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Optimal Social Distancing Policy for COVID-19 Control in Korea: A Model-Based Analysis

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ABSTRACT

Background: Since March 2020, when coronavirus disease 2019 (COVID-19) was declared a pandemic, many countries have applied unprecedented restrictive measures to contain the spread of the virus. This study aimed to explore the optimal social distancing policy for COVID-19 control in South Korea to safely reopen the society.

Methods: We developed an age-specific, deterministic compartment epidemic model to examine the COVID-19 control decision-making process, including the epidemiology of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) between 1 July 2021 and 30 December 2022. The model consists of the natural history of COVID-19, testing performance, vaccinations, and social distancing enforcement measures to detect and control SARS-CoV-2. We modelled potential intervention scenarios with three distinct components: 1) social distancing duration and level; 2) testing intensity; and 3) vaccination uptake rate. The primary and secondary outcomes were COVID-19 incidence and prevalence of severe patients requiring intensive care unit (ICU) care.

Results: Four (or more) months of social distancing (that can reduce 40–60% transmission) may mitigate epidemic resurgence and ICU demand in the future and keep the cases below the capacity limit if the testing intensity and vaccination rate remain constant or increase by 20% (with respect to the current level). In contrast, two months of strict social distancing enforcement may also successfully mitigate future epidemic surge and ICU demand as long as testing intensity and vaccination rates are increased by 20%.

Conclusion: In South Korea, given the relatively high vaccination coverage and low incidence, four or more months of social distancing enforcement can effectively mitigate epidemic resurgence after lifting the social distancing measures. In addition, increasing the testing intensity and vaccination rate may help reduce necessary social distancing levels and duration to prevent a future epidemic resurgence and mitigate social and economic damage.

Keywords: COVID-19; ICU; Pandemic; SARS-CoV-2; Social Distancing Policy

INTRODUCTION

Since March 2020, when coronavirus disease 2019 (COVID-19) was declared a pandemic, many countries have implemented unprecedented restrictive measures to contain the

Disclosure
The authors have no potential conflicts of interest to declare.

Data Availability Statement
The datasets generated during and/or analysed during the current study are not publicly available due to the Korea Disease Control and Prevention Agency (KDCA)'s policy. But are available from the corresponding author on reasonable request. All requests will be reviewed by KDCA.

Author Contributions
Conceptualization: Jo Y, Jung J. Data curation: Jo Y, Jung J. Formal analysis: Jo Y. Methodology: Jo Y, Shrestha S. Software: Park H, Radnaabaatar M. Writing - original draft: Jo Y. Writing - review & editing: Jung J, Shrestha S, Park H, Radnaabaatar M.

spread of the virus.[1] Due to the economic and social damage, governments cannot continue lockdowns indefinitely, and therefore, sustainable and public health-driven exit strategies are required. With limited evidence guiding governments to contain the virus optimally, many countries have taken various measures, including vaccinating, testing, tracing, quarantining, and social distancing,[2] to slow the spread by 'flattening the curve.' South Korea is one of the few countries in the world to have successfully controlled the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) transmissions by implementing the "3T strategy" (tracing, testing, and treating) and social distancing with a mask mandate without a strict lockdown.[3] South Korea collected an enormous amount of precise empirical data through active contact tracing, testing and vaccination, including the variants associated with infections, diagnoses and age-specific symptom onset dates, and detailed information (age, types, doses) on the administered COVID-19 vaccines.[4] Since more than 70% of the total population received a second dose of vaccine,[5] the government announced an exit strategy with a gradual return to normal life beginning November 2021.[6]

Meantime, the spread of highly contagious variants globally, including Delta and Omicron, has made it more difficult for health authorities to curb the spread, despite the increasing vaccinations and stringent social distancing over several months. While increasing vaccinations are expected to have an important contribution in returning life to normal, it may not be the only part of an exit strategy as numerous issues and uncertainties concerning the existing COVID-19 vaccines with emerging new variants.[7] The quality and length of protection the vaccines will provide and their effectiveness in stopping viral transmission are yet to be determined. Supply-chain constraints, pricing, and unequal vaccine procurement across countries mean that coverage across most countries will remain below the level required for herd immunity.[7] While each intervention is expected to reduce transmission, it is difficult to assess the relative or collective impact of multiple interventions under different conditions. Optimal strategies may be different by epidemic conditions (e.g., stage of epidemic curves, transmissibility of virus, population susceptibility), country-specific context (e.g., vaccination coverage, health system capacity), and policy choice (e.g., types and level of social distancing control).

Quantifying the impact of a particular or collective strategy under varying conditions is thus an essential first step to promote social consensus and policy decision-making among competing interests and choices. South Korea, in the settings of relatively low incidence and high vaccination coverage with high health systems capacity/access, one of the critical debates for COVID-19 exit strategies is to determine how long and to what extent social distancing control should be implemented to mitigate epidemic burden and social and economic damage. This study aims to explore the optimal social distancing policy for COVID-19 control in South Korea to reopen society safely. We considered comprehensive intervention scenarios such as testing intensity, vaccination rate, and social distancing measures under uncertain future transmissibility conditions after lifting social distancing measures based on rich empiric data.

## METHODS

Model conceptualization

We developed an age-specific, deterministic compartmental model to capture the epidemiological dynamics of SARS-CoV-2 and the situation facing COVID-19 control decision-making in South Korea during the pandemic (1 July 2021–21 November 2021) and 13 months into the future (22 November 2021–31 December 2022). The model included the

natural history of COVID-19 illness, testing performance, vaccinations, and social distancing control measures (i.e., various non-pharmaceutical interventions such as mask-wearing and community restriction) to detect and control SARS-CoV-2. The model comprised four age groups (0–19, 20–39, 40–59, 60+ years), and eight disease-related states (uninfected, exposed, asymptomatic, false positive, symptomatic, recovered, dead, and vaccinated) (**Fig. 1**). In this model, the unvaccinated susceptible population may be exposed and develop COVID-19 infection, which is detected by mass screening/testing, and manifest symptoms. Infected populations include asymptomatic (undetected/test positive) and symptomatic (detected) populations, and we assumed those who are test positive are isolated and does not contribute to the transmission. We considered the natural recovery of the infected population and progression from asymptomatic to symptomatic groups. The symptomatic population will be either recovered or COVID-19 related dead. The population was subdivided into four groups based on age: 0–19 years, 20–39 years, 40–59 years, 60 years and above, and assumed age-specific contact patterns based on the published reference.[8-10]

