Lives saved and hospitalizations averted by COVID-19 vaccination in New York City: a modeling study

Affan Shoukat,[a,†] *Thomas N. Vilches,*[a,b,†] *Seyed M. Moghadas,*[b,†] *Pratha Sah,*[a,†] *Eric C. Schneider,*[c] *Jaimie Shaff,*[d] *Alexandra Ternier,*[d] *Dave A. Chokshi,*[d] *and Alison P. Galvani,*[a,*]
[a]Center for Infectious Disease Modeling and Analysis (CIDMA), Yale School of Public Health, New Haven, Connecticut, USA
[b]Agent-Based Modelling Laboratory, York University, Toronto, Ontario, Canada
[c]The Commonwealth Fund, New York, NY, USA
[d]New York City Department of Health and Mental Hygiene, New York, NY, USA

The Lancet Regional Health - Americas 2022;5: 100085
Published online 30 October 2021
https://doi.org/10.1016/j.lana.2021.100085

Summary

Background Following the start of COVID-19 vaccination in New York City (NYC), cases have declined over 10-fold from the outbreak peak in January 2020, despite the emergence of highly transmissible variants. We evaluated the impact of NYC's vaccination campaign on saving lives as well as averting hospitalizations and cases.

Methods We used an age-stratified agent-based model of COVID-19 to include transmission dynamics of Alpha, Gamma, Delta and Iota variants as identified in NYC. The model was calibrated and fitted to reported incidence in NYC, accounting for the relative transmissibility of each variant and vaccination rollout data. We simulated COVID-19 outbreak in NYC under the counterfactual scenario of no vaccination and compared the resulting disease burden with the number of cases, hospitalizations and deaths reported under the actual pace of vaccination.

Findings We found that without vaccination, there would have been a spring-wave of COVID-19 in NYC due to the spread of Alpha and Delta variants. The COVID-19 vaccination campaign in NYC prevented such a wave, and averted 290,467 (95% CrI: 232,551 — 342,664) cases, 48,076 (95% CrI: 42,264 — 53,301) hospitalizations, and 8,508 (95% CrI: 7,374 — 9,543) deaths from December 14, 2020 to July 15, 2021.

Interpretation Our study demonstrates that the vaccination program in NYC was instrumental to substantially reducing the COVID-19 burden and suppressing a surge of cases attributable to more transmissible variants. As the Delta variant sweeps predominantly among unvaccinated individuals, our findings underscore the urgent need to accelerate vaccine uptake and close the vaccination coverage gaps.

Funding This study was supported by The Commonwealth Fund.

Keywords: SARS-CoV-2; Coronavirus; mathematical modelling; Delta variant; Gamma variant; Iota variant; Alpha variant

Introduction

New York City (NYC) was one of the hardest-hit populations in the US during the initial phase of the COVID-19 pandemic. Following multiple early introductions of the SARS-CoV-2 virus from different regions globally, the metropolis faced an arduous challenge in controlling rapid community spread. Soon after its first COVID-19 case was identified on 29 February 2020,[1] the number of cases detected rose precipitously. Within two months the city had turned into the world's epicenter of the COVID-19 pandemic, reporting over 100,000 cases, accounting for 21% of cases in the US and 7% worldwide at that time.

Vaccinations in NYC began on December 14 2020[2] and as of July 11, 2021, NYC has distributed 9.6 million doses of vaccines, achieving a coverage of 68.9% of its 6.6 million adult residents with at least one dose.[2] NYC has fully vaccinated 64% of adults,[2] which stands above the national average of 59%. As vaccines have been administered, cases in NYC have declined from more than 5,500 average daily cases in January 2020 to less than 350 average daily cases in early July 2021, despite the emergence of highly transmissible variants.[3]

*Corresponding author: Alison P. Galvani. Yale University School of Public Health, Center for Infectious Disease Modeling and Analysis, 135 College, New Haven, Connecticut 06510, USA.
E-mail address: alison.galvani@yale.edu (A.P. Galvani).

† Authors contributed equally.

Research in context

Evidence before this study

The vaccination campaign in the US has been demonstrated to be highly effective in suppressing COVID-19 burden at the national-level. However, the impact of vaccination in NYC as the largest metropolitan population in the US on reducing disease outcomes in the presence of highly transmissible variants has not been evaluated.

Added value of this study

This is the first study to quantify the population-level impact of NYC's vaccination campaign in the face of highly transmissible variants. Using our COVID-19 agent-based model calibrated to the data of reported incidence, introduction of variants and vaccine rollout, we simulated the COVID-19 outbreak in the city under the counterfactual scenario of no vaccination. We estimated the effectiveness of the vaccination program by comparing the resulting disease burden to the actual number of cases, hospitalizations and deaths reported in NYC.

Implications of all the available evidence

Our study demonstrates the enormous impact of the vaccination program implemented by NYC. The swift vaccine rollout prevented another wave of cases in spring, which otherwise would have been fueled by the Alpha and Delta variants. Our results highlight the need to accelerate vaccination in communities with low vaccine coverage to prevent future resurgence of cases caused by emerging, highly transmissible variants.

