Supplementary

A Calculation of the parameters in our model

Vaccine-related model parameters ($\tau_{v,j}$, e_j, $e_{b,j}$, $1/\omega$) are calculated based on the effectiveness at 12 and 17 weeks from the second dose for viral-vector type, 3 and 8 weeks from second dose for mRNA type, and 3 weeks after inoculation of booster shot. Since the proportion of the population in Korea who were given mRNA as primary doses is 70.3%, then $1/\omega = 0.703 \times 21 + 0.297 \times 84$ [1, 2]. Similarly, weighted arithmetic mean is used to calculate e_j, $e_{w,j}$, $e_{b,j}$ from e_j^{pre}, $e_{w,j}^{\text{pre}}$, $e_{b,j}^{\text{pre}}$, respectively. The values of the parameters e_j^{pre}, $e_{w,j}^{\text{pre}}$, $e_{b,j}^{\text{pre}}$, which we found from the literature, are stated in Table 1. Also, we assume that vaccine-induced immunity wanes exponentially at a rate τ_j^v. Then $h_{\text{eff}}(t) := e_j e^{-\tau_j^v t}$. Since we know two values of vaccine effectiveness at two different time points, then

$$\begin{aligned} & h_{\text{eff}}(35) = e_j e^{-35\tau_j^v} = e_{w,j} \\ \implies \quad & \tau_j^v = -\log(e_{w,j}/e_j)/35. \end{aligned}$$

Finally, the value of f is computed as the percentage of severe patients who died from the disease. Since the fatality rate among all infected individuals is 1% [3] and the proportion of severe cases for Delta is 2.28% [4] then $f = 43.9\%$. All calculation results are shown in Table 1.

Symbol	Description (units)		pre-δ	δ	o	Ref.
e_j^{pre}	Vaccine effectiveness against symptomatic disease after dose 2	viral-vector (10-14 weeks)	70%	70%	30%	[1, 2]
		mRNA (5-9 weeks)	91%	91%	63%	
$e_{w,j}^{\text{pre}}$	Vaccine effectiveness against symptomatic disease after dose 2	viral-vector (15-19 weeks)	52.5%	52.5%	14%	[1, 2]
		mRNA (5-9 weeks)	85%	85%	49%	
$e_{b,j}^{\text{pre}}$	Vaccine effectiveness against symptomatic disease 2-4 weeks after booster shot	viral-vector (primary)	96%	96%	64%	[1, 2]
		mRNA (primary)	96%	96%	68%	
e_j	Adjusted effectiveness of mRNA and viral vector vaccines		84.8%	84.8%	53.2%	Calculated
$e_{w,j}$	Adjusted effectiveness of mRNA and viral vector vaccines after 5 weeks		75.4%	75.4%	38.6%	Calculated
$\tau_{v,j}$	Mean waning rate of vaccine-induced immunity (1/day)		1/297	1/297	1/109	Calculated
$e_{b,j}$	Adjusted effectiveness of booster vaccines		96.0%	96.0%	66.8%	Calculated
$1/\omega$	Mean duration to have immune after normal vaccines (days)		40	40	40	Calculated

Table 1. Vaccine-related parameters.

B Model equations

Our model is an SEIQRD compartment model considering the severity of infected individuals. Each infection-related compartment ($E,\ I,\ Q^{\mathrm{m}},\ Q^{\mathrm{s}},\ R,\ D$) is categorized according to vaccination state and variant, which are distinguished by subscripts. The subscript j represents the type of variant; $j = 1$, 2, or 3 refers to infection with pre-Delta, Delta, or Omicron, respectively. Compartments having only the subscript j mean infected people from the unprotected group (S, V). The subscripts U and P represent infected people from ineffectively vaccinated group (U) and effectively vaccinated group (P_1, P_2, P_3, W, V_b). Equations 1 to 6 describe the infection-related states.