Modelling interventions

We modelled five potential future intervention scenarios consisting of three distinct components: 1) social distancing duration and level; 2) testing intensity; and 3) vaccination uptake rate. The five intervention scenarios for the future epidemic were: 1) Scenario 1 (base case): three months of moderate social distancing control with current testing intensity (based on an average testing rate of the past six months) and current vaccination roll-out plan; 2) Scenario 2: four months of strict social distancing control with current testing intensity and current vaccination roll-out plan; 3) Scenario 3: two months of strict social distancing control, 20% increased testing intensity and vaccination uptake rate; 4) Scenario 4: four months of weak social distancing control, current testing intensity, and current vaccination roll-out plan; and 5) Scenario 5: two months of weak social distancing control, 20% increased testing intensity and vaccination uptake rate. We accounted for three different time intervals: 1) 1 July 2021 to 30 November 2021, to fit the observed incidence data; 2) under social distancing control: from 22 November 2021 to the next three months (28 February 2022), with projected simulated incidence data under social distancing control; and 3) after lifting social distancing control: from 1 March 2022 to 30 December 2022, with projected simulated incidence data without social distancing control. We considered

A Natural history of COVID-19

Isolation: Asymptomatic (detected) + Symptomatic (detected)
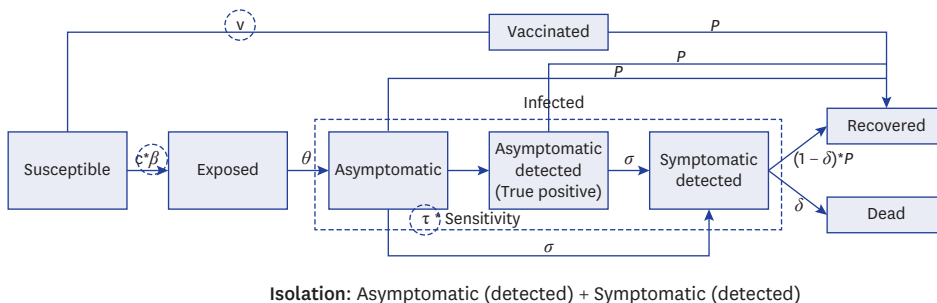
B Age contact matrix

	Age 0–19	Age 20–39	Age 40–59	Age 60+
Age 0–19	2.3	0.6	0.5	0.1
Age 20–39	0.7	1.9	1.0	0.1
Age 40–59	0.9	1.2	1.5	0.2
Age 60+	0.3	0.4	0.5	0.4

Fig. 1. Schematic representation of the modelling approach. We use a compartmental modelling framework to incorporate (**A**) natural history of COVID-19 and (**B**) age structure. (**A**) Natural history was captured by modelling transition of individuals between eight states: uninfected; susceptible, vaccinated, exposed, asymptomatic (undetected), asymptomatic (true positive), symptomatic (detected), recovered, and dead. (**B**) The population was subdivided into four groups based on age: 0–19 years, 20–39 years, 40–59 years, 60 years and above. Population in the four groups were modelled to have different contact patterns. As we focused on the key intervention strategies such as social distancing duration/level, testing rate and vaccination rate, we varied the parameters beta, tau, and v for respective intervention scenarios.
COVID-19 = coronavirus disease 2019.

various interventions independently and in combination to forecast the potential epidemic resurgence after March 2022 after a lift of social distancing measures.

Data

We used four types of empirical demographic and epidemiological data obtained from non-publicly available Korea Disease Control and Prevention Agency (KDCA) databases[11] and publicly available sources.[5] These included data on daily total PCR-confirmed COVID-19 cases, number of tests performed and vaccinations administered, and cases associated with variant type and symptom onset from tested samples between 20 January 2020, and 20 November 2021. Of the 418,252 total cases included in the tested samples, 306,339 reported test results, including variant type information and 271,863 (65%) patients reported COVID-19 infection-related symptoms after testing. Based on the total number of tests performed per day, we accounted for the current level of testing intensity as a median of 34,812 per day (interquartile range 23,401–45,395 per day). In addition, the vaccination data contained information on the weekly number of COVID-19 vaccines administered by type (AstraZeneca, Johnson & Johnson, Pfizer-BioNTech, Moderna), order (1st, 2nd, and 3rd dose) and age group of the vaccinated individuals from 6 March 2021 to 21 November 2021.

Parameters

We estimated the time-varying reproduction number Rt using EpiEstim[12] based on the case notification data and serial interval distribution (the times between successive cases in a transmission chain).[13,14] Based on an available age-stratified contact matrix for South Korea,[9] we constructed a matrix of four age groups (under 20, 20–39, 40–59, and older than 60 years) from the relative population size of the age group.[11] We merged the vaccination data with the age-specific case variants data from the tested samples to account age-specific 'effective vaccination' rates (i.e., rate of vaccination that account number of vaccinated people who can be completely free from COVID-19 infections based on different efficacy levels by respective vaccine types and the number of doses, and the relative proportion of delta variants assuming delta variant has a greater ability of immune escape than other variants) from 6 March 2021.[15,16] We accounted for age-specific symptom progression and case mortality rates and assumed 0.4% of all symptomatic patients would require intensive care unit (ICU) admission from the KDCA data. We applied the estimates of transmissibility, testing intensity, and vaccination rates between 1 July 2021 to 21 November 2021 to fit the observed data. We assumed the social distancing policy to reduce transmission by 40–60% based on other published studies and the expected reduction of future incidence trend.[17,18] These rates were identified within a range of reasonable target measures such as < 10% uninfected population and > 70% effective vaccination coverage by December 2022. **Table 1**, **Supplementary Data 1**, **Supplementary Table 1**, and **Supplementary Figs. 1-3** describe the specific model parameters and estimation processes.[19-23]

