SUPPLEMENTARY MATERIALS

Model Assumptions

1. The natural growth and mortality rate of the population were not considered.
2. The mobility probability of people in the same area was consistent.
3. Recovered cases would not be reinfected with coronavirus disease 2019 (COVID-19).
4. The protective efficacy of the vaccine will not diminish during the forecast period.
5. The rates of population mobility between different regions were consistent and stable.
6. The time taken by the movement of people was ignored.

Grouping Results

We collected the COVID-19 epidemic data of 194 countries and regions except China through the COVID-19 global data of Dingxiangyuan Website (*1*) which included confirmed cases, recovered cases, and deaths up to October 10, 2021 and the population data collected by the World Health Organization (WHO) until October 10, 2021. The prevalence rate of COVID-19 ($R_{pre,i}$) in each country or region was calculated by the following methods:

$$R_{pre,i} = \frac{n_{acc,i} - n_{rec,i} - n_{dea,i}}{N_i} \times 100\%$$

$n_{acc,i}$ denoted the cumulative number of infections, $n_{rec,i}$ represented the cumulative number of recovered cases, $n_{dea,i}$ denoted the cumulative number of deaths, and N_i was the population of country (or region) i.

The 194 countries were ranked by quintile into high risk, medium risk, and low risk regions. China has been selected as a representative country for the COVID-zero regions due to its ongoing zero-COVID-19 prevention and control strategy. The grouping result was shown in the Supplementary Table S1.

SUPPLEMENTARY TABLE S1. The detailed grouping results based on the prevalence of COVID-19 within 194 countries or regions.

Low risk region		Medium risk region		High risk region	
Country or region	Prevalence (/100,000)	Country or region	Prevalence (/100,000)	Country or region	Prevalence (/100,000)
Chad	0.14	Dominican Republic	91.30	Iran	495.50
Niger	0.49	Djibouti	92.51	Cuba	521.52
Gambia	0.54	The Republic of Korea	96.26	Oman	583.34
Senegal	1.25	Monaco	96.83	Ukraine	606.80
Burkina Faso	1.62	Philippines	98.45	Turkey	640.37
Bhutan	2.20	Spain	105.77	Lesotho	651.28
Mali	2.76	Panama	108.84	Singapore	661.37
Liberia	2.79	Congo	116.33	Bahamas	663.96
Zambia	3.67	Czechia	124.86	North Macedonia	691.11
Madagascar	4.94	Equatorial Guinea	127.01	Israel	710.03
Nigeria	5.17	Hungary	129.19	Moldova	710.32
Comoros	5.63	Central African Republic	130.64	Guyana	710.94
Mozambique	6.43	Falkland Islands	136.89	Seychelles	718.04
Kenya	7.49	Italy	139.27	Armenia	760.45
Saudi Arabia	7.57	Cape Verde	152.34	Brunei	795.00
Sudan	8.53	Nicaragua	161.58	Anguilla	824.19
South Sudan	9.44	Greenland	172.09	Bulgaria	873.81
Guinea	9.70	Iceland	172.75	Georgia	883.76
Bangladesh	10.16	Montserrat	172.98	Romania	904.68
Paraguay	10.77	Vietnam	175.20	Belize	956.69
Ghana	15.30	Denmark	179.53	Latvia	999.82
New Zealand	17.52	Algeria	182.49	Saint Lucia	1,034.69

TABLE S1. (Continued)