$$\begin{cases} \frac{dE_j}{dt} &= (S+V)\lambda_1 - \kappa_j E_j \\ \frac{dE_{U,j}}{dt} &= (U)\lambda_2 - \kappa_j E_{U,j} \\ \frac{dE_{P,1}}{dt} &= (W+V_b)\lambda_3 - \kappa_1 E_{P,1} \\ \frac{dE_{P,2}}{dt} &= (W+V_b+P_1)\lambda_3 - \kappa_2 E_{P,2} \\ \frac{dE_{P,3}}{dt} &= (W+V_b+P_1+P_2)\lambda_3 - \kappa_3 E_{P,3} \end{cases} \tag{1}$$

$$\begin{cases} \frac{dI_j}{dt} &= \kappa_j E_j - \alpha I_j \\ \frac{dI_{U,j}}{dt} &= \kappa_j E_{U,j} - \alpha I_{U,j} \\ \frac{dI_{P,j}}{dt} &= \kappa_j E_{P,j} - \alpha I_{P,j} \end{cases} \tag{2}$$

$$\begin{cases} \frac{dQ^{\mathrm{m}}_j}{dt} &= (1-p_j)\alpha I_j - \gamma^{\mathrm{m}} Q^{\mathrm{m}}_j \\ \frac{dQ^{\mathrm{m}}_{U,j}}{dt} &= (1-(1-e^{\mathrm{s}})p_j)\alpha I_{U,j} - \gamma^{\mathrm{m}} Q^{\mathrm{m}}_{U,j} \\ \frac{dQ^{\mathrm{m}}_{P,j}}{dt} &= (1-(1-e^{\mathrm{s}})p_j)\alpha I_{P,j} - \gamma^{\mathrm{m}} Q^{\mathrm{m}}_{P,j} \end{cases} \tag{3}$$

$$\begin{cases} \frac{dQ^{\mathrm{s}}_j}{dt} &= p_j \alpha I_j - \gamma^{s} Q^{\mathrm{s}}_j \\ \frac{dQ^{\mathrm{s}}_{U,j}}{dt} &= (1-e^{\mathrm{s}})p_j \alpha I_{U,j} - \gamma^{s} Q^{\mathrm{s}}_{U,j} \\ \frac{dQ^{\mathrm{s}}_{P,j}}{dt} &= (1-e^{\mathrm{s}})p_j \alpha I_{P,j} - \gamma^{s} Q^{\mathrm{s}}_{P,j} \end{cases} \tag{4}$$

$$\begin{cases} \frac{dR_j}{dt} &= \gamma^{\mathrm{m}} Q^{\mathrm{m}}_j + (1-f)\gamma^{\mathrm{s}} Q^{\mathrm{s}}_j - \omega R_j \\ \frac{dR_{U,j}}{dt} &= \gamma^{\mathrm{m}} Q^{\mathrm{m}}_{U,j} + (1-f)\gamma^{\mathrm{s}} Q^{\mathrm{s}}_{U,j} - \omega R_{U,j} \\ \frac{dR_{P,j}}{dt} &= \gamma^{\mathrm{m}} Q^{\mathrm{m}}_{P,j} + (1-f)\gamma^{\mathrm{s}} Q^{\mathrm{s}}_{P,j} - \omega R_{P,j} \end{cases} \tag{5}$$

$$\begin{cases} \frac{dD_j}{dt} &= f\gamma^{\mathrm{s}} Q^{\mathrm{s}}_j \\ \frac{dD_{U,j}}{dt} &= f\gamma^{\mathrm{s}} Q^{\mathrm{s}}_{U,j} \\ \frac{dD_{P,j}}{dt} &= f\gamma^{\mathrm{s}} Q^{\mathrm{s}}_{P,j}. \end{cases} \tag{6}$$

The susceptible compartments are also categorized according to vaccination state. S and V are unprotected groups since they are not vaccinated or need more time to get immunity. The ineffectively vaccinated group (U) cannot get immunity by any vaccine. Any variant can infect the unprotected and ineffectively vaccinated groups. The effectiveness of vaccines against each variant is different, and hence, V may become P_1, P_2, or P_3, which means fully protected against some or all variants. As vaccine-induced immunity of individuals in P_j wane over time, they move to the W compartment. Individuals in W and U can get booster shots, but U cannot get immunity in our

assumption. Right after receiving booster shots, individuals in W move to V_b, and eventually to P_j.