Table 1. Model input parameters

Characteristics	Age, yr				Reference
	0–19	20–39	40–59	60+	
Population as of 1 Jul 2021					
Total population	8,809,740	13,991,940	17,101,260	11,919,060	KDCA (total population = 51,822,000)[11]
Uninfected	8,758,016	12,682,284	15,688,592	4,525,342	Total population-infected-vaccinated-recovered-dead
Vaccinated	724	1,257,656	1,360,168	7,290,718	KDCA by 30 Jun 2021[11]
Exposed	1,000	2,000	2,000	2,000	Assumed by incidence level
Asymptomatic	1,000	2,000	2,000	2,000	
Test positive (PCR)	100	200	400	300	KDCA[11]
Symptomatic	100	200	400	300	KDCA[11]

(continued to the next page)

Table 1. (Continued) Model input parameters

Characteristics	Age, yr				Reference
	0–19	20–39	40–59	60+	
Recovered	50,000	50,000	50,000	100,000	KDCA[11] & assumptions: cumulative confirmed cases + natural recovery since Mar 2020
Dead	0	0	500	1,000	KDCA[11]
Model parameters					
Contact matrix					References [8],[9]
Age 0–19 yr	2.3	0.6	0.5	0.1	
Age 20–39 yr	0.7	1.9	1.0	0.1	
Age 40–59 yr	0.9	1.2	1.5	0.2	
Age 60+ yr	0.3	0.4	0.5	0.4	
Effective vaccinations per day[a] (%)					
1 Jul–20 Nov 2021	9,787 (0.1%)	53,998 (0.4%)	73,070 (0.4%)	29,964 (0.3%)	The average number of vaccinations per day by age group from KDCA data[11]
21 Nov–30 Dec 2021	29,361 (0.3%)	26,999 (0.2%)	36,335 (0.2%)	2,996 (0.3%)	Assumed age specific vaccination uptake by Jun 2022
1 Jan–30 Jun 2022	19,574 (0.2%)	16,199 (0.1%)	14,614 (0.01%)	300 (0.0%)	to reach 70% effective coverage (± 20% were assumed
1 Jul–30 Dec 2022	1,957 (0.0%)	1,079 (0.0%)	1,461 (0.0%)	60 (0.0%)	for variation for sensitivity analyses)
Progression rate from (unvaccinated) asymptomatic to symptomatic status	0.14	0.2	0.15	0.12	Probability of symptoms given infection: 66% (age 0–19 years), 74% (age 20–39 years), 68% (age 40–59 years), 62% (age 60 years and over) from KDCA data[11]
					Estimated daily progression rate by the formula: Probability of Symptoms Given Infection × Recovery Rate/(1 − Recovery Rate)
Symptomatic case fatality risk	0.0001	0.0003	0.002	0.0853	KDCA[11]
Vaccine effectiveness against infection (against new variants)					
1st dose AstraZeneca		50% (30%)			Reference [16] & assumptions: the efficacy was multiplied to respective age group along with the respective proportion of delta variants among tested individuals
1st dose Johnson & Johnson		50% (30%)			
1st dose Pfizer/Moderna		50% (35%)			
2nd dose AstraZeneca		77% (66%)			
2nd dose Pfizer/Moderna		95% (88%)			
3rd dose AstraZeneca		80% (70%)			
3rd dose Pfizer/Moderna		98% (90%)			
Transmissibility					
1 Jul–15 Oct 2021		0.04			Estimated by EpiEstim[12] based on serial interval distribution and case reporting data
16 Oct–21 Nov 2021		0.06			
21 Nov 2021–30 Dec 2022		0.12 (0.1–0.14)			Taken by the assumption of 3 or 4 times greater transmissibility of the new variants from the average Rt estimate between 1 Jul to 21 Nov 2021 (base case)[22],[23] (± 5% were assumed for variation for sensitivity analyses)
Social distancing control (21 Nov 2021–30 Feb 2022)					
Weak control		General 40% reduction in transmission			References [17],[18] & assumptions: strong control to immediately decrease the curve; moderate control to gradually decrease the curve; and weak control to continuously increasing incidence for the next months
Moderate control		General 50% reduction in transmission			
Strong control		General 60% reduction in transmission			
Testing rate among asymptomatic patients (1 Jul 2021–30 Dec 2022)		0.14 (0.11–0.17)			Estimated daily testing rate among asymptomatic patients based on the total daily testing volume[5] and the proportion of testing of exposed and asymptomatic individuals (assumed as 30% from seropositive prevalence data); Daily testing rate (14%) = average daily testing volume (35,000)/total suspected individuals including uninfected, exposed and asymptomatic populations (assumed as 250,000) (± 20% were assumed for variation for sensitivity analyses during 21 Nov 2021 to 30 Dec 2022)
Recovery rate		0.07 (0.06–0.08)			14 days[19]
Incubation rate		0.33			3–4 days[20]; daily rate estimated as 1/3
Diagnostic sensitivity		0.95			Reference [23]

KDCA = Korea Disease Control and Prevention Agency, PCR = polymerase chain reaction.
[a]Vaccination rates differ by age group by the government strategies and population size. The government prioritized vaccination to 60+ years age group, incrementally expanded access to 40–59, 20–39, and 0–19 years age groups.

Model outcomes

The primary and secondary outcomes were total COVID-19 cases and the number of severe patients (ICU admission) between 1 July 2021 to 30 December 2022 in South Korea. To determine the optimal COVID-19 response strategies to suppress the epidemic resurgence after lifting social distancing control, we compared the projected epidemic waves, cumulative incidence, and the total number of severe COVID-19 patients between July 2021 and December 2022 for the four intervention scenarios (Scenario 2 to 5) relative to the base case (Scenario 1) (**Table 2**). We conducted multivariate sensitivity analysis to examine how the changes in various model parameters affected the primary outcomes.[24] We used Latin Hyper Cube sampling to randomly sample 1,000 parameter sets, and simulated the model using these parameters sets to generate 95% confidence intervals in simulated model outcomes.[25] We also estimated partial rank correlation coefficient (PRCC) for each of the model parameters, to compare the relatively sensitivity of the model outcome to variation in each of these parameters (**Figs. 2, 3**, and **4; Supplementary Table 2; Supplementary Data 2**).[25] We also conducted multi-way sensitivity analyses to comprehensively explore the impact of the combination of intervention components such as duration and level of social distancing control, effective vaccination rate, and testing intensity, with different levels of transmissibility after lifting social distancing control (**Fig. 4**).