Clinical trials of authorized vaccines in the US have demonstrated a high degree of direct individual-level protection in terms of preventing severe disease outcomes from the original Wuhan-I strain. Mathematical modeling provides complementary evidence of population-level effectiveness of vaccination through simulations and can be used to evaluate outbreak trajectories under counterfactual scenarios. We have employed this approach to evaluate the national-level effectiveness of COVID-19 vaccination in averting infections and severe outcomes in the US.[4,5] However, the impact of vaccination on saving lives and averting hospitalizations and infections in NYC has not been investigated.

We used an age-structured dynamic agent-based model of COVID-19 transmission and vaccination to quantify the impact of NYC's vaccine rollout in reducing the disease burden. The model was calibrated to simulate COVID-19 outbreak in NYC under the counterfactual scenario of no vaccination. We then compared the resulting disease outcomes to the actual number of cases, hospitalizations and deaths reported in NYC. Our results indicate that the NYC vaccination program has been highly effective in averting additional toll of COVID-19, and preventing a spring-wave of highly transmissible variants without vaccination.

Methods

Model structure

We extended our previously established age-stratified agent-based model of COVID-19,[6] incorporating Alpha (B.1.1.7), Gamma (P.1), Delta (B.1.617.2) and Iota (B.1.526) variants as identified in NYC, along with the original Wuhan-1 strain. The model implemented the natural history of disease (Appendix, Figure S1) with epidemiological classes for susceptible; latently infected (not yet infectious); asymptomatic (and infectious); pre-symptomatic (and infectious); symptomatic (and infectious) with either mild or severe illness; recovered; and dead. Disease-specific parameters were sampled from their associated distributions (Appendix, Table S1). The model population was stratified into five age groups resembling the demography of New York City. Contact patterns between and within age groups were derived from empirical data from the pre-pandemic and pandemic eras.[7,8]

Transmissibility

Risk of infection for susceptible individuals depended on their interaction with infectious individuals in the pre-symptomatic, symptomatic, or asymptomatic stages of infection. The transmission probability was calibrated by fitting the model to the reported incidence per 100,000 population in NYC from September 1, 2020 to July 15, 2021, accounting for the chronological introduction of the Iota, Alpha, Gamma, and Delta variants, as well as the daily vaccine doses administered to each age class in NYC. In this process, the transmission probability of the original Wuhan-I strain of SARS-CoV-2 was calibrated to an effective reproductive number of 1.17 as reported in early October 2020,[9] accounting for the effect of non-pharmaceutical interventions (NPIs) and 50% lower rate of contacts within and between age-groups (compared to pre-pandemic normal behavior). After calibration of the transmission probability for the original strain, we adjusted the age-specific contact rates throughout the simulations to minimize the difference between the mean cumulative incidence predicted by the model using Monte-Carlo replications and the cumulative reported cases on each day along with simulation timelines. We also adjusted the transmissibility of different variants relative to the original strain after their introduction. The Iota variant emerged in New York State in early September with an estimated 35% higher transmissibility compared with the original Wuhan-I strain.[10] We then introduced the Alpha variant on January 3, 2021, with a 50% higher transmissibility compared to the original strain.[11–13] The Delta variant was introduced on February 20, 2021, as reported by the NYC Department of Health and Mental Hygiene, with an elevated transmissibility of 30% compared with the Alpha variant.[15] Finally, we inserted the Gamma variant on March 20, 2021, with 60% higher transmissibility compared to the original strain.[14]

Disease dynamics

We simulated COVID-19 outbreak in NYC from October 1, 2020 to July 15, 2021 assuming 20% pre-existing immunity due to infections prior to October 2020.[16,17] Asymptomatic, mild symptomatic, and severe symptomatic individuals were considered to be 26%, 44%, and 89% infectious relative to those in the pre-symptomatic stage.[18–20] We assumed that these relative infectivities remained the same for all variants in the model.

Recent studies suggest that antibodies from prior infection with the original strain may have reduced neutralizing activity against Gamma and Delta.[21–24] We assumed that these variants evade naturally acquired immunity by an average of 21% (95% CI: 11%-36%).[25,26] This evasion rate was implemented as a 79% reduction in the risk of acquiring infection by the Gamma or Delta variant for individuals who had previously recovered from the original strain, Iota, or Alpha. We further assumed that recovery from infection with the Gamma or Delta variant provides protection against all variants in the model, preventing reinfection for at least one year.

Infection outcomes

We assumed that asymptomatic and mild symptomatic cases recover from infection without hospitalization. A proportion of those with severe disease were hospitalized within 2-5 days of symptom onset [27,28] and were therefore removed from the transmission chain. Symptomatic cases who were not hospitalized self-isolated within 24 hours of symptom onset, and reduced their number of daily contacts by an additional 72% (Appendix, Table S2). Intensive care unit (ICU) and non-ICU hospitalization rates were parameterized (Appendix, Table S3) based on clinical and epidemiological data stratified by age and comorbidities in the US.[29–31] Infection with Alpha variant was associated with 64% higher risk of death, while Iota, Gamma, Delta variants are associated with the same case fatality risk as the original Wuhan-I variant.[12,13,32]

