Modelling the impact of a high-uptake bivalent booster scenario on the COVID-19 burden and healthcare costs in New York City

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Summary

Background Uptake of the COVID-19 bivalent booster vaccine (targeting the original SARS-CoV-2 strain and subvariants BA.4 and BA.5 of the Omicron variant) among eligible residents of New York City (NYC) has been modest and declining. Assessing the impact of improved population-level booster coverage with bivalent vaccines in NYC can help inform investment towards vaccination and potential cost-savings.

Methods We calibrated an agent-based model of disease transmission to confirmed and probable cases of COVID-19 in NYC and simulated it to project outcomes under two scenarios. In the base case scenario, we assumed that vaccination continued with the average daily rate of 92 vaccine doses per 100,000 administered during December 2022. In the counterfactual scenario, we modeled a high-uptake scenario between January 1, 2023 and March 31, 2023, with an average daily rate of 296 vaccine doses per 100,000 population that increased bivalent coverage in NYC to match the age-specific influenza vaccine coverage of the 2020–2021 season. Vaccination rate outside the campaign duration remained the same as the base case scenario.

Findings Compared to the base case, the high-uptake scenario averted 88,274 (95% Confidence Interval [CI]: 77,097–100,342) cases, and prevented 2,917 (95% CI: 2,557–3,267) hospitalizations between January 1 through the end of June 2023. Averted outcomes resulted in net savings of $217.2 (95% CI: 190.0–242.2) million in direct healthcare costs. We estimated that the high-uptake scenario would avert 72,879 (95% CI: 63,894–82,228) days of student absenteeism from schools due to COVID-19 illness.

Interpretation Our results illustrate the continued benefits of COVID-19 vaccines in preventing severe health outcomes, averting healthcare costs, and maintaining educational continuity in NYC.

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Keywords: Bivalent booster; New York City; COVID-19; School absenteeism

Introduction

COVID-19 vaccines have played a vital role in curbing transmission of COVID-19 and lowering its socioeconomic burden worldwide.[1] In New York City (NYC), an early epicenter of the pandemic, daily cases declined over 10-fold within the first six months of the vaccination program.[2] Despite the emergence of multiple highly infectious SARS-CoV-2 variants, vaccines in NYC were estimated to have prevented at least 300,000 hospitalizations and over 44,000 deaths by the end of

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Research in context

Evidence before this study
Early stages of COVID-19 inflicted a devastating toll on New York City (NYC), with the number of cases and deaths far exceeding those seen in other urban centers in the United States. After the rollout of COVID-19 vaccines, NYC combated the pandemic more effectively with significant investment in the vaccination campaign. Previous work demonstrated that this investment resulted in a substantial reduction of COVID-19 burden, and suppressed a surge of cases attributable to more transmissible variants in 2021. A bivalent booster that protects against both the original SARS-CoV-2 strain and Omicron-specific subvariants was approved in early September 2022. However, uptake of the bivalent booster in NYC has been modest and declining since December 2023.

Added value of this study
Using an agent-based model of COVID-19 transmission tailored to NYC demography and epidemiological trajectory of pandemic waves, we evaluated the benefits of improving bivalent coverage among New Yorkers. We quantified the impact of achieving age-stratified bivalent coverage similar to that achieved in a typical influenza season in terms of averted health outcomes and prevented direct healthcare costs. Our results demonstrate that such a high-uptake scenario would have averted 2,917 hospitalizations, including 1,010 ICU admissions, a cumulative of 72,879 days of school absenteeism, and reduced direct medical costs by $217 million by the end of March 2023. Therefore, improving overall bivalent coverage in NYC is also beneficial for schoolchildren and continuous functioning of schools in the city.

Implications of all the available evidence
The combination of waning immunity and advent of more transmissible and immune escaping variants of SARS-CoV-2 continue to pose risk of COVID-19 outbreaks and disrupting everyday life. Our results from NYC highlight the importance of preventing the decline of immunity with updated booster doses to ensure personal safety, while mitigating risk of large outbreaks.

January 2022.[3] Moreover, the success of the vaccination campaign in mitigating transmission helped the City normalize societal and economic activities progressively, including easing travel restrictions and allowing reopening of businesses and schools.