Low risk region		Medium risk region		High risk region	
Country or region	**Prevalence (/100,000)**	**Country or region**	**Prevalence (/100,000)**	**Country or region**	**Prevalence (/100,000)**
Mauritania	20.28	Jordan	190.29	Jamaica	1,036.55
Uzbekistan	21.16	San Marino	191.53	Barbados	1,105.54
India	21.55	Canada	196.76	Bosnia and Herzegovina	1,107.93
Malawi	22.89	Ecuador	198.26	Mauritius	1,124.16
Kuwait	23.04	Andorra	199.31	Libya	1,152.96
Sierra Leone	23.08	Bolivia	203.64	Dominica	1,198.76
Yemen	24.84	Brazil	208.87	Isle of Man	1,228.95
Pakistan	26.07	Turks and Caicos Islands	209.21	Estonia	1,307.31
Benin	26.78	Guernsey	210.52	Lithuania	1,398.40
Democratic Republic of Congo	28.12	Iraq	212.04	Antigua and Barbuda	1,471.49
Zimbabwe	28.74	Azerbaijan	216.25	Fiji	1,497.08
Ethiopia	29.41	Gabon	217.73	Palestine	1,526.13
Togo	30.95	Malta	221.21	Montenegro	1,530.60
Japan	31.32	Indonesia	222.68	Grenada	1,748.15
Egypt	34.66	Cayman Islands	223.68	Norway	1,910.30
Angola	35.39	Guatemala	227.54	Costa Rica	1,938.34
Guinea-Bissau	37.75	Sri Lanka	238.31	Finland	2,053.73
Papua New Guinea	41.57	Aruba	243.52	United Kingdom	2,165.33
Tanzania	41.96	Laos	249.69	Saint Kitts and Nevis	2,286.48
Morocco	42.29	Thailand	251.62	Mongolia	2,335.06
Rwanda	42.91	El Salvador	269.31	Honduras	2,509.91
Haiti	44.14	Botswana	281.85	Bermuda	2,580.47
Cote d'Ivoire	48.33	Belarus	292.94	Suriname	2,714.13
Kyrgyzstan	48.53	Mexico	296.26	Greece	2,725.79
Argentina	50.25	Germany	310.60	United States	2,731.09
Cameroon	50.66	Luxembourg	312.52	Slovakia	2,832.00
Cambodia	53.11	Portugal	335.31	New Caledonia	3,168.48
South Africa	56.52	Sao Tome and Principe	365.03	Saint Vincent and the Grenadines	3,411.54
Syria	58.55	Australia	365.17	Eswatini	3,625.69
Uruguay	58.73	Austria	368.74	Kazakhstan	4,475.39
Afghanistan	60.30	Liechtenstein	374.96	Sint Maarten (Dutch part)	5,388.14
Colombia	60.32	Faeroe Islands	378.59	Switzerland	6,005.94
Chile	63.40	Lebanon	391.62	Ireland	7,350.34
Qatar	64.42	Gibraltar	391.80	Curacao	7,475.07
Uganda	65.72	Jersey	395.59	French Polynesia	8,281.83
Namibia	66.04	Maldives	396.27	Cyprus	9,804.61
Somalia	66.05	Malaysia	398.72	France	10,123.30
United Arab Emirates	67.92	Trinidad and Tobago	426.87	Belgium	10,503.50
Bahrain	68.35	Albania	437.07	Sweden	10,983.86
Myanmar	69.79	British Virgin Islands	439.86	Netherlands	11,607.85
Nepal	79.25	Poland	464.92	Slovenia	13,917.69
Venezuela	83.12	Russia	474.02	Serbia	14,227.67
Tunisia	86.69	Croatia	477.59		

Model Formulation

Considering that the effectiveness of COVID-19 vaccination was mainly focused on avoiding infection, avoiding symptomatic disease, and avoiding severe illness and death, this study extended the traditional epidemic model to include asymptomatic infection compartment and five corresponding compartments for vaccination. In addition, in order to assess the impact of population mobility on the spread of COVID-19, we assumed that high, medium, and low-risk regions would have a mobility rate of R_{trans} with COVID-zero regions. To describe this flow, we randomly selected a population of size $R_{trans} \times N_{clean}$ from the total population of the clean region and a population of the same number from other regions separately to exchange. Using this method, we could realize the population mobility with the constant total population of each region.

Given the unknown safety of the vaccine in infants and young children, we assumed that this population would not be vaccinated. According to the population age distribution announced by China in 2020, infants aged 0–4 accounted for about 5% of the total population. Therefore, we assumed that the maximum proportion of vaccination was 95%. This study focused on the epidemic trend of COVID-19 when a fairly high proportion of people have been vaccinated and international mobility resumed normal levels. Therefore, the starting of the prediction was that 95% of people have been vaccinated and no new vaccinations have taken place after all regions were totally opened.