Vaccination

Starting on December 14, 2020, vaccination was implemented as a two-dose program with the reported daily number of vaccines distributed as first and second doses in NYC. [33] For the Pfizer-BioNTech and Moderna vaccines, intervals of 21 and 28 days between the first and second doses were implemented, respectively. [34,35] We used published estimates to parameterize vaccine efficacies following each dose of vaccines against infection, symptomatic disease, and severe disease caused by the original strain (Appendix, Table S4).[36–38] These efficacies were implemented as a reduction in the probability of acquiring infection, probability of developing symptomatic disease if infection occurred, and probability of severe illness if symptomatic disease developed. Until April 2, 2021, age-specific contact rates of all individuals were based on adjusted rates of the fitting process. From April 3, 2021, based on the guidelines by the US Centers for Disease Control and Prevention (CDC), the daily contact rates for fully vaccinated individuals were set to age-specific pre-pandemic patterns 14 days after the second dose of vaccine.[39]

Model implementation

We implemented the model in Julia, and calibrated with case incidence data to simulate a counterfactual scenario without vaccination. We ran 500 independent simulations to obtain the daily incidence, hospitalizations, and deaths with their associated ranges, and used a bias-corrected and accelerated bootstrap method to derive the estimates of averted outcomes and their 95% credible intervals resulting from vaccination in NYC. The computational codes for reproducibility are available at https://github.com/thomasvilches/multiple_strains/tree/NYC.

Role of the Funding Source

Dr. Schneider is an employee of the funding organization and participated in the formulation of research questions, interpretation of results, and review of the manuscript, but not the conduct, data collection, or analysis. The Commonwealth Fund did not play any role in the decision to submit the manuscript for publication.

Results

Without vaccination, we estimated that a total of 893,539 (95% CrI: 835,623 — 945,736) infections, 90,836 (95% CrI: 85,024 — 96,061) hospitalizations, and 17,522 (95% CrI 16,388 — 18,557) deaths would have occurred in NYC between December 14, 2020 and July 15, 2021. Of the expected COVID-19 burden in NYC, the vaccination campaign averted 290,467 (95% CrI: 232,551 — 342,664) cases, 48,076 (95% CrI: 42,264 — 53,301) hospitalizations, and 8,508 (95% CrI: 7,374 — 9,543) deaths, corresponding to an average reduction of 32.5% cases, 52.9% hospitalizations and 48.6% deaths during the evaluation period (Figures 1 and 2).

