Estimate of COVID-19 Deaths, China, December 2022–February 2023

Zhanwei Du, Yuchen Wang, Yuan Bai, Lin Wang, Benjamin John Cowling, Lauren Ancel Meyers

China announced a slight easing of its zero-COVID rules on November 11, 2022, and then a major relaxation on December 7, 2022. We estimate that the ensuing wave of SARS-CoV-2 infections caused 1.41 million deaths in China during December 2022–February 2023, substantially higher than that reported through official channels.

For almost 3 years, China maintained a zero-COVID policy that effectively suppressed SARS-CoV-2 transmission. China began rolling back those rules on November 11, 2022, and ended most restrictions on December 7, 2022 (China Focus, 2023, https://english.news.cn/20221207/ca014c043bf24728b8dcbc0198565fdf/c.html), in response to the reduced severity of the Omicron variant or the growing socioeconomic and political costs of the restrictions. COVID-19 immediately surged; China reported nearly 82,000 COVID-19–related deaths during December 16, 2022–February 17, 2023 (*1*).

In December 2022, China disbanded its national COVID testing system and twice modified its criteria for classifying COVID-19–related deaths (*2*,*3*). The resulting uncertainties in reported occurrences and low official death counts have spurred speculation that official mortality reports from China substantially underestimate the full burden of the December 2022–January 2023 wave (*4*). In early December of 2022, the Chinese Center for Disease Control and Prevention (China CDC) launched a sentinel household surveillance program, tracking SARS-CoV-2 test positivity in 420,000 people in 22 provinces across China (*5*). We used those data to estimate a plausible range for the total number of COVID-19–related deaths during December 2022–January 2023. We classified a death as COVID-19–related if it occurred within 28 days of confirmed infection (*6*).

Author affiliations: World Health Organization Collaborating Center for Infectious Disease Epidemiology and Control, School of Public Health, University of Hong Kong, Hong Kong, China (Z. Du, Y. Bai, B.J. Cowling); Laboratory of Data Discovery for Health Limited, Hong Kong Science and Technology Park, Hong Kong (Z. Du, Y. Wang, Y. Bai, B.J. Cowling); University of Cambridge, Cambridge, UK (Y. Wang); University of Texas at Austin, Austin, Texas, USA (L.A. Meyers); Santa Fe Institute, Santa Fe, New Mexico, USA (L.A. Meyers)

DOI: http://doi.org/10.3201/eid2910.230585

The Study

We estimated COVID-19–related deaths by using an individual-based simulation that incorporated daily test positivity reports from the China CDC sentinel household surveillance system during December 16, 2022–January 19, 2023. We also incorporated age-specific vaccination and boosting rates reported in China and published estimates of infection fatality rates, vaccine effectiveness, and rates of immunity waning. We built a stochastic model to generate COVID-19 death reports from infections occurring during December 8, 2022–January 19, 2023, in a population of 1 million persons whose ages were randomly assigned according to the national age distribution in China. Each simulation was based on the reported SARS-CoV-2 test positivity rate (*5*) to stochastically determine the number of persons who would have initially tested positive on that day. Those testing positive were assigned a vaccination history generated stochastically from the daily age-specific vaccination rates reported in China (*7*) and given a level of vaccine-acquired protection against death based on the date of their last dose and published estimates for vaccine effectiveness (*7*). The simulation used that value and the age-specific infection-fatality rate (Leung K, Leung GM, Wu J, unpub. data, https://www.medrxiv.org/content/10.1101/2022.12.14.22283460) to determine probabilistically whether the patiet died from COVID-19 (Appendix, https://wwwnc.cdc.gov/

EID/article/29/10/23-0585-App1.pdf). Results were based on 1,000 model simulations. We conducted sensitivity analyses for assumed age-specific vaccine effectiveness (VE) against death, population size, and increase in infection-fatality rates as the healthcare system in China reached capacity.

The sentinel surveillance report from China CDC suggests that roughly 90% of China's population were infected during the focal 35-day period (*5*). This large and rapid wave caused ≈1.41 (95% credibility interval [CrI] 1.14–1.73) million deaths across China; 0.80 (95% CrI 0.60–1.05) million of those deaths occurred among adults >80 years of age. Estimated COVID-19 mortality rates (per 1 million population) ranged from roughly 0 (95% CrI 0–17) among children <9 years of age to 22,400 (95% CrI 16,500–30,000) among adults >80 years of age (Figure; Appendix Tables 2, 3).