Since both vaccine-induced and naturally elicited protection wane over time or become less effective against novel variants, boosters will continue to play an important role in COVID-19 control. The bivalent mRNA booster vaccines targeting both the original virus strain as well as the highly transmissible subvariants BA.4 and BA.5 of Omicron were rolled out in September 2022.[4,5] Before the bivalent booster rollout in 2022, the daily vaccination rate in NYC had been steadily declining over the course of the summer. While introduction of the bivalent booster was followed by a transient acceleration in daily vaccinations, this rate started to decline once again.[6] By January 19, 2023, only 14% of eligible individuals in NYC had received their bivalent booster.[6] Improving bivalent booster coverage among NYC residents may markedly reduce COVID-19 hospitalizations and deaths in NYC.

In the current study, we used a simulation model to evaluate the impact of bivalent booster vaccination in NYC that accelerates population-level uptake over three months to reach the age-specific influenza vaccine coverage achieved during the 2020-21 season. We quantified the benefits of this booster scenario in terms of averted health outcomes such as hospitalizations and deaths, as well as direct healthcare costs saved. We specifically calculated pediatric isolation days and days of school absenteeism to demonstrate the benefits which would accrue to the pediatric population of NYC as a result of improved bivalent booster coverage among NYC residents.

Methods

Ethics

This study used non-identifiable data, and thus no ethical approval and informed consent were required in accordance with York University research ethics guidelines for program evaluation activities relying on secondary use of anonymous data.

Modelling framework

To evaluate the impact of a high-uptake bivalent booster scenario in NYC, we adapted an agent-based model of disease transmission[7] and calibrated to reported confirmed and probable cases of COVID-19 in NYC from October 1, 2020, to December 31, 2022.[8] Details of the model structure (Fig. 1) and parameterizations for infection, transmissibility of SARS-CoV-2 variants, and vaccine effectiveness are provided in the Supplementary Material. After the calibration period, we performed simulations to compare the outcomes for a base case scenario representing the NYC vaccination program and a counterfactual scenario under which high-uptake of booster vaccination was achieved between January 1, 2023 and March 31, 2023 (Fig. 2).

The model population was stratified into pediatric age groups of 0–4, 5–10, 11–13, 14–17, and adult age groups of 18–20, 21–29, 30–39, 40–49, 50–64, and 65+ years based on the NYC demographics.[9,10] We incorporated age-specific prevalence of comorbidities[11,12] and risks of severe health outcomes due to COVID-19, as