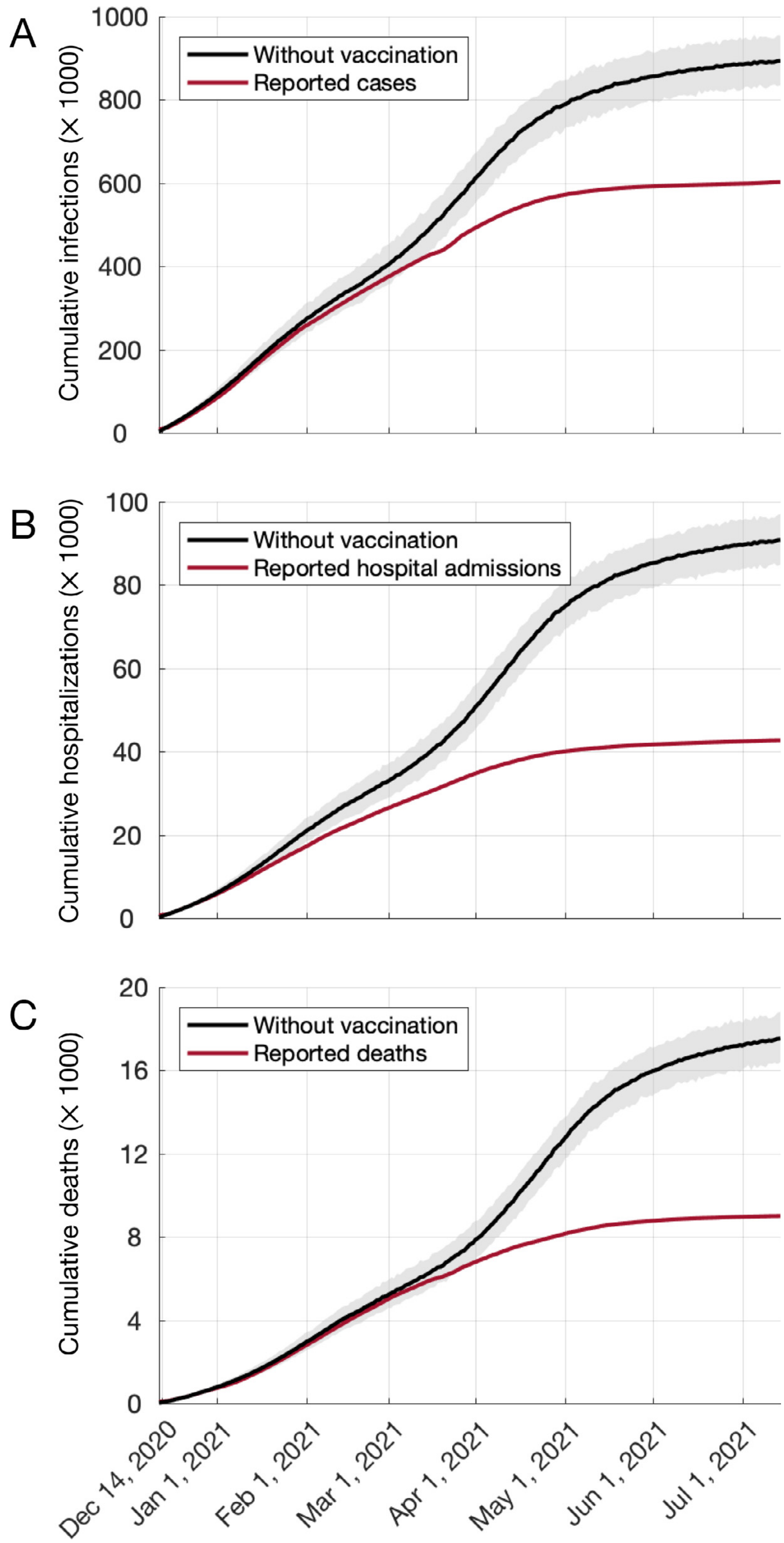

Figure 1. Projected cumulative infections (A), hospitalizations (B), and deaths (C) from December 14, 2020 through July 15, 2021 without vaccination in New York City. Red curves represent cumulative reported cases, hospitalizations, and deaths with the actual pace of vaccination.

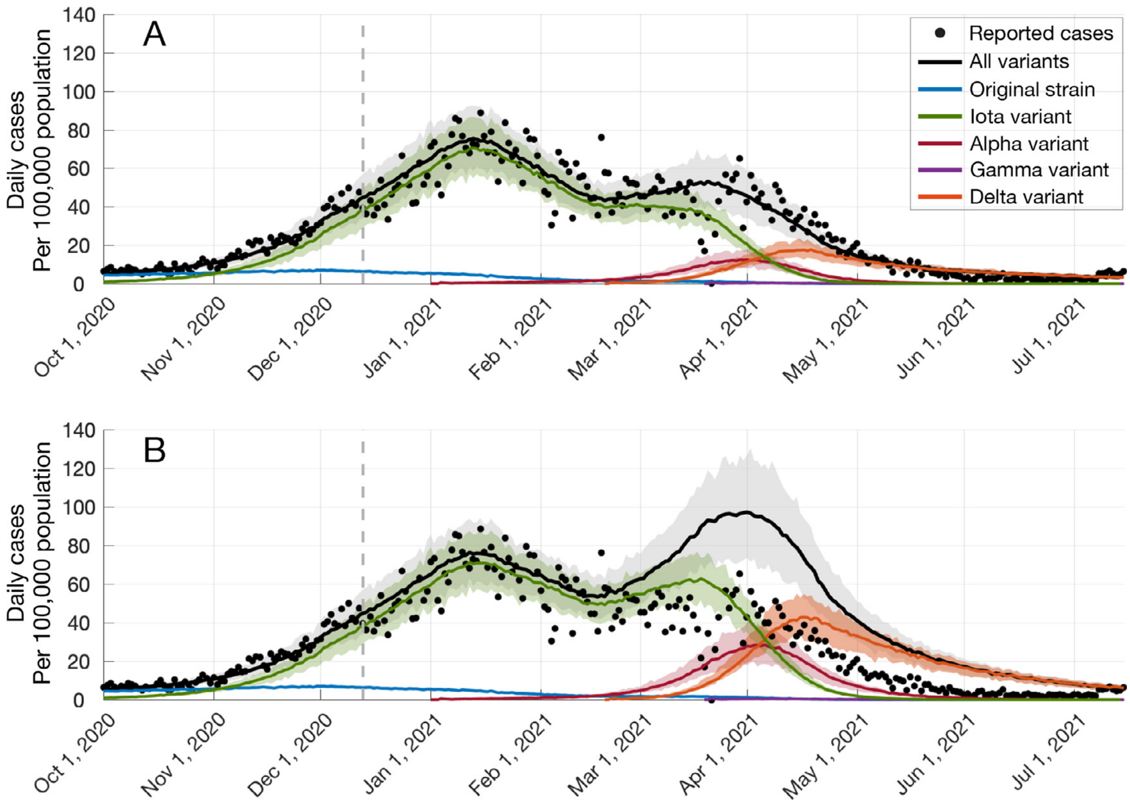

Figure 2. Projected daily incidence per 100,000 population (A) with the actual pace of vaccination; and (B) without vaccination. Dashed grey line indicates the start of vaccination in NYC.

Notably, the swift vaccine rollout prevented another wave of COVID-19 that would have occurred due to the surge in cases of Alpha and Delta variants with a projected peak incidence of 97.2 cases per 100,000 population, corresponding to a 28.7% increase compared to the apex of pandemic in NYC in January 2021. Such a wave also would have led to marked increases in hospitalizations and deaths (Figures 3 and 4). Specifically, without vaccination, NYC would have experienced an average of more than 900 hospitalizations and 184 deaths per day at the peak of the projected wave in April 2021.

Discussion

The high individual-level efficacy of COVID-19 vaccines in reducing the risk of infection and or transmission, symptomatic disease, and severe outcomes including hospitalization and death is well established. [35,40–45] However, the population-level effectiveness of COVID-19 vaccination programs that have been implemented remains undetermined in many settings, especially in the context of highly transmissibilible and immune-evading variants. We evaluated the effectiveness of COVID-19 vaccination in NYC, which has had an accelerated rollout and remains among top 10 metropolitan cities in the US regarding vaccination coverage for both first and second doses.[46]

Our results demonstrate that the swift vaccine rollout in NYC played a pivotal role in reducing COVID-19 burden as well as in suppressing potential outbreak of more transmissible variants. Without vaccination, we projected that the total numbers of hospitalizations and deaths would have been over 2-fold higher than what were reported in NYC between December 14, 2020 and July 15, 2021. The considerable rise in projected disease outcomes without vaccination is attributable to the higher disease severity of the Alpha and Delta variants.[12] We further found that the vaccination campaign averted over 30% of the expected cases in NYC during the study period, and cut hospitalizations and deaths by nearly half. Hospitalizations and deaths were averted to a greater extent than incidence due to higher efficacy of the vaccines against severe disease compared with infection and transmission. Furthermore, vaccine rollout prioritized individuals at higher risk of severe illness and deaths from COVID-19.