Conclusions

COVID-19 deaths are related to a variety of health complications, including septic shock, multiorgan failure, respiratory failure, heart failure, and secondary infections (*8*). China's official reports may underestimate the COVID-19 death toll by a factor of 17 (95% CrI 14–22). Our analyses suggest that, in barely a month, COVID-19 killed >1 million persons in China. The difference between China's official mortality reports and our estimates may stem from delays in hospital reporting (*9*), omission of deaths happening outside of hospitals (*2*), gaps in China's vital registration system (*4*), or intentional reclassification after the insurance industry in China largely stopped covering COVID-19 in December 2022 (South China Morning Post, December 17, 2022, https://www.scmp.com/news/china/science/article/3203695/chinas-covid-19-patients-face-insurance-battle-over-pandemic-related-payouts).

As our findings indicate, the relaxation of China's zero-COVID policies in late 2022 precipitated an explosive wave of infections that caused an estimated 1,000 (95% CrI 843–1,230) deaths/1 million population. By comparison, during the large Omicron

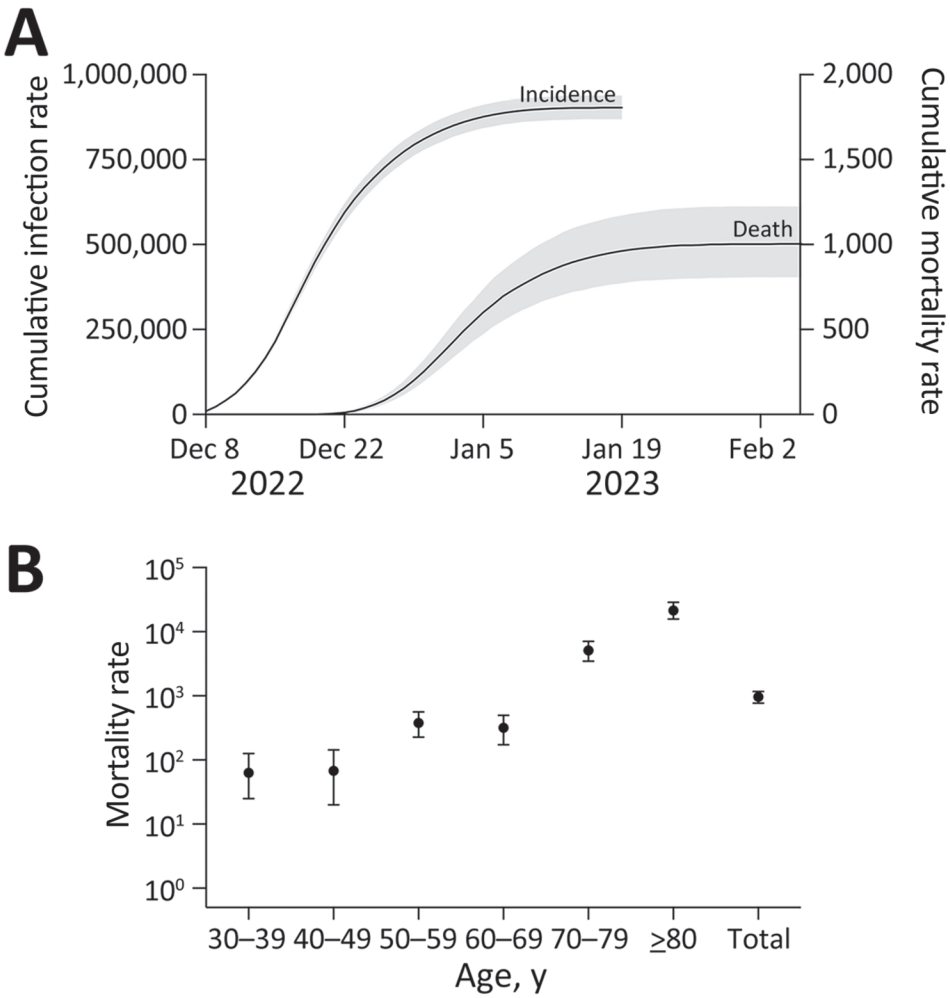

Figure. Estimated SARS-CoV-2 infection incidence in China during December 16, 2022–January 19, 2023, and resulting COVID-19 mortality rates. A) Estimated cumulative infection and mortality rates (per 1 million population) during December 8, 2022–February 7, 2023, based on test positivity data from the Chinese Center for Disease Control and Prevention sentinel community surveillance system, reported on January 26, 2023 (*5*). Gray shading indicates 95% credibility intervals derived from 1,000 stochastic simulations. B) Estimated age-specific COVID-19 mortality rates (deaths/1 million population, log scale), based on simulations that incorporate vaccine timing, coverage, effectiveness, and waning in each age group.