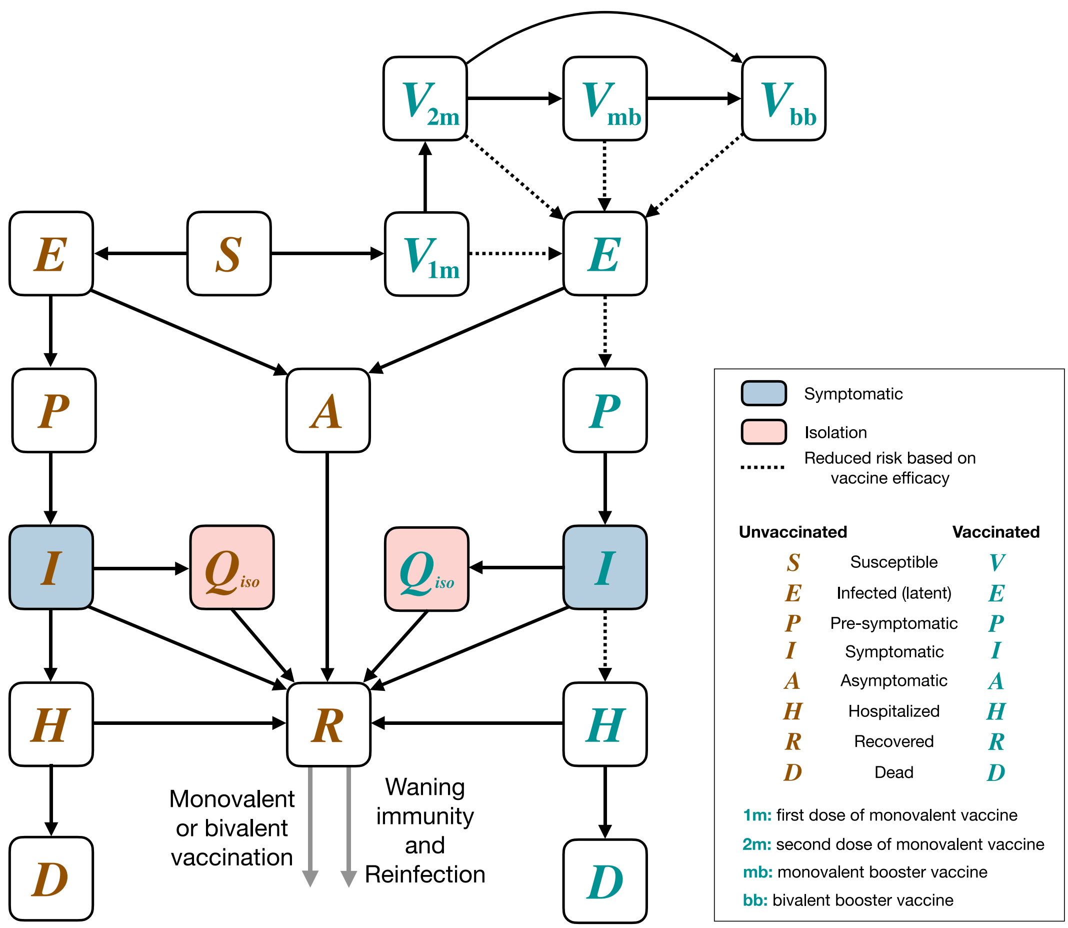

Fig. 1: **Schematic representation of the model dynamics for infection and vaccination.** Infected individuals stay in an exposed period (as part of their incubation period), before becoming infectious and move to the stage of pre-symptomatic or asymptomatic without manifestation of clinical symptoms. Those who develop symptomatic disease after pre-symptomatic stage may practice self-isolation. All symptomatic cases without hospitalization recover after their infectious period. Severe symptomatic cases may be hospitalized and recover or die. Asymptomatically infected individuals recover without self-isolation or hospitalization. Vaccination reduces the risk of infection, symptomatic disease, and severe disease based on the efficacy of each dose in primary series (i.e., monovalent vaccination) and booster (i.e., monovalent or bivalent). Prior to September 15, 2022, booster doses were assumed to be monovalent vaccines. After September 15, 2022, all booster vaccines were assumed to be bivalent. An individual was considered eligible for bivalent booster if the time elapsed since last infection, or a previous dose of monovalent vaccines exceeded 2 months.

well as an empirically determined contact network accounting for changes in pandemic restrictions and mobility patterns (SI). Transmission was parameterized based on the characteristics of five SARS-CoV-2 variants (i.e., the original strain, and the Iota, Alpha, Gamma, Delta, and Omicron variants) that prominently circulated in NYC, each with cumulative prevalence of at least 3%.[13,14]

We parameterized the daily, age-specific distribution of vaccine doses using data provided by the NYC Department of Health and Mental Hygiene (DOHMH).[15] Vaccine efficacies against infection, symptomatic infection and severe disease were derived from published studies for mRNA vaccines, for each variant, and by time since vaccination (Supplementary Tables A2 and A3). The model accounts for the waning and boosting of naturally acquired or vaccine-elicited immunity, as well as hybrid immunity (Supplementary Material).

Simulation scenarios

For the base case scenario, we simulated our calibrated model from January 1 to June 30, 2023 with a daily rate of 92 bivalent vaccine doses per 100,000 population, corresponding to the reported rate for December 2022 in NYC, in accordance with DOHMH data. Under the counterfactual scenario, we implemented a bivalent booster scenario in NYC starting on January 1, 2023 and completing on March 31, 2023. During this period, a

