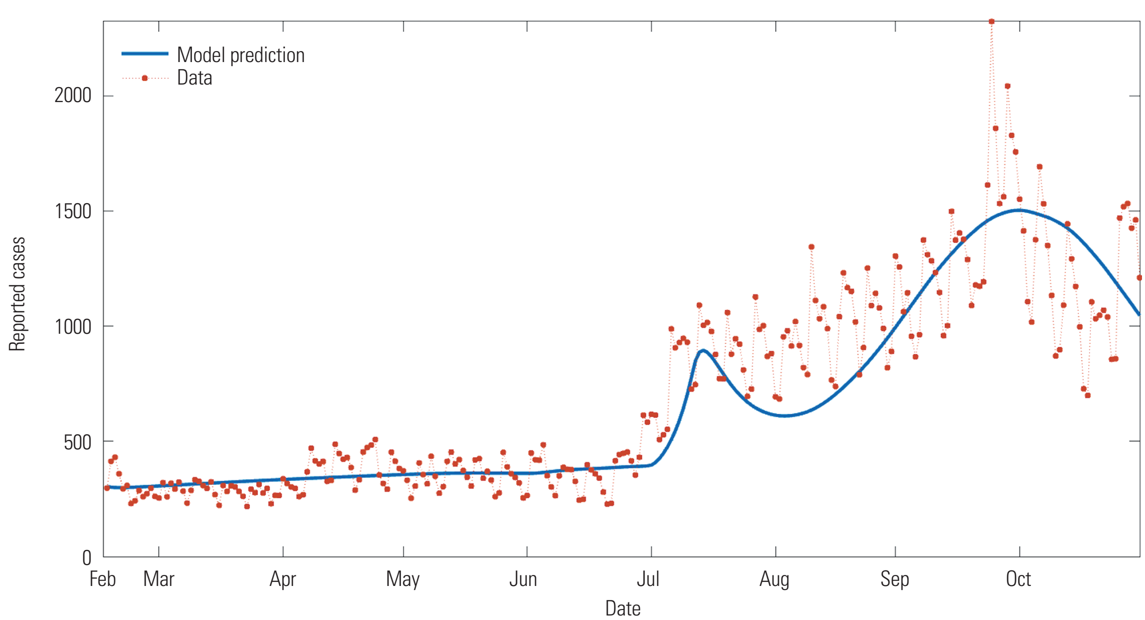

Fig. 4. Model prediction using estimated parameters compared to the reported daily confirmed cases.

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RESULTS

To investigate the impact of intervention measures on COVID-19 transmission in the Seoul/Gyeonggi region, we simulated 16 scenarios by considering social distancing and school attendance policies (Table 4). The first scenario reflected the baseline situation as of November 1, 2021, when level 4 social distancing was implemented and schools ran only online classes. Fig. 5A shows that the declining trend in the number of confirmed and severe cases continued, owing to strict distancing policies. In Fig. 5B and Supplementary Fig. 3B (only online), one-step mitigation of social distancing while maintaining online classes slightly increased the incidence but had little impact on severe cases and deaths. Two-step mitigation of social distancing resulted in a rapid increase in confirmed cases up to 10000 but kept severe cases within a manageable range of the healthcare system, as shown in Fig. 5C. The impact of gradual mitigation was similar to that of the one-step mitigation (Fig. 5D), where gradual mitigation of distance lowers one level on November 1, 2021 and another on December 13, 2021.

In the next four scenarios, it was assumed that in-person classes would increase social contact among the school-age group by 40%. The results of simulation in terms of incidence, severe cases, and deaths are illustrated in Fig. 6 and Supplementary Fig. 4 (only online). As long as level 4 social distancing was maintained, all indicators of disease burden remained very similar to the baseline scenario, as shown in Fig. 6A. If the distancing policy was lowered in one step, then the number of confirmed cases was predicted to reach a peak of 3000. However, the overall situation did not worsen, keeping the severe cases in single-digit condition (Fig. 6B). Two-step mitigation of social distancing and 40% increased contacts in the school-age group caused the daily incidence to soar rapidly as much as 40000 and the severe cases to exceed 50 in Fig. 6C. This exceeded the manageable range of the current healthcare system and preparations, such as the addition of hospital beds, were required. Fig. 6D shows that the disease burden under gradual mitigation of social distancing assuming 40% increased contacts in the school-age was similar to that under two-step mitigation of social distancing maintaining online classes.