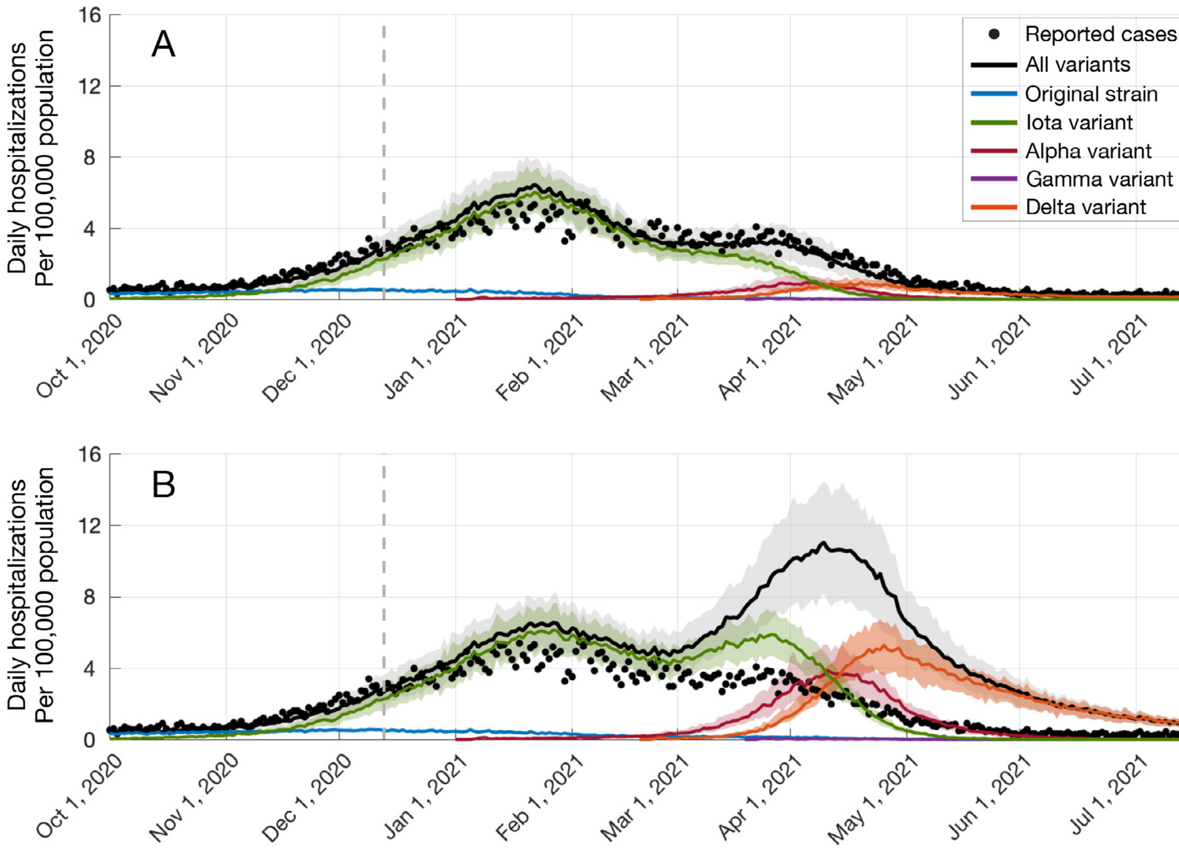

Figure 3. Projected daily hospital admissions per 100,000 population (A) with the actual pace of vaccination; and (B) without vaccination. Dashed grey line indicates the start of vaccination in NYC.

Our study is subject to some limitations. First, our results are based on reported cases and deaths in NYC which are subject to underreporting.[47] The actual impact of vaccination may thus be higher than our projections. Second, following the recommendation by the CDC,[39] only the contact patterns of fully vaccinated individuals were assumed to revert to pre-pandemic levels. If unvaccinated individuals also concomitantly increased their contacts, we would expect higher levels of infections without vaccination and an even greater impact of vaccine rollout in preventing severe outcomes. Our current estimates may therefore be conservative with respect to these assumptions. Lastly, any modelling rests upon a host of simplifying assumptions. Although the model was parameterized based on available empirical estimates, epidemiological and behavioral dynamics of real populations cannot be fully captured through *in-silico* populations. Therefore, the precise quantitative estimates and credible intervals should not be over interpreted.

Our results highlight that vaccination remains the key strategy in preventing future resurgence of cases due to these variants. As the Delta variant, the most contagious SARS-CoV-2 variant identified thus far, spreads predominantly among unvaccinated individuals, the overall incidence has tripled from June to July in NYC. This underscores the continued need to expand vaccination to maximize protection against future variants.