surges in early 2022, reported maximum 52-day mortality rates (deaths/1 million population) were 345 for the United States, 144 for the United Kingdom, and 1,166 for Hong Kong (*1*). Hong Kong's high COVID-19 mortality rate may have resulted from its large proportion of older adults and relatively low vaccination rates in this vulnerable group; 26% of Hong Kong's population is >60 years of age, and only 49% of that population had received ≥2 doses of a SARS-CoV-2 vaccine before March 2022 (*10*). By comparison, 90% of Australia's population >60 years of age, which comprises 22% of the total population, were double-vaccinated by March 2022; the peak 52-day mortality rate in Australia was roughly 88% lower than that of Hong Kong (137 deaths/1 million population) (*10*).

The unprecedented speed and severity of the wave in China is not surprising, given lack of infection-acquired immunity, moderate effectiveness of vaccines commonly administered in China, relatively low vaccine coverage in the oldest populations, and limited access to effective antiviral drugs. Mainland China had among the lowest estimated levels of excess mortality during the COVID-19 pandemic in 2020 and 2021 compared with 74 other countries worldwide (*11*), perhaps because of China's dynamic zero-COVID strategy. The abrupt relaxation of zero-COVID rules without measures to protect high-risk populations likely led to the surge in hospitalizations and deaths we examined. As of June 21, 2023, the cumulative reported mortality rate in China is 85 deaths/1 million persons, considerably lower than rates for countries such as the United States (3,332/1 million persons), which sustained high levels of mortality before December 2022, and Japan (603/1 million persons), which experienced a substantial wave starting in December 2022, around the same time as China (E. Mathieu et al., 2020, https://ourworldindata.org/coronavirus). Our estimates suggest that China's true death toll is closer to 1,014 deaths/1 million persons, roughly double that of Japan and 30% of that of the United States.

Our estimates are robust to moderate changes in the assumed age-specific vaccine efficacy and infection-fatality rates (Appendix Table 4). If the large surge in COVID-19 hospitalizations in late 2022 and early 2023 compromised patient care, we may have significantly underestimated the overall mortality rate. Assuming that COVID-19 mortality increased by a factor of 3.39 during China's 3-day peak in reported test positivity (based on an estimate from a COVID-19 healthcare surge in Hong Kong in March 2022 [*12*]), our estimate of overall mortality increases to 2.11 (95% CrI 1.71–2.60) million.

Our findings rely on the validity of data from the China CDC's sentinel household surveillance program, which might have some quality issues (e.g., double counting of persons who test multiple times). China CDC reports include graphs of daily positivity in this sample that enable rapid approximation of epidemic trends on a national scale (*5*). In addition, we assume that reported vaccinations were the only source of prior immunity and that all infections were by Omicron variants; surveillance data suggest that only 0.4% of specimens collected during this period were not Omicron (*5*).

In summary, our study suggests that the official mortality reports from China substantially underestimate the full burden of the December 2022–January 2023 COVID-19 wave, raising concerns about the accuracy and transparency of China's reporting system, as well as potential underestimation of reports from other countries that limit data collection and reporting. The decision to relax China's zero-COVID policies without adequate measures to protect high-risk populations had severe consequences. Other countries prioritized vaccines for older age groups and other vulnerable populations (*13*), and many studies have indicated that targeting medical countermeasures and protective measures toward groups with high infection-fatality rates can be life and cost saving (*14*,*15*). We expect that the true toll of COVID-19 in China will become clearer as additional epidemiologic data become available.

This work was supported by grants from the US Centers for Disease Control and Prevention (U01IP001136) and US National Institutes of Health (R01AI151176) and the AIR@InnoHK Programme from Innovation and Technology Commission of the Government of the Hong Kong Special Administrative Region. The funders had no role in the design and conduct of the study; collection, management, analysis, and interpretation of the data; preparation, review, or approval of the manuscript; or decision to submit the manuscript for publication.

B.J.C. consults for AstraZeneca, GlaxoSmithKline, Moderna, Pfizer, Roche, and Sanofi Pasteur.

About the Author

Dr. Du is a research assistant professor in the School of Public Health, LKS Faculty of Medicine, The University of Hong Kong, Hong Kong, China. He develops mathematical models to elucidate the transmission dynamics, surveillance, and control of infectious diseases.