We considered four different policies of social distancing, assuming that in-person classes would increase social contact in the school-age group by 96%, from scenarios 9 to 12 (refer to Fig. 7 and Supplementary Fig. 5 (only online) for the simulation results). Fig. 7A shows that maintaining level 4 social distancing yielded similar results as the one-step mitigation of distancing along with online classes in which there was a slight increase in daily confirmed cases but little change in severe cases. While the overall impact of taking down the distancing level by one step was comparable to Scenario 3, the peak numbers of incidence and severe cases were higher, as shown in Fig. 7B. Implementation of two-step mitigation of social distancing along with a 96% increase in contacts among the school-age group dramatically increased confirmed and severe cases by over 80000 and 100, respectively, as early as the beginning of December (Fig. 7C). This also exceeded the manageable range of the current healthcare system, and it was not feasible to control the situation, considering the scale to response and time to prepare. Fig. 7D indicates that gradual mitigation resulted in a smaller peak of the outbreak, although the suggestion was not much different from scenario 11.

The last four scenarios were designed to explore the impact of full recovery of school life for students on disease burden, as shown in Supplementary Figs. 6 and 7 (only online). Under all scenarios, the consequences were similar because they were dominated by the effects of increased contacts among the school-age group owing to school policy. Daily confirmed and severe cases were predicted to be around 200000 and 150–350, respectively, which were considered to be out of control.

DISCUSSION

An age-structured compartmental model of the COVID-19 outbreak was developed to investigate the impact of control measures on disease transmission. We simulated different scenarios for non-pharmaceutical interventions by varying social distancing and school attendance strategies. Indicators of disease burden were obtained, including incidence, severe cases, and deaths, to better prepare for the spread of COVID-19.

The implementation of distancing measures affects target populations. The self-employed are hardest hit by social distancing, and it is students who suffer academic losses from school closures. The indicators of disease transmission depend on the groups that benefit from the policy: for example, strategies to minimize severe cases and deaths mainly concern older adults.

The simulation results of the various scenarios verified that no policy benefited everyone. It is desirable to implement relaxed social distancing and in-person classes simultaneously, to take one step closer to daily life. However, two-step or gradual mitigation of social distancing along with a 96% increase in contacts among school-age groups would cause the situation to spiral out of control. For the current healthcare system to manage the pandemic, a compromise between social distancing and school attendance policy is required, such as one-step mitigation of distancing without in-person classes or one-step mitigation of distancing with twice the number of contacts at the school.

This study has several strengths. We developed a dynamic compartmental mathematical model to assess the impact of social distancing and school attendance strategies on the transmission of COVID-19 in the Seoul metropolitan area. Age structure was incorporated to account for the heterogeneity of contacts and disease-related characteristics by age. The model was calibrated using a set of values based on actual data and realistic situations. The daily vaccine dose by age group and the proportion of delta variants were considered. We designed a heterogeneous transmission model using contact patterns obtained through a survey conducted during the COVID-19 pandemic in Korea. It was then fitted to age-specific confirmed cases in the Seoul/Gyeonggi region.

Despite these strengths, this study had several limitations. It is critical to quantify the impact of in-person classes on contacts among school-age groups to evaluate the school attendance policy. However, no information was available because only online classes were held at most educational institutes during the pandemic. Therefore, the extent of a change in contact among