Contributors

Affan Shoukat, Thomas N. Vilches: Conceptualization, Data curation, Validation, Model fitting and simulations. Seyed M. Moghadas, Alison P. Galvani: Conceptualization, Data analysis, Visualization, Formal analysis, Writing — original draft, Writing — review and editing, Investigation. Pratha Sah: Conceptualization, Writing — original draft, Writing — review and editing, Investigation. Eric C. Schneider: Conceptualization, Writing — review & editing. Jaimie Shaff, Alexandra Ternier, Dave A. Chokshi: Conceptualization, Data curation, Writing - review and editing. Affan Shoukat, Thomas N. Vilches and Seyed M. Moghadas have verified the underlying data.

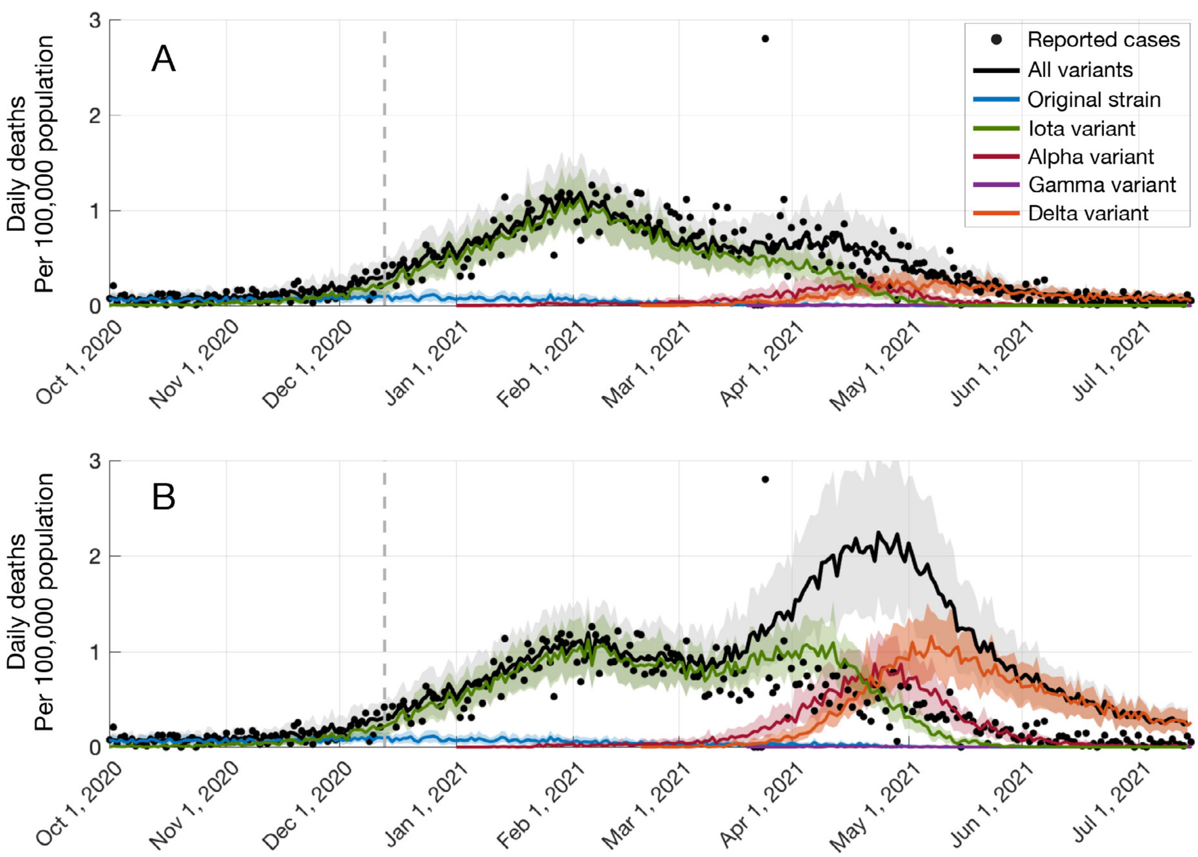

Figure 4. Projected daily deaths per 100,000 population (A) with the actual pace of vaccination; and (B) without vaccination. Dashed grey line indicates the start of vaccination in NYC.

Declaration of Competing Interest

None.

Acknowledgements

Jane Zucker, Celia Quinn, Vassiliki Papadouka, Iris Cheng, Mohammed Almashhadani, Ariel Charney, Charles Ko, and colleagues across the Bureau of Immunization and Integrated Data Team for processing, preparing, and analyzing vaccination data. Surveillance and Epidemiology and Vital Statistics for processing, preparing, and analyzing data on COVID-19 cases, hospitalizations, and deaths. Public Health Laboratory for variant data. Scott Harper for scientific expertise.

Data Availability

The computational codes for reproducibility are available at https://github.com/thomasvilches/multiple_strains/tree/NYC.

Supplementary materials

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.lana.2021.100085.

References

1 COVID-19: Data totals - NYC health. https://www1.nyc.gov/site/doh/covid/covid-19-data-totals.page (accessed July 13, 2021).

2 COVID-19: Data on Vaccines - NYC Health. https://www1.nyc.gov/site/doh/covid/covid-19-data-vaccines.page (accessed July 8, 2021).