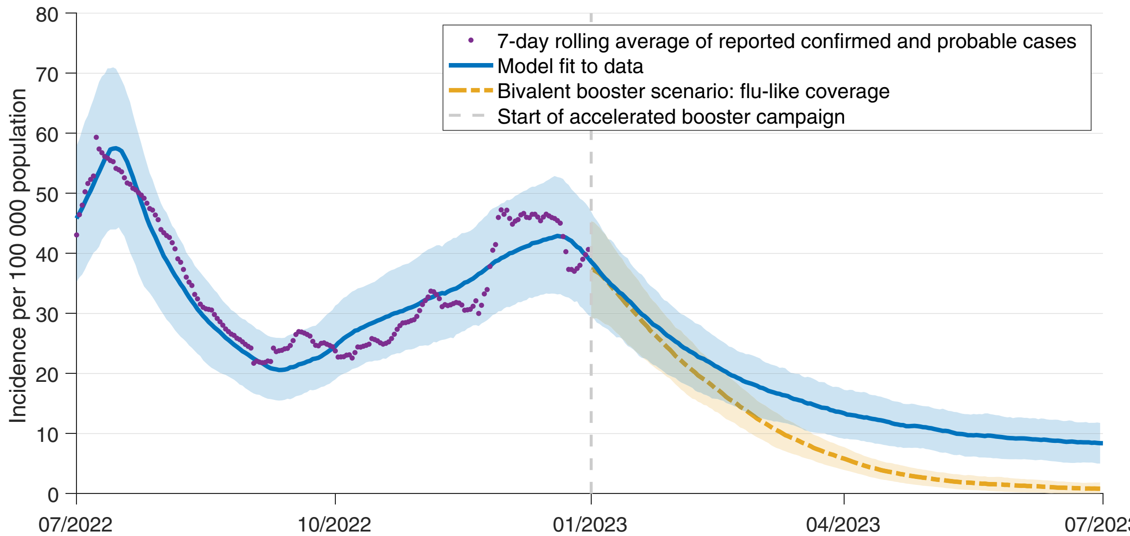

***Fig. 2:* Model fit and projection.** Model fit to 7-day rolling average of incidence per 100,000 population with simulated scenarios of bivalent booster vaccination from January 1 to June 20, 2023.

population level coverage similar to the age-specific influenza vaccine coverage in 2020–2021 season[16] was achieved among the eligible individuals aged 5 years and older, with a daily rate of 296 bivalent booster doses per 100 000 population. The coverage of bivalent booster in this scenario were 59%, 51%, 38%, 54%, and 75% for age groups of 5–11, 12–17, 18–49, 50–64, and 65+ years old.[17] This counterfactual scenario provided an exploration of whether an ambitious booster campaign, compared to the reported bivalent booster coverage in NYC and other population settings, was worth the additional efforts and resources. Outside the scenario period (after March 31, 2023), vaccination was continued using the same rate as in the base case scenario.

Model outcomes

We used simulations to compute the age-specific number of total projected cases, hospitalizations, ICU admissions, and deaths in NYC across the six-month study period and estimate the outcomes averted by the high-uptake booster vaccination scenario compared to the base case scenario. Similarly, we estimated the number of isolation days among the pediatric population and school absenteeism among those aged 5–17 years. Following the US Centers for Disease Control and Prevention (CDC) guidance about the number of isolation days for mild and severe COVID-19 infections,[18] we calculated the pediatric isolation days by applying 5 days of isolation for children experiencing mild symptomatic illness, and 10 days for those with severe illness or hospitalization. To calculate total days of school absenteeism, we accounted for a 5-day school schedule to discount weekends. We further adjusted school absenteeism for an estimated 1.5% of NYC children aged 5–17 years old who are homeschooled.[19]

We also estimated healthcare costs averted due to high-uptake of the booster vaccination using direct costs associated with COVID-19 illness and hospitalizations (Table 1). We included costs attributed to outpatient visits for symptomatic infection, hospitalizations and/or intensive care for severe illness,[27] emergency medical services (EMS) calls,[28] and emergency department visits.[29]

Model implementation and analysis

The model was implemented in Julia language version 1.6, and statistical analyses were conducted in R, version 4.1.3 (R Foundation for Statistical Computing), and Matlab, version R2022b (MathWorks). We ran and averaged 500 independent Monte-Carlo realizations for calibration, fitting, and simulations of scenarios (Fig. 2). To generate 95% confidence intervals for the mean of simulated outcomes, we used a bias-corrected and accelerated (BCa) bootstrap method[30] with 500 replications for the mean function. This nonparametric resampling method accounts for skewness by adjusting for asymmetrical resampling distributions. Specifically, we first calculated the difference in cumulative outcomes (i.e., cases, hospitalizations, ICU admissions, and deaths) between the high-uptake and the base case booster scenarios for each independent Monte-Carlo simulation. We then used these data points as averted outcomes and generated 500 samples by employing the BCa method to derive the 95% confidence intervals for the mean values of the averted outcomes in the original Monte-Carlo simulations. A similar approach was used to derive estimates of costs averted between the