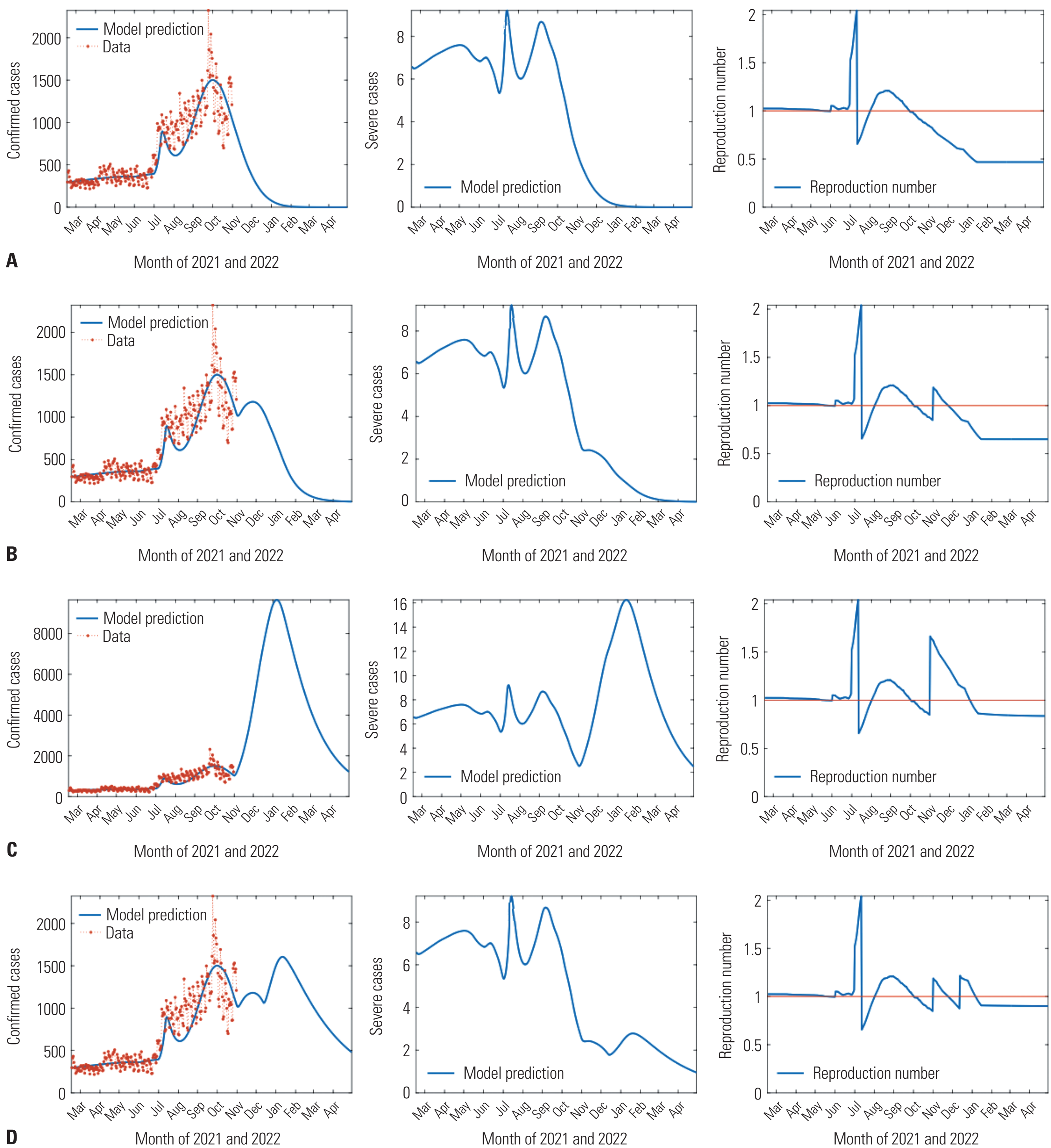

Fig. 5. Prediction of daily confirmed, severe cases, and time-varying reproduction number under four different policies of social distancing maintaining online classes. (A) Maintaining the level 4 social distancing and online classes. (B) One-step mitigation of social distancing maintaining online classes. (C) Two-step mitigation of social distancing maintaining online classes. (D) Gradual mitigation of social distancing maintaining online classes.

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students due to school policy attendance was assumed to be analogous to social distancing. In addition, we have presented several kinds of vaccines manufactured by Pfizer and AstraZeneca, assuming an average value of effectiveness regardless of age. Finally, only alpha and delta variants were considered because this study was conducted before the occurrence of omicron mutations. Thus, the application of the results of this study might be limited in situations where the omicron variant is predominant. Analyzing the effect of different variant ratios considering age-specific vaccine effectiveness will be another