References

1. Mathieu E, Ritchie H, Rodés-Guirao L, Appel C, Giattino C, Hasell J, et al. Coronavirus pandemic (COVID-19). Our World in Data. 2020 Mar 5 [cited 2023 Feb 4]. https://ourworldindata.org/covid-cases
2. China CDC. National epidemic situation of COVID-19 disease (2023–01–15). 2023 [cited 2023 Feb 14]. https://www.chinacdc.cn/jkzt/crb/zl/szkb_11803/jszl_13141/202301/t20230115_263381.html
3. National Health Commission. Transcript of press conference of the State Council's joint prevention and control mechanism for the novel coronavirus pneumonia outbreak (December 20, 2022). 2023 [cited 2023 Feb 1]. http://www.nhc.gov.cn/xcs/s3574/202212/a9510969ad85461297016f6ad1c87770.shtml
4. Lewis D. China's COVID wave has probably peaked, model suggests. Nature. 2023;613:424–5. https://doi.org/10.1038/d41586-023-00075-4
5. Chinese Center for Disease Control and Prevention. COVID-19 clinical and surveillance data—Dec 9, 2022 to Jan 23, 2023, China. 2023 Jan 26 [cited 2023 Jan 28]. https://en.chinacdc.cn/news/latest/202301/t20230126_263523.html
6. Nyberg T, Ferguson NM, Nash SG, Webster HH, Flaxman S, Andrews N, et al.; COVID-19 Genomics UK (COG-UK) consortium. Comparative analysis of the risks of hospitalisation and death associated with SARS-CoV-2 omicron (B.1.1.529) and delta (B.1.617.2) variants in England: a cohort study. Lancet. 2022;399:1303–12. https://doi.org/10.1016/S0140-6736(22)00462-7
7. Cai J, Deng X, Yang J, Sun K, Liu H, Chen Z, et al. Modeling transmission of SARS-CoV-2 Omicron in China. Nat Med. 2022;28:1468–75. https://doi.org/10.1038/s41591-022-01855-7
8. Gundlapalli AV, Lavery AM, Boehmer TK, Beach MJ, Walke HT, Sutton PD, et al. Death certificate–based ICD-10 diagnosis codes for COVID-19 mortality surveillance—United States, January–December 2020. MMWR Morb Mortal Wkly Rep. 2021;70:523–7. https://doi.org/10.15585/mmwr.mm7014e2
9. Liu J, Zhang L, Yan Y, Zhou Y, Yin P, Qi J, et al. Excess mortality in Wuhan city and other parts of China during the three months of the covid-19 outbreak: findings from nationwide mortality registries. BMJ. 2021;372:n415. https://doi.org/10.1136/bmj.n415
10. Smith DJ, Hakim AJ, Leung GM, Xu W, Schluter WW, Novak RT, et al. COVID-19 Mortality and vaccine coverage—Hong Kong Special Administrative Region, China, January 6, 2022–March 21, 2022. MMWR Morb Mortal Wkly Rep. 2022;71:545–8. https://doi.org/10.15585/mmwr.mm7115e1
11. Wang H, Paulson KR, Pease SA, Watson S, Comfort H, Zheng P, et al.; COVID-19 Excess Mortality Collaborators. Estimating excess mortality due to the COVID-19 pandemic: a systematic analysis of COVID-19-related mortality, 2020–21. Lancet. 2022;399:1513–36. https://doi.org/10.1016/S0140-6736(21)02796-3
12. Wong JY, Cheung JK, Lin Y, Bond HS, Lau EHY, Ip DKM, et al. Intrinsic and effective severity of COVID-19 cases infected with the ancestral strain and Omicron BA.2 variant in Hong Kong. J Infect Dis. 2023 Jun 27 [Epub ahead of print]. https://doi.org/10.1093/infdis/jiad236
13. Hale T, Angrist N, Goldszmidt R, Kira B, Petherick A, Phillips T, et al. A global panel database of pandemic policies (Oxford COVID-19 Government Response Tracker). Nat Hum Behav. 2021;5:529–38. https://doi.org/10.1038/s41562-021-01079-8
14. Wang X, Du Z, Huang G, Pasco RF, Fox SJ, Galvani AP, et al. Effects of cocooning on coronavirus disease rates after relaxing social distancing. Emerg Infect Dis. 2020;26:3066–8. https://doi.org/10.3201/eid2612.201930
15. Wang X, Du Z, Johnson KE, Pasco RF, Fox SJ, Lachmann M, et al. Effects of COVID-19 vaccination timing and risk prioritization on mortality rates, United States. Emerg Infect Dis. 2021;27:1976–9. https://doi.org/10.3201/eid2707.210118