3 COVID-19: Latest data - NYC health. https://www1.nyc.gov/site/doh/covid/covid-19-data.page (accessed July 12, 2021).

4 Moghadas SM, Sah P, Fitzpatrick MC, et al. COVID-19 deaths and hospitalizations averted by rapid vaccination rollout in the United States. *bioRxiv* 2021. https://doi.org/10.1101/2021.07.07.21260156. published online July 8.

5 Deaths and Hospitalizations Averted by Rapid U.S. Vaccination Rollout. DOI:10.26099/wm2j-mz32.

6 Moghadas SM, Sah P, Vilches TN, Galvani AP. Can the USA return to pre-COVID-19 normal by July 4? *Lancet Infect Dis* 2021. https://doi.org/10.1016/S1473-3099(21)00324-8. published online June 2.

7 Mossong J, Hens N, Jit M, et al. Social contacts and mixing patterns relevant to the spread of infectious diseases. *PLoS Med* 2008;5:e74.

8 Jarvis CI, Van Zandvoort K, Gimma A, et al. Quantifying the impact of physical distance measures on the transmission of COVID-19 in the UK. *BMC Med* 2020;**18**:124.
9 Krieger M, Owens T. Rt COVID-19. https://github.com/rtcovidlive/ (accessed May 2, 2021).
10 Allen AH, Vusirikala A, Flannagan J, et al. Increased household transmission of COVID-19 cases associated with SARS-CoV-2 Variant of Concern B.1.617.2: a national case- control study. https://khub.net/documents/135939561/405676950/Increased+Household+Transmission+of+COVID-19+Cases+-+national+case+study.pdf/7f7764fb-ecb0-da31-77b3-b1a8ef7be9aa (accessed July 1, 2021).
11 Davies NG, Abbott S, Barnard RC, et al. Estimated transmissibility and impact of SARS-CoV-2 lineage B.1.1.7 in England. *Science* 2021;**372**. https://doi.org/10.1126/science.abg3055.
12 Davies NG, Jarvis CI. CMMID COVID-19 Working Group. Increased mortality in community-tested cases of SARS-CoV-2 lineage B.1.1.7. *Nature* 2021. https://doi.org/10.1038/s41586-021-03426-1. published online March 15.
13 Challen R, Brooks-Pollock E, Read JM, Dyson L, Tsaneva-Atanasova K, Danon L. Risk of mortality in patients infected with SARS-CoV-2 variant of concern 202012/1: matched cohort study. *BMJ* 2021;**372**:n579.
14 Faria NR, Mellan TA, Whittaker C, et al. Genomics and epidemiology of the P.1 SARS-CoV-2 lineage in Manaus, Brazil. *Science* 2021;**372**:815–21.
15 coronavirus-data. Github https://github.com/nychealth/coronavirus-data (accessed July 13, 2021).
16 Bajema KL, Wiegand RE, Cuffe K, et al. Estimated SARS-CoV-2 Seroprevalence in the US as of September 2020. *JAMA Intern Med* 2021;**181**:450–60.
17 Arora R, Yan T. *SeroTracker*. *SeroTracker*. 2021. published online May 2. https://serotracker.com (accessed May 2, 2021).
18 Ferretti L, Wymant C, Kendall M, et al. Quantifying SARS-CoV-2 transmission suggests epidemic control with digital contact tracing. *Science* 2020;**368**. https://doi.org/10.1126/science.abb6936.
19 Moghadas SM, Fitzpatrick MC, Sah P, et al. The implications of silent transmission for the control of COVID-19 outbreaks. *Proc Natl Acad Sci U S A* 2020;**117**:17513–5.
20 Sayampanathan AA, Heng CS, Pin PH, Pang J, Leong TY, Lee VJ. Infectivity of asymptomatic versus symptomatic COVID-19. *Lancet* 2021;**397**:93–4.
21 Zhou D, Dejnirattisai W, Supasa P, et al. Evidence of escape of SARS-CoV-2 variant B.1.351 from natural and vaccine-induced sera. *Cell* 2021;**184**:2348–61. e6.
22 Planas D, Bruel T, Grzelak L, et al. Sensitivity of infectious SARS-CoV-2 B.1.1.7 and B.1.351 variants to neutralizing antibodies. *Nat Med* 2021. https://doi.org/10.1038/s41591-021-01318-5. published online March 26.
23 Vaidyanathan G. Coronavirus variants are spreading in India - what scientists know so far. *Nature* 2021;**593**:321–2.
24 Liu C, Ginn HM, Dejnirattisai W, et al. Reduced neutralization of SARS-CoV-2 B.1.617 by vaccine and convalescent serum. *Cell* 2021. https://doi.org/10.1016/j.cell.2021.06.020. published online June 17.
25 Centre for Mathematical Modelling of Infectious Diseases. Estimates of severity and transmissibility of novel SARS-CoV-2 variant 501Y.V2 in South Africa. Estimates of severity and transmissibility of novel SARS-CoV-2 variant 501Y.V2 in South Africa. published online Jan 11 https://cmmid.github.io/topics/covid19/sa-novel-variant.html (accessed May 2, 2021).
26 Jangra S, Ye C, Rathnasinghe R, et al. SARS-CoV-2 spike E484K mutation reduces antibody neutralisation. *Lancet Microbe* 2021;**2**:e283–4.