Ethics statement

The datasets used in our study were de-identified and fully anonymized in advance. The research was conducted ethically in accordance with the World Medical Association Declaration of Helsinki and was approved by the appropriate Institutional Review Board of the Gachon University College of Medicine, Incheon, Republic of Korea (GFIRB2021-232). No informed consent was required from patients due to the nature of data from KDCA.

RESULTS

Based on the calibrated model representing the COVID-19 epidemic trends in South Korea between 1 July and 20 November 2021, we projected the future epidemic curves after 21 November 2021 for the five scenarios (**Table 1**). Assuming that new variants increase transmissibility 3–4 times from the current level, our findings suggest that an epidemic resurgence may be expected with a lift of social distancing control depending on the level and duration of the social distancing control as well as the extent of testing intensity and effective vaccination uptake rate. First, three months of social distancing control (assuming a reduction in transmissibility by 50% between 21 November 2021 to 30 March 2022) with the current level of testing intensity and vaccination uptake rate may result in a gradual drop in the epidemic curve but a high epidemic resurgence after March 2022 (Scenario 1), while four months of strict social distancing control (assuming a reduction in transmissibility by

Table 2. Projected health outcome by intervention scenarios

| Scenario	Intervention policy				Health outcome			
	From 21 Nov 2021 to the next 2–4 mon	From 21 Nov 2021 to 30 Dec 2022			From 1 Jul 2021 to 30 Dec 2022			
	Social distancing control	Social distancing duration, mon	Testing	Vaccination	Total cumulative cases (in thousand)	Total ICU admission	Total cases averted (in thousand)	Total ICU admission averted
Scenario 1	Moderate	3	Base	Base	1,737	2,169	NA	NA
Scenario 2	Strong	4	Base	Base	410	403	−1,327	−1,766
Scenario 3	Strong	2	+20%	+20%	1,032	978	−705	−1,191
Scenario 4	Weak	4	Base	Base	1,374	1,421	−363	−748
Scenario 5	Weak	2	+20%	+20%	2,483	3,257	746	1,088

ICU = intensive care unit, NA = not available.
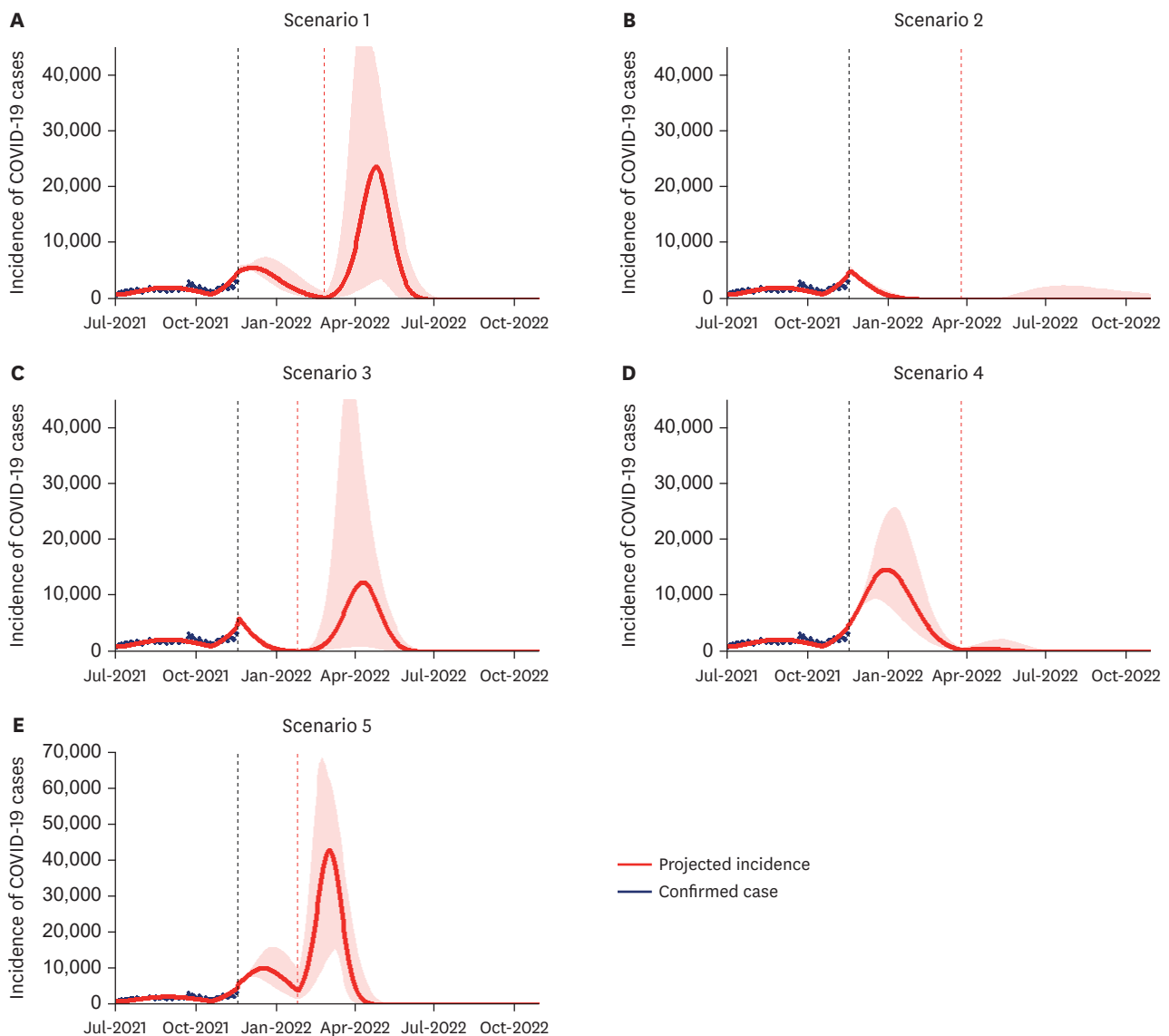
Fig. 2. Projected incidence of COVID-19 in South Korea between November 2021 and December 2022. The impacts of possible COVID-19 response scenarios were compared. The black dashed line indicates the time of projection (21 November 2021) and the red dashed line indicates the time of lifting social distancing control (in 2, 3, or 4 months). The pink shaded area projected results with 95% confidence intervals by varying transmissibility, testing intensity and vaccination rate. (**A**) Scenario 1 (base case: 3 months of moderate social distancing control with current level of testing and vaccination rates); (**B**) Scenario 2 (4 months of strict social distancing control with current level of testing and vaccination rates); (**C**) Scenario 3 (2 months of strict social distancing control with 20% increased level of testing and vaccination rates than the current rates); (**D**) Scenario 4 (4 months of weak social distancing control with current level of testing and vaccination rates); (**E**) Scenario 5 (2 months of weak social distancing control with 20% increased level of testing and vaccination rates than the current rates). COVID-19 = coronavirus disease 2019.