Address for correspondence: Lauren Ancel Meyers, Department of Integrative Biology, University of Texas at Austin, 2415 Speedway #C0930, Austin, TX 78712, USA; email: laurenmeyers@austin.utexas.edu

Article DOI: http://doi.org/10.3201/eid2910.230585

Estimate of COVID-19 Deaths, China, December 2022–February 2023

Appendix

Estimating Omicron COVID-19 mortality in China based on sentinel surveillance data from December 16, 2022, to January 19, 2023

We ran 1000 simulations each with one million individuals assigned ages according to the national age distribution in China. Each simulation produces an estimated number of COVID-19 deaths resulting from infections occurring between December 8, 2022 and January 19, 2023, as described below. We report the 2.5th percentile (lower CrI bound), median, and 97.5th percentile (upper CrI bound) values across the 1000 simulations.

The full parameter specification is given in Appendix Table 1. In each simulation, we do the following:

- For each age group a, select a random IFR (IFR_a) from the estimated distributions given in Table S1 and assign each individual their age-specific IFR. (For each age group, draw from triangle distributions with lower bound, mode, and upper bound equal to the corresponding lower CI, mean, and upper CI, respectively.)
- For each day between December 16, 2022, and January 19, 2023, we use the reported SARS-CoV-2 test positivity from the China CDC sentinel surveillance system *(1)* to determine a random number of people in our simulated population of one million who would have first tested positive on that day. Specifically, for each day, we estimate the confidence interval for the reported test positivity *(1)* assuming a sample size of 2,500 (i.e., the reported minimum number of individuals in each community participating in the sentinel surveillance system). We then determine the number of newly positive

individuals by drawing a random deviate from the normally distributed sampling distribution for the test positivity statistic and multiplying that number by one million.

For each of those individuals, we determine their date of infection assuming that the earliest possible date was December 8, 2022 (restrictions ended on December 7, 2022 *(2)*), as follows:

- Track time in terms of the number of days after December 7 and use t_{pos} to denote the number of days between December 7 and the day on which the individual first tested positive.
- Assume that they tested negative in the prior sampling period. For example, an individual first testing positive on December 24 ($t_{\text{pos}} = 17$) presumably tested negative during the December 20–22 and the December 16–19 sampling periods. Randomly assign dates in each of those periods for their negative tests. We use T_{neg} to denote the vector of negative test dates, where dates are again represented by the number of days since December 7.
- Let $P_{\text{pos}}(t_{\text{test}} - t_{\text{inf}})$ denote the probability of testing positive on day t_{test} given infection on day t_{inf} (Table S1). Determine the probability of having been infected on day t_{inf}, given negative tests on T_{neg} and a positive test on t_{pos} as given by

$$P(t_{\text{inf}}|T_{\text{neg}}, t_{\text{pos}}) = \frac{P(T_{\text{neg}}, t_{\text{pos}}|t_{\text{inf}})(P(t_{\text{inf}}))}{P(T_{\text{neg}}, t_{\text{pos}})}$$

where

$$P(T_{\text{neg}}, t_{\text{pos}}|t_{\text{inf}}) = P_{\text{pos}}(t_{\text{pos}} - t_{\text{inf}})\Pi_{u \in T_{\text{neg}}}(1 - P_{\text{pos}}(u - t_{\text{inf}}))$$

$$P(t_{\text{inf}}) = \frac{1}{t_{\text{pos}}}$$

$$P(T_{\text{neg}}, t_{\text{pos}}) = \frac{1}{t_{\text{pos}}} \sum_{t=1}^{t_{\text{pos}}} (P(T_{\text{neg}}, t_{\text{pos}}|t))$$

where $P(t_{\text{inf}})$ denotes the base probability that an individual was infected on day t_{inf} in the absence of information about their testing history and is assumed to be uniformly distributed over all days between December 7 and the day they tested positive; $P(T_{neg}, t_{pos})$ denotes the

probability of having negative tests on T_{neg} followed by a positive test on t_{pos} and is obtained by averaging the probability of a case experiencing both T_{neg} and t_{pos} given that they were infected on day *t* ($P(T_{neg}, t_{pos}|t)$) over all days *t* in between December 7 and the day they tested positive.

  - Use this probability distribution to randomly assign an infection date.