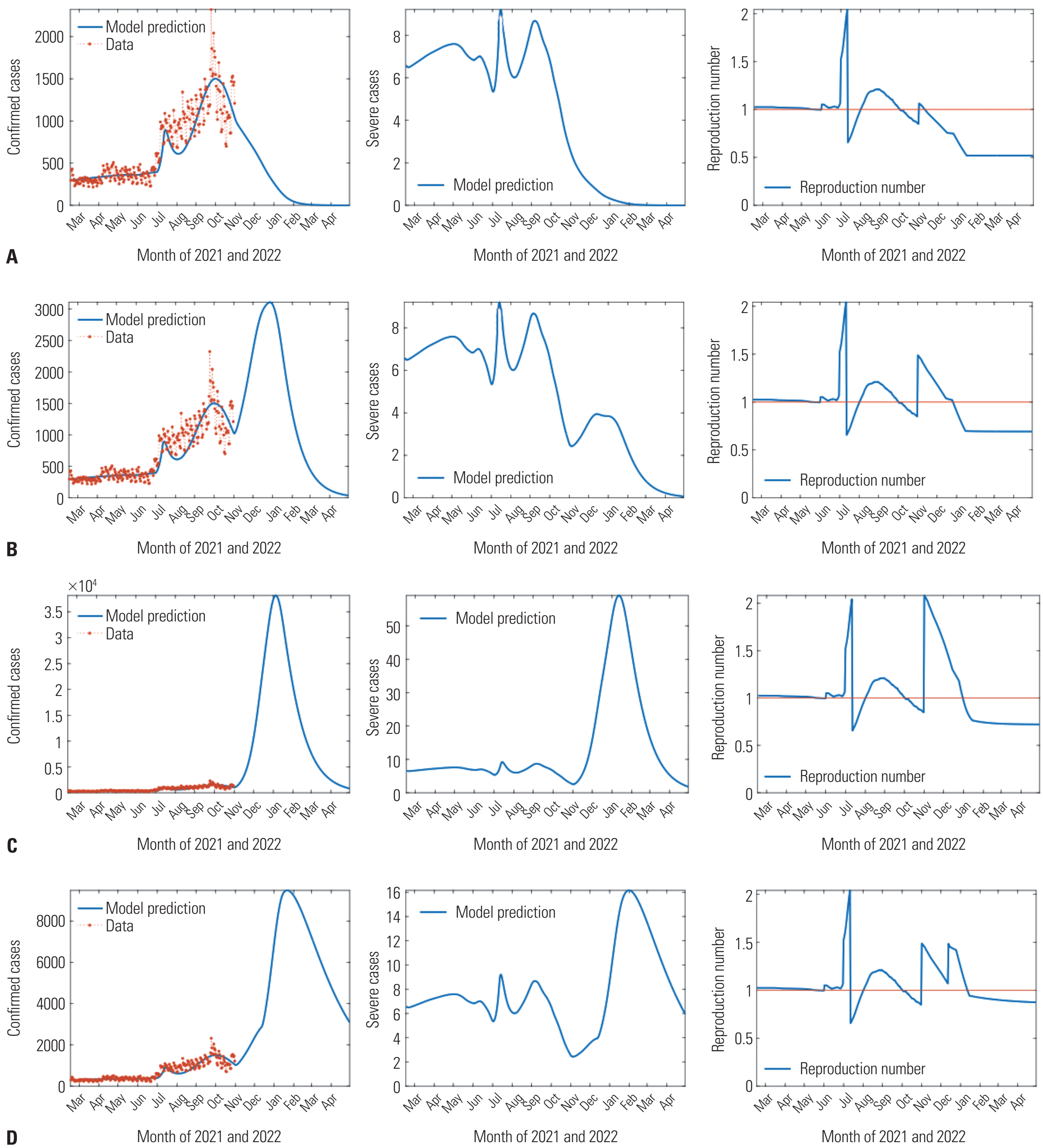

Fig. 6. Prediction of daily confirmed, severe cases, and time-varying reproduction number four different policies of social distancing assuming that in-person classes would increase the social contacts in the school-age group by 40%. (A) Maintaining the level 4 social distancing assuming 40% increase in contacts at shool. (B) One-step mitigation of social distancing assuming 40% increase in contacts at school. (C) Two-step mitigation of social distancing assuming 40% increase in contacts at school. (D) Gradual mitigation of social distancing assuming 40% increase in contacts at school.

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interesting research topic as simulation results can be greatly influenced.

Our modeling study predicted incidence, severe cases, and deaths through the simulation of various non-pharmaceutical intervention scenarios. The current healthcare system could manage the situation under some policies, including two-step