60%) may result in an immediate and sustained drop in the epidemic curve (Scenario 2), averting 1,327,000 cases and 1,766 ICU admissions compared to the base case. In contrast, despite increased testing intensity and vaccinations rates by 20%, two months of strict social distancing control may result in an epidemic resurgence, averting 705,000 cases and 1,191 ICU admission compared to the base case (Scenario 3). Four months of weak social distancing control (assuming a reduction in transmissibility by 40%) may result in an increased incidence between 21 November 2021 to 30 March 2022, if testing intensity and vaccination rate remain constant to the current level (Scenario 4), averting 363,000 cases and 748 ICU admissions compared to the base case. Even if the testing intensity and vaccination
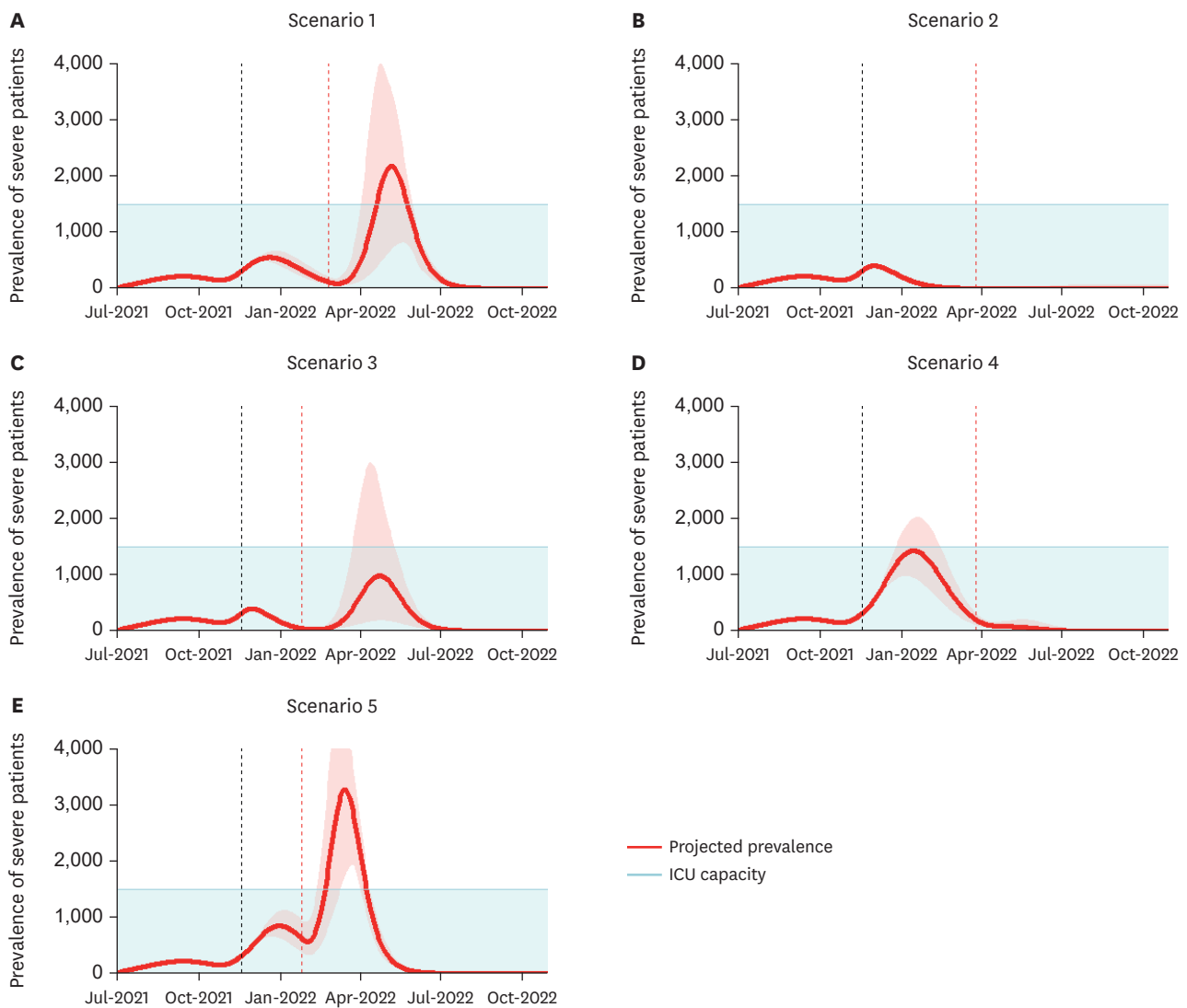
Fig. 3. Projecting prevalence of severe patients in South Korea between November 2021 and December 2022. The impacts of possible COVID-19 response scenarios were compared. The black dashed line indicates the time of projection (21 November 2021) and the red dashed line indicate the time of lifting social distancing control (in 2, 3, or 4 months). The pink shaded area projected results with 95% confidence intervals by varying transmissibility, testing intensity and vaccination rate. The light blue shaded area indicates the ICU capacity for COVID-19 patients in South Korea. (**A**) Scenario 1 (base case: 3 months of moderate social distancing control with current level of testing and vaccination rates); (**B**) Scenario 2 (4 months of strict social distancing control with current level of testing and vaccination rates); (**C**) Scenario 3 (2 months of strict social distancing control with 20% increased level of testing and vaccination rates than the current rates); (**D**) Scenario 4 (4 months of weak social distancing control with current level of testing and vaccination rates); (**E**) Scenario 5 (2 months of weak social distancing control with 20% increased level of testing and vaccination rates than the current rates).
COVID-19 = coronavirus disease 2019, ICU = intensive care unit.

uptake rate are increased by 20%, two months of weak social distancing control may result in a high epidemic resurgence with a lift of social distancing control (Scenario 5), having additional 746,000 cases and 1,088 ICU admissions compared with the base case scenario.