- For each positive individual, determine their vaccination history according to reported daily age-specific vaccination rates in China, as follows *(3)*:
  - Randomly select the date of the first dose (t_1) based on the estimated first-dose rate, $C^1_a(t)$.
    - For children aged 3 to 11, first doses started on November 1, 2021.
    - For children aged 12 to 17, first doses started on August 1, 2021.
    - For adults aged 18 to 59, first doses started on December 1, 2020.
    - For adults aged over 60, first doses started on April 1, 2021.
  - Randomly select the date of the second dose (t_2) based on the estimated second-dose rate, $C^2_a(t)$, beginning 3 weeks after their first dose *(4)*.
  - Randomly select the date of the booster dose (t_3) for adults aged over 18 according to the estimated booster rate, $C^3_a(t)$, starting at the CDC-recommended time waiting period after their second dose (i.e., 6 months before December 4, 2022, and 3 months after December 5, 2022*(5)*).
- For each positive individual, determine their level of vaccine-acquire protection against death based on the date of their last dose and published estimates for vaccine effectiveness (VE). Assume that vaccine-acquired protection begins 2 weeks after each dose has been administered and that protection wanes stepwise 6 months following each dose *(3)*.
- For each positive individual, probabilistically determine whether they died from COVID based on their IFR and vaccine-acquired protection. If so, determine the day of death as follows:
  - Randomly select the date of symptom onset based on the estimated distribution of incubation periods (D_{inc}).

- Randomly select the date of death based on the estimated distribution of days from symptom onset to death (D_{death}) *(6)*.

- Scale total deaths from a simulated population of 1M to the entire population of China by age group.

References

1. Chinese Center for Disease Control and Prevention. COVID- 19 Clinical and surveillance data–Dec 9, 2022 to Jan 23, 2023, China. chinacdc. 2023 [cited 2023 Jan 28]. https://en.chinacdc.cn/news/latest/202301/t20230126_263523.html

2. China Focus. COVID-19 response further optimized with 10 new measures. [cited 2023 Feb 4]. https://english.news.cn/20221207/ca014c043bf24728b8dcbc0198565fdf/c.html

3. Cai J, Deng X, Yang J, Sun K, Liu H, Chen Z, et al. Modeling transmission of SARS-CoV-2 Omicron in China. Nat Med. 2022;28:1468–75. PubMed https://doi.org/10.1038/s41591-022-01855-7

4. Covid-Vaccine Technical Working Group. Technical Vaccination Recommendations for COVID-19 Vaccines in China (First Edition). China CDC Wkly. 2021 May 21;3(21):459–61.

5. China Joint Prevention and Control Mechanism of the State Council. Strengthen the work plan for the COVID-19 vaccination of the elderly, 2023 [cited 2023 Jun 5]. https://www.samr.gov.cn/ltb/tzgg/art/2022/art_3216bd0086c74d70a55cc25891ec1b05.html

6. HKUMed updates on modelling the fifth wave of COVID-19 in Hong Kong (Update #8 as of March 14, 2022). [cited 2022 Apr 25]. https://sph.hku.hk/en/News-And-Events/Press-Releases/2022/TBC

7. National Bureau of Statistics of China. China Statistical Yearbook 2021. stats.gov.cn. [cited 2023 Jan 28]. http://www.stats.gov.cn/tjsj/ndsj/2021/indexch.htm

8. Mefsin Y, Chen D, Bond HS, Lin Y, Cheung JK, Wong JY, et al. Epidemiology of infections with SARS-CoV-2 Omicron BA.2 variant in Hong Kong, January-March 2022. https://doi.org/10.1101/2022.04.07.22273595

9. Chu VT, Schwartz NG, Donnelly MAP, Chuey MR, Soto R, Yousaf AR, et al.; COVID-19 Household Transmission Team. Comparison of Home Antigen Testing With RT-PCR and Viral Culture During the Course of SARS-CoV-2 Infection. JAMA Intern Med. 2022;182:701–9. PubMed https://doi.org/10.1001/jamainternmed.2022.1827

10. National Health Commission. Transcript of Press Conference of the State Council's Joint Prevention and Control Mechanism for the Novel Coronavirus Pneumonia Outbreak (November 29, 2022). 2022 [cited 2023 Jan 30]. http://www.nhc.gov.cn/xcs/s3574/202211/6fedb556a9324cd3b5b986446ee7ca34.shtml

11. Leung K, Leung GM, Wu J. Modelling the adjustment of COVID-19 response and exit from dynamic zero-COVID in China. medRxiv. 2022 [cited 2022 Dec 14]. https://www.medrxiv.org/content/10.1101/2022.12.14.22283460.abstract https://doi.org/10.1101/2022.12.14.22283460