27 Shoukat A, Wells CR, Langley JM, Singer BH, Galvani AP, Moghadas SM. Projecting demand for critical care beds during COVID-19 outbreaks in Canada. *CMAJ* 2020;**192**:E489–96.
28 Moghadas SM, Shoukat A, Fitzpatrick MC, et al. Projecting hospital utilization during the COVID-19 outbreaks in the United States. *Proc Natl Acad Sci U S A* 2020;**117**:9122–6.
29 Garg S, Kim L, Whitaker M, et al. Hospitalization rates and characteristics of patients hospitalized with laboratory-confirmed Coronavirus disease 2019 - COVID-NET, 14 states, March 1-30, 2020. *MMWR Morb Mortal Wkly Rep* 2020;**69**:458–64.
30 Team CC-19 R, CDC COVID-19 Response TeamChow N, et al. Preliminary Estimates of the Prevalence of Selected Underlying Health Conditions Among Patients with Coronavirus Disease 2019 — United States, February 12–March 28, 2020. *MMWR. Morbidity and Mortality Weekly Report* 2020;**69**:382–6.
31 Nyberg T, Twohig KA, Harris RJ, et al. Risk of hospital admission for patients with SARS-CoV-2 variant B.1.1.7: cohort analysis. *BMJ* 2021;**373**:n1412.
32 Annavajhala MK, Mohri H, Wang P, et al. A Novel SARS-CoV-2 Variant of Concern, B.1.526, Identified in New York. *medRxiv* 2021. https://doi.org/10.1101/2021.02.23.21252259. published online Feb 25.
33 coronavirus-data. Github https://github.com/nychealth/coronavirus-data (accessed July 13, 2021).
34 Anderson EJ, Rouphael NG, Widge AT, et al. Safety and Immunogenicity of SARS-CoV-2 mRNA-1273 Vaccine in Older Adults. *N Engl J Med* 2020;**383**:2427–38.
35 Polack FP, Thomas SJ, Kitchin N, et al. Safety and Efficacy of the BNT162b2 mRNA Covid-19 Vaccine. *N Engl J Med* 2020;**383**:2603–15.
36 Moghadas SM, Vilches TN, Zhang K, et al. Evaluation of COVID-19 vaccination strategies with a delayed second dose. *PLoS Biol* 2021;**19**:e3001211.
37 Sah P, Vilches TN, Moghadas SM, et al. Accelerated vaccine rollout is imperative to mitigate highly transmissible COVID-19 variants. *EClinicalMedicine* 2021;**35**. https://doi.org/10.1016/j.eclinm.2021.100865.
38 Abu-Raddad LJ, Chemaitelly H, Butt AA. National Study Group for COVID-19 Vaccination. Effectiveness of the BNT162b2 Covid-19 Vaccine against the B.1.1.7 and B.1.351 Variants. *N Engl J Med* 2021. published online May 5. DOI:10.1056/NEJMc2104974.
39 CDC. Interim public health recommendations for fully vaccinated people. published online April 30 https://www.cdc.gov/coronavirus/2019-ncov/vaccines/fully-vaccinated-guidance.html (accessed May 2, 2021).
40 Dagan N, Barda N, Kepten E, et al. BNT162b2 mRNA Covid-19 Vaccine in a Nationwide Mass Vaccination Setting. *N Engl J Med* 2021;**384**:1412–23.
41 Haas EJ, Angulo FJ, McLaughlin JM, et al. Impact and effectiveness of mRNA BNT162b2 vaccine against SARS-CoV-2 infections and COVID-19 cases, hospitalisations, and deaths following a nationwide vaccination campaign in Israel: an observational study using national surveillance data. *Lancet* 2021;**397**:1819–29.
42 Hyams C, Marlow R, Maseko Z, et al. Effectiveness of BNT162b2 and ChAdOx1 nCoV-19 COVID-19 vaccination at preventing hospitalisations in people aged at least 80 years: a test-negative, case-control study. *Lancet Infect Dis* 2021. https://doi.org/10.1016/S1473-3099(21)00330-3. published online June 23.
43 Tenforde MW, Olson SM, Self WH, et al. Effectiveness of Pfizer-BioNTech and Moderna Vaccines Against COVID-19 Among Hospitalized Adults Aged ≥65 Years - United States, January-March 2021. *MMWR Morb Mortal Wkly Rep* 2021;**70**:674–9.
44 Sadoff J, Gray G, Vandebosch A, et al. Safety and Efficacy of Single-Dose Ad26.COV2.S Vaccine against Covid-19. *N Engl J Med* 2021;**384**:2187–201.
45 Baden LR, El Sahly HM, Essink B, et al. Efficacy and Safety of the mRNA-1273 SARS-CoV-2 Vaccine. *N Engl J Med* 2021;**384**:403–16.
46 Durkee A. Seattle Is First Major U.S. City To Vaccinate 70% Of Eligible Population — Here's The Cities That Could Be Next. *Forbes Magazine* 2021. published online June 10https://www.forbes.com/sites/alisondurkee/2021/06/10/seattle-is-first-major-us-city-to-vaccinate-70-of-eligible-population—heres-the-cities-that-could-be-next/ (accessed July 21, 2021).
47 Kalish H, Klumpp-Thomas C, Hunsberger S, et al. Undiagnosed SARS-CoV-2 seropositivity during the first 6 months of the COVID-19 pandemic in the United States. *Sci Transl Med* 2021;**13**. https://doi.org/10.1126/scitranslmed.abh3826.