The prevalence of severe patients was compared to the country's ICU capacity (n = 1,500) for COVID-19 patients (**Fig. 3**). Increasing transmissibility of new variants and reduced social distancing level/duration may result in a substantial number of severe patients exceeding the current ICU capacity. We found four months of strict social distancing control or strong two months social distancing control with increased testing intensity and vaccination uptake rate may contain the ICU demand below the capacity limit (Scenario 2 and 3). On the other

hand, moderate or weak social distancing control may result in substantial numbers of severe patients which are close to or exceed the current ICU capacity (Scenarios 1, 4, and 5) regardless of the duration of control (2–4 months) or testing intensity and vaccination increase by 20%.

The impact of all combination scenarios is presented in **Fig. 4** as the cumulative incidence (**Fig. 4A**) and the peak number of severe patients (**Fig. 4B**). In general, the epidemic burden is greater as the levels of social distancing control, testing intensity and vaccination rate decrease, and transmissibility increases, as shown a change of cumulative incidence ranging from 393,000 to 4.4 million and the peak number of severe patients ranging from 394 to 10,000 between July 2021 and December 2022. Four months of strict social distancing control with constant testing intensity and vaccination uptake rate resulted in a cumulative incidence of 408,000 cases (under the condition of transmissibility increase three times of the current level) from 1 July 2021–30 December 2022. However, reducing to two months of strict social distancing control and increasing testing intensity and vaccination uptake rate by 20% may achieve a similar level of cumulative incidence (414,000 cases). However, with four months of strict social distancing control, ICU capacity is never to be breached unless both testing intensity and vaccination uptake rate decrease by 20% under increased transmissibility four times the current level. Meanwhile, two months of social distancing control will result in ICU
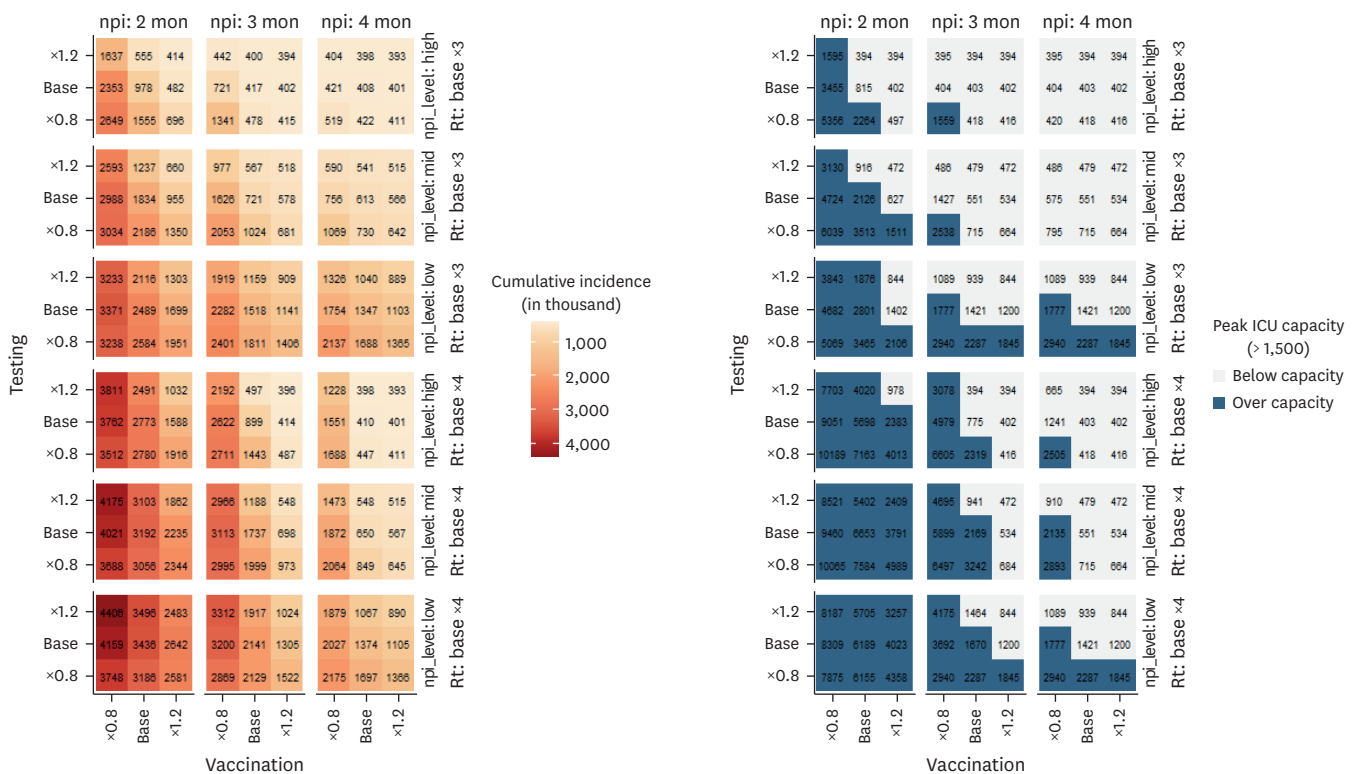

Fig. 4. Cumulative incidence of COVID-19 cases and the peak number of severe COVID-19 patients in South Korea between 1 July 2021 to 31 December 2022. This heat map displays the cumulative incidence of COVID-19 cases (**A**) and the peak number of severe COVID-19 patients (**B**) between 1 July 2021 to 31 December 2022. Each panel corresponds to the social distancing duration (2, 3, 4 months from 22 November 2022), social distancing control level (strong as reducing 60% transmissibility, medium as reducing 50% transmissibility, and weak as reducing 40% transmissibility), testing rate (base as the average daily testing rate between 1 July 2021 to 21 November 2021, ×0.8 as 20% decrease of the average rate, and ×1.2 as 20% increase of the average rate), and vaccination rate (base as the uptake rate by the current vaccine roll-out plan, ×0.8 as 20% decrease of the current rate, and ×1.2 as 20% increase of the average rate). Rt base corresponds to the current average transmissibility between 1 July 2021 to 21 November 2021 and Rt base ×3 and Rt base ×4 as the 3 times and 4 times increase of the current level of transmissibility from 22 November 2021 to 31 December 2022.
COVID-19 = coronavirus disease 2019, ICU = intensive care unit.

capacity being more likely breached unless both testing intensity and vaccination uptake rate increased by 20% under strict social distancing enforcement.