12. COVID-19 Forecasting Team. Variation in the COVID-19 infection-fatality ratio by age, time, and geography during the pre-vaccine era: a systematic analysis. Lancet. 2022;399:1469–88. PubMed https://doi.org/10.1016/S0140-6736(21)02867-1

13. Wong JY, Cheung JK, Lin Y, Bond HS, Lau EHY, Ip DKM, et al. Intrinsic and effective severity of COVID-19 cases infected with the ancestral strain and Omicron BA.2 variant in Hong Kong. medRxiv. 2023. [cited 2023 Feb 13]. https://www.medrxiv.org/content/10.1101/2023.02.13.23285848v1.full https://doi.org/10.1101/2023.02.13.23285848

14. McMenamin ME, Nealon J, Lin Y, Wong JY, Cheung JK, Lau EHY, et al. Vaccine effectiveness of one, two, and three doses of BNT162b2 and CoronaVac against COVID-19 in Hong Kong: a population-based observational study. Lancet Infect Dis. 2022;22:1435–43. PubMed https://doi.org/10.1016/S1473-3099(22)00345-0

Appendix Table 1. Model parameters and data sources.

Symbol	Description	Values	Sources
N_a	Age-specific population size in China	Age 0–9: 168127944 Age 10–19: 157940134 Age 20–29: 166789007 Age 30–39: 223158122 Age 40–49: 207180217 Age 50–59: 222565082 Age 60–69: 147388498 Age 70–79: 80828885 Age ≥80: 35800835	China Statistical Yearbook 2021 *(7)*
D_{inc}	Incubation period	Triangular (4.1, 4.58, 5.08) days	Ref. *(8)*
D_{death}	Days from symptom onset to death	Lognormal (10.5, 0.043) days	Ref. *(6)*
$P_{test}(t)$	Probability of testing positive *t* days after initial infection	Test positivity *t* days after infection	Derived combining values given in Figure 1 in Ref. *(9)* for the daily PCR-RT positive rate post symptom onset and the distribution of incubation periods (D_{inc})
$I_{tot}(t)$	Proportion of the population newly infected at time *t*	Daily positive rate between December 16, 2022 to January 19, 2023	Extracted from Figure 1–5 in Ref. *(1)*.
$C^i_a(t)$	Age-specific vaccine coverage of the i-th dose (first, second, and booster) from December 2020 to September 2022 in China		We assume the cumulative vaccination rates of the first, second, and booster doses before March 1, 2022 follows the published values in Ref. *(3)*. For adults <60 y, cumulative vaccination coverage hardly changes between March and December of 2022. For adults ≥60 y, cumulative vaccination rates for first, second, and booster doses are reported as 90.68%, 86.42%, and 68.8%, respectively, as of November 28, 2022 *(10)*, and 96%, 96%, and 92% as of January 20, 2023 *(1)*. We assume a constant daily rate of vaccine administration during this period.
$VE(t)$	Vaccine effectiveness (VE) against mortality for an individual with most recent dose administered at time *t*, as of December 2022 in China	First dose: after two weeks 53.0%; after six months 53.0% Second dose: after two weeks 66.3%; after six months 59.7% Booster dose: after two weeks 79.2%; after six months 76.3%	Ref. *(3)*
IFR_a	Age-specific infection-fatality (IFR) without vaccination or antiviral treatment	Age 0–9: 0.0005% (95% CI: 0.0004%, 0.0008%) Age 10–19: 0.0005% (95% CI: 0.0003%, 0.0008%) Age 20–29: 0.0005% (95% CI: 0.0004%, 0.0008%) Age 30–39: 0.023% (95% CI: 0.016%, 0.034%) Age 40–49: 0.023% (95% CI: 0.016%, 0.036%) Age 50–59: 0.126% (95% CI: 0.088%, 0.196%) Age 60–69: 0.126% (95% CI: 0.087%, 0.198%) Age 70–79: 2.00% (95% CI: 1.38%, 3.15%) Age ≥80: 8.70% (95% CI: 6.12%, 13.01%)	Mean values are based on estimates in Ref. *(11)*. 95% confidence intervals are derived from Ref. *(12)* which estimates age-specific IFR's at 10 y intervals (ages 5, 15, 25 …) between April 15, 2020 and January 1, 2021, before broad vaccination and the emergence of the Delta and Omicron variants. Specifically, we use the ratios of the lower and upper CI's to the mean in Ref. *(12)* to scale the estimates in Ref. *(11)*. For example, consider the 70–79 age group. The estimate of 4.84% (95% CI: 3.33%, 7.63%) given in Ref. *(12)* for 75 y olds yields ratios of 0.69 to 1.58. We use these values to scale the mean for 70–79 y olds in Ref. *(11)* to obtain 2.00% (95% CI: 1.38%, 3.15%).