$$\begin{cases} \frac{dS}{dt} = & -(\lambda_1+\lambda_2+\lambda_3)S - \theta + \tau_n R_j \\ \frac{dV}{dt} = & -(\lambda_1+\lambda_2+\lambda_3)V + e_1\theta - \omega V \\ \frac{dU}{dt} = & -(\lambda_1+\lambda_2+\lambda_3)U + (1-e_1)\theta + \tau_n R_{U,j} \\ \frac{dP_1}{dt} = & -(\lambda_2+\lambda_3)P_1 + (e_1-e_2)\omega V - \tau_{v,1}P_1 + (e_{b,1}-e_{b,2})\omega_b V_b \\ \frac{dP_2}{dt} = & -\lambda_3 P_2 + (e_2-e_3)\omega V - \tau_{v,2}P_2 + (e_{b,2}-e_{b,3})\omega_b V_b \\ \frac{dP_3}{dt} = & e_3\omega V - \tau_{v,3}P_3 + e_{b,3}\omega_b V_b \\ \frac{dW}{dt} = & -W(\lambda_1+\lambda_2+\lambda_3) + \tau_{v,1}P_1 + \tau_{v,2}P_2 + \tau_{v,3}P_3 - q\theta_b + \tau_n R_{P,j} \\ \frac{dV_b}{dt} = & -V_b(\lambda_1+\lambda_2+\lambda_3) + q\theta_b - \omega_b V_b. \end{cases} \tag{7}$$

The forces of infection consider the variants and their transmissibility, social distancing, and transmission reduction by vaccines. The forces of infection are defined as

$$\begin{cases} \lambda_1 = & (1-\mu)\mathcal{R}_0\alpha\frac{(I_1+\eta_j(I_{U,1}+I_{P,2}))}{N} \\ \lambda_2 = & (1-\mu)\mathcal{R}_0^\delta\alpha\frac{(I_2+\eta_j(I_{U,2}+I_{P,2}))}{N} \\ \lambda_3 = & (1-\mu)\mathcal{R}_0^o\alpha\frac{(I_3+\eta_j(I_{U,3}+I_{P,3}))}{N}. \end{cases} \tag{8}$$

At the beginning of our estimation, vaccine, Delta, and Omicron-related compartments are zero since there are no vaccines and such variants. Since we have no data on infected people who are not yet confirmed, $E_1(0) = 400/\kappa_1 = 1600$ and $I_1(0) = 400/\alpha = 2400$ are calculated from average daily confirmed cases at the end of February 2021. The initial values for $Q^{\mathrm{s}}, Q^{\mathrm{m}}, R_1$, and D_1 are obtained from the data [5]. The initial value for S is calculated as the remaining number of individuals based on the total population and other initial values. With these, our proposed mathematical model consists of Equations 1-8 with initial values given in Table 2.

The administration of COVID-19 pill started on January 14, 2022 [6], which is only two days before the end of our estimation. Hence, we did not incorporate this in the model when fitting the data. Except for Figure 6, the properties of Omicron variant and the government's response, such as social distancing and daily booster shots, are considered. Only Figure 6 considers the effect of antiviral therapy by multiplying $(1-e_{\mathrm{pill}})$ to p_j in the first terms of equations for the quarantined individual $(Q^{\mathrm{s}}, Q^{\mathrm{m}})$ (Equations 3, 4) and hence, the severity of new confirmed cases will be reduced. We set that value of e_{pill} to 0.89 [7, 8].

Symbol	Value	Description (units)	Ref.
N	51,705,905	Population of Korea in March 2021	[9]
$E_1(0)$	1,600	Initial value for unvaccinated latent group infected by pre-delta variant	Calculated
$I_1(0)$	2,400	Initial value for unvaccinated infectious group infected by pre-delta variant	Calculated
$Q_1^{\mathrm{m}}(0)$	7,313	Initial value for unvaccinated isolated group with mild symptom infected by pre-delta variant	[5]
$Q_1^{\mathrm{s}}(0)$	144	Initial value for unvaccinated isolated group with severe symptom infected by pre-delta variant	[5]
$R_1(0)$	79,880	Initial value for unvaccinated recovered group infected by pre-delta variant	[5]
$D_1(0)$	1,585	Initial value for unvaccinated death group infected by pre-delta variant	[5]
$S(0)$	51,612,983	Initial value of susceptible group	Calculated
E_{import}^{δ}	1	Initial expected patient when the first delta case was confirmed	Estimated
E_{import}^{o}	100	Initial expected patient when the first omicron case was confirmed	Estimated

Table 2. Initial value for model compartments; other initial of compartment are zero.

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