INTRODUCTION

After the first case of coronavirus disease-19 (COVID-19) on January 20, 2020, 642,207 confirmed COVID-19 cases and 5,730 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. At the beginning of the Spring semester, education in all institutes was delayed until online classes started on April 9, 2020. These non-pharmacological 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.

Along with non-pharmacological interventions, vaccination...
started on February 26, 2021; \(^3\) 83% of total population had completed the first dose, and 80% were fully vaccinated as of December 7, 2021. \(^4\) The priority of vaccination was given to older adults and those at high risk of infection. \(^5\) Vaccination is effective in preventing both infection and progression to serious conditions. \(^6\) 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.

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.](https://doi.org/10.3349/ymj.2022.63.8.707)
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:

\[
S_i(t_{i+1}) = S_i(t_i) + \Delta t \left[ -\lambda_i(t_i) S_i(t_i) - \delta V_i(t_i) - \gamma I_i(t_i) - \kappa R_i(t_i) \right] - \kappa I_i(t_i)
\]

\[
E_i(t_{i+1}) = E_i(t_i) + \Delta t \left[ \lambda_i(t_i) S_i(t_i) + (1-e_1) V_i(t_i) + (1-e_2) V_o(t_i) \right] - \kappa E_i(t_i)
\]

\[
I_i(t_{i+1}) = I_i(t_i) + \Delta t \left[ \kappa E_i(t_i) - \alpha I_i(t_i) - \gamma H_i(t_i) \right] - \kappa I_i(t_i)
\]

\[
R_i(t_{i+1}) = R_i(t_i) + \Delta t [ \gamma H_i(t_i) ]
\]

\[
V_i(t_{i+1}) = V_i(t_i) + \Delta t \left[ N_V(t_i) - (1-e_i) \lambda_i(t_i) V_o(t_i) - \gamma I_i(t_i) \right] - \kappa V_i(t_i)
\]

\[
V_o(t_{i+1}) = V_o(t_i) + \Delta t \left[ N_V(t_i) - (1-e_2) \lambda_o(t_i) V_o(t_i) \right] - \kappa V_o(t_i)
\]

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.](image)

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

where \( \Delta t \) is the unit time interval, the subscript \( i \) denotes the \( i^{th} \) age group, and \( N_V \) is the number of people who received the \( k^{th} \) dose in the \( i^{th} \) age group.

The force of infection \( \lambda \) was modeled by incorporating the effects of social distancing and the delta variant:

\[
\lambda(t) = \frac{(1-p(t)) + p(t) \times \delta \times \text{SD}(t) \times C \times I(t)}{\alpha}
\]

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 \( \delta \) is the adjusting factor for the transmission rate of delta variants relative to the alpha variant. Scalar \( \beta \) is the proportionality to calibrate social contacts to transmission rates. \( \text{SD}(t) \) represents the quantified impact of social distancing measures on pathogen transmission. \( \kappa \) is the progression rate from exposure to infection, where \( 1/\kappa \) represents the pre-infectious period of COVID-19. \( \alpha \) is the isolation rate, and \( 1/\alpha \) represents the time taken from infection to confirmation and isolation. Isolated patients leave the compartment at recovery \( \gamma \), 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

![Fig. 3. Contact rates among different age groups estimated from a contact survey conducted in Korea during 2020.](image)

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

| Parameter | Description | Value | Reference |
|-----------|-------------|-------|-----------|
| \( \lambda \) | Force of infection | Formula |          |
| \( p(t) \) | Proportion of delta variant | Table 1 | 20 |
| \( \delta \) | Relative infectivity of delta variant | 3.2568 | Estimated |
| \( \beta \) | Proportionality of transmission rate | 0.0426 | Estimated |
| \( \text{SD}(t) \) | Effect of social distancing | One step 1.40 | Assumed |
| \( C \) | Contact matrix | Fig. 3 |          |
| \( 1/\kappa \) | Average pre-infectious period | 4 | 21 |
| \( 1/\alpha \) | Average infectious period | 4 | 21 |
| \( \gamma \) | Recovery rate | 1/14 | 21 |
| \( e_i \) | 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). Then, $\beta$ and the relative infectivity of delta variant $\delta$ 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.

**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. 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  | Delta variant 77.5  |                       |
| Prevention of severe cases | 75%14,15           | 94%14,15            | 94%14,15             |
| Prevention of death | 85%16               | 96.1%17             |                       |

Data are presented as %.

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

**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%                                               |

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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, 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 20000 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 policies 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

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**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.
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 Astra-Zeneca, 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 school. (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.
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 school. (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.
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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