Appendix Table 2. Estimated age-specific COVID mortality in China due to the December 2022–January 2023 wave. We estimate the total numbers of deaths occurring in each age group.

Age group, y	Total deaths, median [95% CrI]
0–9	0 [0 - 2860]
10–19	0 [0 - 2820]
20–29	0 [0 - 2820]
30–39	15500 [5640 - 29600]
40–49	14100 [4230 - 29600]
50–59	87400 [53600 - 130000]
60–69	49300 [26800 - 76100]
70–79	431000 [292000 - 595000]
≥80	802000 [592000 - 1070000]
Total	1410000 [1140000 - 1730000]

Appendix Table 3. Estimated age-specific COVID deaths per million people in China due to the December 2022–January 2023 wave. We estimate the overall death rate for each age group.

Age group, y	Total rate, median [95% CrI]
0–9	0 [0 - 17]
10–19	0 [0 - 18]
20–29	0 [0 - 17]
30–39	69 [25 - 133]
40–49	68 [20 - 143]
50–59	393 [241 - 583]
60–69	335 [182 - 517]
70–79	5340 [3610 - 7360]
≥80	22400 [16500 - 30000]
Total	1000 [807 - 1220]

Appendix Table 4. Results of Sensitivity Analyses. Values are the estimated median [95% CrI] in million deaths across China between December 2022 and February 2023 based on 1000 stochastic simulations. Each scenario (S1-S6) changes one of the base assumptions, as indicated in the second column.

Scenarios	Description	Estimated deaths (millions)	
		>80 years age group	Total
Base	VE_a against mortality and IFR_a as specified in Table 1; Population of 1 million	0.80 [0.59 - 1.07]	1.41 [1.14 - 1.73]
S1	Ineffective vaccines: VE_a = 0% for all primary and booster doses	2.93 [2.16 - 3.91]	5.11 [4.15 - 6.28]
S2	Durable vaccines: VE_a does not decline after six months	0.76 [0.55 - 1.01]	1.32 [1.06 - 1.62]
S3	Surge-related increase in mortality rate: IFR_a increases 3.39-fold December 20–22 [+].	1.21 [0.89 - 1.62]	2.11 [1.71 - 2.60]
S4	Population of 2 million	0.82 [0.61 - 1.09]	1.43 [1.16 - 1.76]
S5	Population of 500 thousand	0.82 [0.59 - 1.09]	1.43 [1.13 - 1.76]
S6	Alternative age-specific VE_a*	0.90 [0.66 - 1.21]	1.56 [1.28 - 1.93]

[+] The weekly hospitalization fatality risk was estimated to be 3.39 times higher at the March 2022 COVID-19 peak in Hong Kong relative to estimates from the end of October 2022, after the wave had subsided *(13)*. We assume that the IFR_a's increase by this amount during the three-day peak in the average daily positive rate reported by China *(1)*.

* Our Base scenario assumes the vaccines afford the same level of protection against mortality across all age groups. (i.e., Reduction in mortality risk following the **first dose**: after two weeks 53.0%; after six months 53.0%; **second dose**: after two weeks 66.3%; after six months 59.7%; **booster dose**: after two weeks 79.2%; after six months 76.3%). Scenario S6 assumes variable levels across age groups, derived from the following estimates provided in Ref. *(14)*: VE_a against mortality for the [60–69y, 70–79y, 80+y] age groups relative to that for 20–59y is: [84%, 58%, 57%] after the first dose, [90%, 82%, 68%] after the second dose, and [100%, 0.98%, 0.98%] after the third dose. We scale the Base VE's by these estimates to obtain the VE_a assumed in S6 for the [0–59y, 60–69y, 70–79y, 80+y] groups:

- First dose: after two weeks 53.0%·[100%, 84%, 58%, 57%]; after six months 53.0%·[100%, 84%, 58%, 57%]
- Second dose: after two weeks 66.3%·[100%, 90%, 82%, 68%]; after six months 59.7%·[100%, 90%, 82%, 68%]
- Booster dose: after two weeks 79.2% · [100%,100%, 0.98%, 0.98%]; after six months 76.3%· [100%, 100%, 0.98%, 0.98%]