Model Equations

$$\frac{dS_i}{dt} = -\beta \times S_i \times \frac{\left[\left(I_{sym,i} + I_{sym,v,i}\right) + r_{a-s} \times \left(I_{asym,i} + I_{asym,v,i}\right)\right]}{N_i} - Out_{S_i} + In_{S_i}$$

$$\frac{dS_{v,i}}{dt} = -\beta \times (1 - e_{inf}) \times S_{v,i} \times \left[\left(I_{sym,i} + I_{sym,v,i}\right) + r_{a-s} \times \left(I_{asym,i} + I_{asym,v,i}\right)\right]/N_i - Out_{S_{v,i}} + In_{S_{v,i}}$$

$$\frac{dI_{sym,i}}{dt} = r_{sym} \times \beta \times r_{sym} \times S_i \times \left[\left(I_{sym,i} + I_{sym,v,i}\right) + r_{a-s} \times \left(I_{asym,i} + I_{asym,v,i}\right)\right]/N_i - Out_{I_{sym,i}} + In_{I_{sym,i}}$$

$$\frac{dI_{asym,i}}{dt} = (1 - r_{sym}) \times \beta \times r_{sym} \times S_i \times \left[\left(I_{sym,i} + I_{sym,v,i}\right) + r_{a-s} \times \left(I_{asym,i} + I_{asym,v,i}\right)\right]/N_i - Out_{I_{asym,i}} + In_{I_{asym,i}}$$

$$\frac{dI_{sym,v,i}}{dt} = r_{sym} \times \left(1 - e_{sym}\right) \times \beta \times (1 - e_{inf}) \times S_{v,i} \times \left[\left(I_{sym,i} + I_{sym,v,i}\right) + r_{a-s} \times \left(I_{asym,i} + I_{asym,v,i}\right)\right]/N_i - Out_{I_{sym,v,i}} + In_{I_{sym,v,i}}$$

$$\frac{dI_{asym,v,i}}{dt} = \left[1 - r_{sym} \times \left(1 - e_{sym}\right)\right] \times \beta \times (1 - e_{inf}) \times S_{v,i} \times \left[\left(I_{sym,i} + I_{sym,v,i}\right) + r_{a-s} \times \left(I_{asym,i} + I_{asym,v,i}\right)\right]/N_i - Out_{I_{asym,v,i}} + In_{I_{asym,v,i}}$$

$$\frac{dR_i}{dt} = r_{rec} \times (I_{sym,i} + I_{asym,i} + I_{sym,v,i} + I_{asym,v,i}) - Out_{R_i} + In_{R_i}$$

$$\frac{dD_i}{dt} = r_{dea} \times I_{sym,i} + \left(1 - e_{dea}\right) \times r_{dea} \times I_{sym,v,i}$$

Symbol i included 0, 1, 2, 3 indicating clean, low risk, medium risk, and high-risk regions. We used the symbol j to represent each compartment and the number of population mobility in different regions could be described by following equations.

For the COVID-zero Regions:

$$Out_{j,0} = \sum_{1}^{3} R_{trans} \times N_{j,0}$$

$$In_{j,0} = \sum_{i=1}^{3} \frac{R_{trans} \times N_{j,0} \times N_{j,i}}{N_i}$$

For the high risk, medium risk, and low risk regions (i=1, 2, 3)

$$Out_{j,i} = \frac{R_{trans} \times N_{j,0} \times N_{j,i}}{N_i}$$

$$In_{j,0} = R_{trans} \times N_{j,0}$$

Parameter Estimation of E_{inf}

At present, there were no definitive studies on the effectiveness of CoronaVac in preventing infection. After reviewing the literature, we found that in August 2021, Paul Elliott et al. (*2*) analyzed the efficacy against infection of COVID-19 vaccines administered in the UK. The conclusion was that the vaccine was 49% to 62% effective in preventing severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) infection in people aged 18 to 64 years old. Taking into account the higher efficacy of the Oxford/AstraZeneca COVID-19 vaccine in its published Phase III clinical data than CoronaVac, and the immune decline in the population after vaccination, we finally made an E_{inf} estimate of 30%.

REFERENCES

1. Dingxiangyuan. Real time epidemic of New Coronavirus pneumonia 2020. 2021. https://ncov.dxy.cn/ncovh5/view/pneumonia. [2021-10-10]. (In Chinese).
2. U.S. Center for Disease Control and Prevention. COVID-19 pandemic planning scenarios. 2021. https://www.cdc.gov/coronavirus/2019-ncov/hcp/planning-scenarios.html#table-1. [2021-10-10].