DISCUSSION

This modelling analysis explored different intervention scenarios for an optimal COVID-19 exit strategy to reduce social distancing measures while minimising the epidemic burden, social and economic damage. After lifting social distancing control, our findings indicate a potential epidemic surge in three months (> 10,000 incidence cases). Four (or more) months of social distancing may mitigate a future epidemic resurgence and ICU demand keeping it below the capacity limit in both strong or weak social distancing levels if testing intensity and vaccination rate remain constant or increased by 20% of the current level. On the other hand, two months of strict social distancing may also successfully mitigate future epidemic surge and ICU demand as long as testing intensity and vaccination rates increase by 20% than the current level. Increasing testing intensity and vaccination uptake rate may help reduce necessary social distancing levels and duration to prevent future epidemic resurgence.

In South Korea, at the beginning stage of increasing incidence trend with emerging new variants, duration and level of social distancing greatly influence the future epidemic trend. Increasing the testing intensity and vaccination rates may help reduce the level and duration of mandatory social distancing to prevent the epidemic resurgence. Reducing the current testing intensity may result in an immediate small drop in the number of cases, but it would allow ongoing transmission by infected but undetected patients, and the number of cases will eventually increase over time, with an epidemic surge in June 2022. Similarly, reducing the current vaccination uptake rate may result in an epidemic surge in July 2022 due to the increase in the unvaccinated population. The impact and benefit of vaccination or testing are, however, greater, especially when the duration of social distancing is short (2 months) and the level of the control is strong (414,000 with 20% increased testing and vaccination vs. 2.6 million with 20% decreased testing and vaccination under three times increased transmissibility condition). In other words, in settings where and when testing intensity and vaccination uptake rate are relatively high, increasing social distancing duration from two to four months may result in marginal reduction of cumulative incidence (5% from 414,000 to 393,000 under strong control measure; 32% from 1.3 million to 880,000 with weak control measure). However, in settings wherein testing intensity and vaccination uptake rate are relatively lower, increasing social distancing duration from two to four months may reduce cumulative incidence substantially (79% from 2.5 million to 519,000) with strict social distancing enforcement.

Our findings are consistent with other modelling studies which have explored exit strategies, highlighting the critical considerations of a low reproduction number[18] and timing/duration of lockdown.[26] Dickens et al.[26] using an agent-based model in Singapore, found that the lockdown start time has a greater impact than its duration and suggested that three months gradual release exit strategies are critical in suppressing the epidemic. Marziano et al.[27] suggested controlling the reproduction number and incidence of infection are crucial. Social distancing/lockdown interventions have proven successful in curbing the spread of the disease.[28,29] Our study also showed the duration and level as the key drivers of the epidemic impact (**Fig. 4**). Nonetheless, the decision around the optimal duration/level of social distancing should be carefully considered based on the current epidemic stage in the country, expected transmissivity after lifting social distancing control, and the demographic profiles of the unvaccinated population. For example,

low- and middle-income countries with high incidence and low vaccination coverage, the impact of vaccination and testing to reduce epidemic burden may be greater than our findings; high income countries with low incidence and high vaccination coverage, the impact of social distancing to reduce epidemic burden may be greater than our findings. As the impact of one particular or a set of strategies may differ by settings specific conditions as well as changing epidemic stages over time, our model may be utilised in various settings and repeated times to promote social consensus on policy decision and efficient resource allocation.

Our study has some limitations. First, our model did not consider possible reinfections and breakthrough infections among the vaccinated population due to a lack of data/data limitations. If we account for these factors, the level of the potential epidemic surge may be greater than our estimates. However, the impact on ICU demand may depend on the efficacy of the vaccine or available treatments (e.g., molnupiravir and paxlovid) to reduce disease progression.[30] Second, it is difficult to assess the impact of the social distancing policies on reducing transmission levels (Rt). The current and future adherence to social distancing measures and their effects are subject to not only when and how long they are implemented but also who is targeted and where. Studies have shown a drop in the effects of social distancing over time with increasing behavioural fatigue and social/economic pressure. Moreover, the introduction of variants with increased transmissibility may require more stringent lockdown policies with stricter and longer social distancing to control the epidemic, especially in a setting with low vaccination coverage and constrained health systems capacity/access. As age-specific empirical data (e.g., different infectivity/transmissibility, progression, case fatality rates by age groups) become more available, future studies should explore the optimal targeting intervention strategies by age groups to minimize the extent of necessary restriction and achieve the best resource utilization. Third, the future epidemic resurgence will also be influenced by other factors such as herd immunity and immune waning effects.[31] As seroprevalence data is yet to be released, the exact proportion of the undetected exposed population, their contribution to the transmission in the community, and their subclinical progression to natural recovery remain to be established. However, these factors may influence the overall susceptibility and herd immunity. While herd immunity along with high vaccination coverage may mitigate the potential epidemic resurgence, immune escape of new variants or waning immune effects against existing variants over time may collectively balance each other. The model can be calibrated in the future with real-time forecasting efforts and serological surveys to better reflect the COVID-19 prevalence and incidence within South Korea. Fourth, we did not consider other potential synergistic or counterbalancing effects when evaluating the parameters and combination scenarios. For example, the level of vaccine coverage may influence the susceptibility or progression rates in the population over time, influencing the infection levels and ICU demand. Similarly, the impact of testing (i.e., the number needs to test positivity) may differ with changing prevalence levels in society. In addition, strict countermeasures may reduce the testing rate itself or the testing effects, changing the population's overall susceptibility. Finally, the model output may be heterogeneous due to population migration, mobility, and density; epidemic stage; and health system capacity. Future studies can further explore such heterogeneity across populations and regions and guide optimal control policies by setting specific conditions.