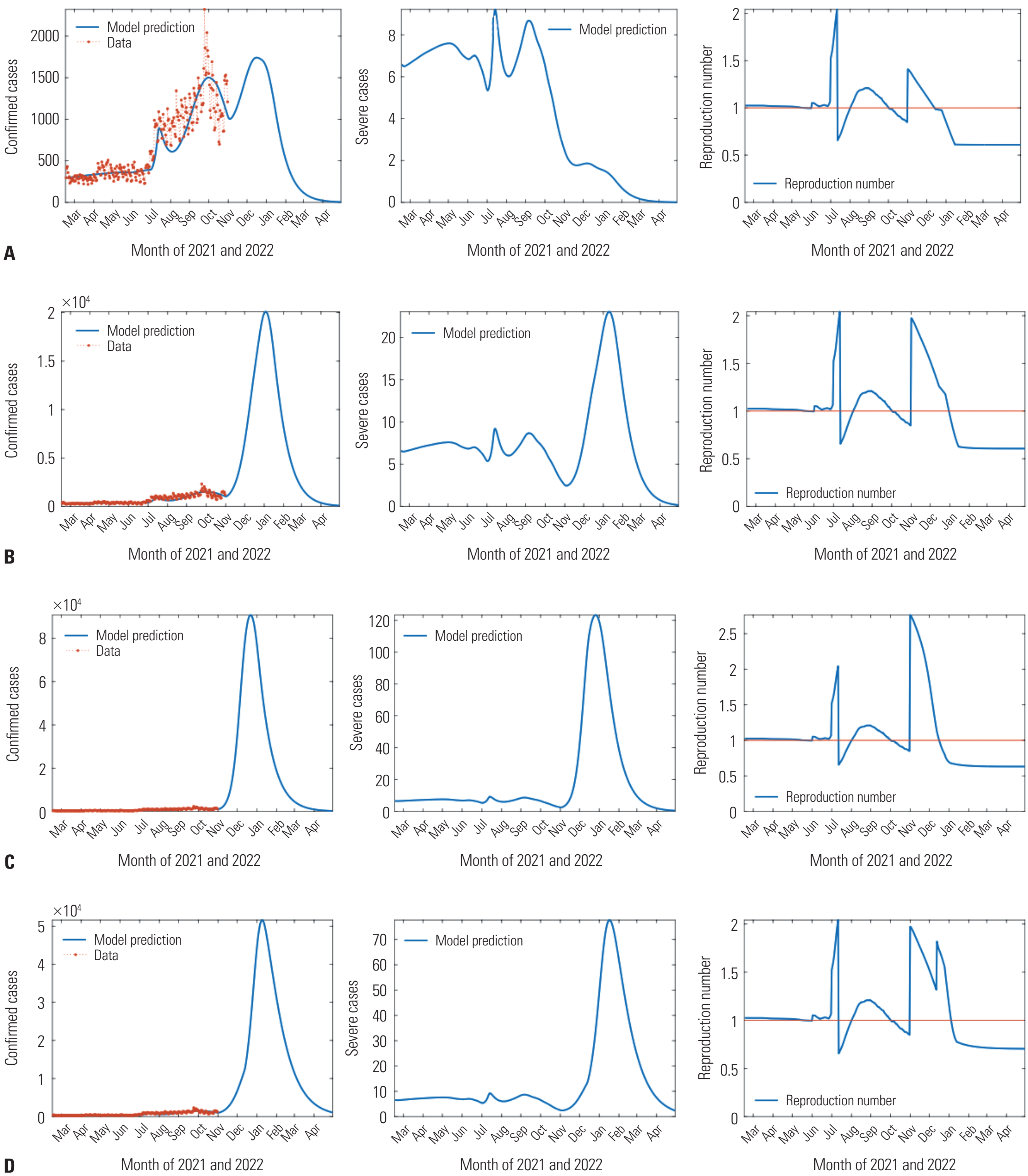

Fig. 7. Prediction of daily confirmed, severe cases, and time-varying reproduction number under four different policies of social distancing assuming that in-person classes would increase the social contacts in the school-age group by 96%. (A) Maintaining the level 4 social distancing assuming 96% increase in contacts at shool. (B) One-step mitigation of social distancing assuming 96% increase in contacts at school. (C) Two-step mitigation of social distancing assuming 96% increase in contacts at school. (D) Gradual mitigation of social distancing assuming 96% increase in contacts at school.

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mitigation of distancing without in-person classes or one-step mitigation of distancing with twice the number of contacts at school. However, two-step or gradual mitigation of social distancing along with a 96% increase in contacts among school-age groups would cause the situation to spiral out of control. Other scenarios went beyond the manageable range of the current healthcare system but were able to deal with the situation if prepared. Therefore, a compromise between social distancing and school attendance policies, as well as timely preparation for the spread of COVID-19, is required.

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AUTHOR CONTRIBUTIONS

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