Despite these limitations, our model is the first compartment model to evaluate the relative intervention impact in South Korea based on detailed surveillance data obtained from the KDCA and other publicly available resources. By incorporating both the natural history of the COVID-19 infection and health system performance features, such as diagnostic performance and vaccination uptake and efficacy, this model comprehensively quantified the extent of

uncertainty to examine competing policy options and guide an optimal exit strategy under possible epidemic and intervention scenarios.

In conclusion, this modelling analysis explored different intervention scenarios for an optimal COVID-19 exit strategy to reduce necessary social distancing measures and avoid epidemic surge in the future. We considered comprehensive intervention scenarios with different levels/duration of social distancing and testing intensity and vaccination rate under uncertain epidemic conditions with new emerging variants after lifting social distancing restrictions. Our findings suggest four or more months of social distancing control that can reduce 50% or more personal contact can effectively mitigate potential epidemic resurgence. In addition, increasing the testing intensity and vaccination rate by 20% may help reduce the level and duration of mandatory social distancing to prevent the epidemic resurgence and mitigate social and economic damage.

ACKNOWLEDGMENTS

SUPPLEMENTARY MATERIALS

Supplementary Data 1
Model details

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Supplementary Data 2
Multivariate uncertainty analyses

Click here to view

Supplementary Table 1
Model parameters, input values, and governing equations

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Supplementary Table 2
Input parameters and ranges used in sensitivity analyses

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Supplementary Fig. 1
Estimating key rate parameters. Rt from EpiEstim. We used EpiEstim ("estimate_R" function)[1] to estimate time varying Rt based on the daily reported coronavirus disease 2019 cases in South Korea from 6 June to 21 November 2021 and assumed serial interval distribution (mean: 6, standard deviation: 2). The estimated Rt mean was 1.09 (median 1.04, interquartile range: 0.97–1.19), which was used to fit the observed data between 1 July to 21 November 2021. We calculated transmissibility based on Average Rt × Recovery Rate (1/14) × (1/contact)

and assumed 1.7 times increased transmissibility from 17 October to 20 November 2021 by dominant delta variant influence and assumed three times increased transmissibility from 21 November 2021 to 31 December 2022 by the emerging new variant (e.g., Omicron) influence.

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Supplementary Fig. 2

Estimating testing rate. The testing data represented information on the total number of tests performed per day, which was gradually increased since 2020. We estimated about average daily 35,000 (interquartile range 23,000–45,000) tests conducted in 2021 in South Korea. Since these tests were performed on both susceptible and exposed population, we assumed the average daily testing rate to be 0.14 among undetected asymptomatic population to fit to the observed incidence data, along with the current vaccination and transmissibility parameters. We then applied ±20% variation for the future testing rate from 21 November 2021 to 30 December 2022, for the sensitivity analyses.

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Supplementary Fig. 3

Estimating age specific vaccination rates. We used information on COVID-19 vaccines administered between 6 March and 21 November 2021 from non-publicly available Korea Disease Control and Prevention Agency data. The vaccination data contained information on the weekly number of COVID-19 vaccines administered by type (AstraZeneca, Johnson & Johnson, Pfizer/Moderna) and order (1st, 2nd, and 3rd dose) by age group of vaccinated individuals (17 or younger, 18–19, 20–29, 30–39, 40–49, 50–59, 60–69, 70–74, 75–79, 80 or older years). We recategorized the 10 age groups into four (0–19, 20–39, 40–59, 60+ years). We used the respective vaccine efficacy for AstraZeneca, Johnson & Johnson, Pfizer/Moderna and assumed reduced vaccine efficacy by potential immune escape of the delta variant as shown (**Table 1**). We then combined the respective number of administered vaccinations by type and dose with the empirically observed proportion of the delta variants among all tested samples, to estimate variant and age specific effective vaccination rates per week. We then transformed the weekly rate into daily rate and calculated the average number of effective vaccinations administered per day by age group, and fitted them to the observed data (base case model) between 1 July to 20 November 2021 (9,787 for ages 0–19; 53,998 for ages 20–39; 73,070 for ages 40–59; 29,964 for ages 60+). In terms of the future vaccination rates, we assumed 3, 0.5, 0.5, and 0.1 times greater rates for the 0–19, 20–39, 40–59, and 60+ years age groups between 21 November to 30 December 2021 (29,361 for ages 0–19; 26,999 for ages 20–39; 36,335 for ages 40–59; 2,996 for ages 60+), 2, 0.3,0.2, 0.01 times greater rates for ages 0–19, 20–39, 40–59, and 60+ groups between 1 January 2022 to 30 June 2022 (19,574 for ages 0–19; 16,199 for ages 20–39; 14,614 for ages 40–59; 300 for ages 60+) and 0.2, 0.02, 0.02, 0.002 times (1,957 for ages 0–19; 1,079 for ages 20–39; 1,461 for ages 40–59; 60 for ages 60+) greater rates for ages 0–19, 20–39, 40–59, and 60+ between 1 July 2022 to 30 December 2022 based on the national vaccine priority and target strategies. We calibrated the future vaccination rates to satisfy the condition of an effective vaccination coverage of > 70% for each population group by December 2022. In our model, we assumed a prompt and lifelong vaccination immunity to be acquired from the day of immunization, given the vaccine effectiveness, by dose and by type of COVID-19 vaccine.

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Supplementary Fig. 4

Partial rank correlation coefficient between input parameters and the COVID-19 incidence. We also computed PRCC[4] describing the correlation between each input parameter and model output (i.e., the projected COVID-19 incidence in Scenario 1 as base case), adjusting for values of other input parameters. The PRCC ranked each parameter and output by the magnitude and measured the sensitivity of an output variable to each parameter. PRCC values range from −1 (perfect negative correlation between input parameter and model output) to +1 (perfect positive correlation), with values of 0 indicating no correlation. According to this finding, we conducted the multi-way sensitivity analysis based on the identified top three drivers (transmissibility, vaccination rate, testing rate) of the incidence outcome in **Fig. 4**.

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Supplementary References

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