Outcomes of COVID-19 illness	Estimate	Source
Direct		
Outpatient treatment per visit	$1,146	[20,a]
Round-trip to healthcare facility for outpatient treatment	$50	[21]
Hospitalization without ICU (average per patient)	$44,381	[20,a]
Hospitalization with ICU (average per patient)	$127,247	[20,a]
ED care (average per visit)	$3,713	[22]
EMS transportation	$1,011	[23]
Average number of outpatient visits per symptomatic, non-hospitalized case	0.5	Assumption
Number of ED visits for non-hospitalized severe cases	1	Assumption
Number of EMS calls relative to the number of hospitalized patients	2.5	[24]

[a]Cost estimates were adjusted considering 8.3% higher healthcare costs in NYC compared to the state of New York.[25,26]

Table 1: **Direct costs (adjusted to 2023 US$ with 3% discounting rate) and units associated with health outcomes due to COVID-19 illness.**

simulated bivalent booster scenarios. The computational code is available at https://github.com/thomasvilches/NYC_twoyears_estimation.

Role of the funding source

The study funders had no role in study design, data collection, data analysis, interpretation, writing of the report or decision to submit.

Results

Our results suggest that a high-uptake bivalent booster scenario achieving age-specific vaccination coverage akin to the 2020–21 influenza season could substantially alleviate the burden of COVID-19 in NYC (Table 2). We estimated that this scenario, compared to the base case, could avert 88,274 (95% Confidence Interval [CI]: 77,097–100,342) projected cases, and prevent 2,917 (95% CI: 2,557–3,267) hospitalizations, of which 1,010 (95% CI: 890–1,152) were expected to require intensive care admissions. We further estimated that the high-uptake booster scenario would prevent an additional 304 (95% CI: 243–386) deaths from January 1, 2023 to June 30, 2023.

Compared to the base case, we estimated $41.3 (95% CI: 35.7–47.3) million in savings associated with

NYC population		
Outcome	Averted, mean	95% confidence interval
Cases	88,274	77,097–100,342
Hospitalizations	2,917	2,557–3,267
ICU admissions[a]	1,010	890–1,152
Deaths	304	243–386
Healthcare outcome	Costs averted[b] (US$ million)	95% confidence interval
Outpatient	$41.3	$35.7–$47.3
EMS transportation	$2.7	$2.4–$3.1
ED visit	$40.6	$35.2–$46.2
Inpatient	$131.7	$116.8–$152.3
Total medical costs	$217.2	$190.0–$242.2
NYC pediatric populationy		
Outcome	Averted, mean	95% confidence interval
Isolation days	103,585	90,814–116,872
School absenteeism days[c]	72,879	63,894–82,228
Hospitalizations	215	181–249
ICU admissions[c]	47	34–59

Bivalent booster scenario corresponds to achieving a population-level coverage equivalent to 2020–21 age-specific influenza vaccination levels between January 1 and March 31, 2023. Costs are converted to US dollars in 2023. [a]ICU admission is a subset of hospitalization. [b]Direct costs of COVID-19 illness averted. [c]Estimates are for children 5–17 years.

Table 2: **Estimates of averted outcomes and direct healthcare costs between January 1 and June 30, 2023, comparing an accelerated bivalent booster vaccination scenario with the base case scenario of daily vaccination rates matching those from December 2022 in NYC.**

outpatient care in the high-uptake bivalent booster scenario. Savings associated with EMS transportation, ED visit, and inpatient care were estimated to be $2.7 (95% CI: 2.4–3.1) million, $40.6 (95% CI: 35.2–46.2) million, and $131.7 (95% CI: 116.8–152.3) million, respectively. Averted outcomes were estimated to have a total of $217.2 (95% CI: 190.0–242.2) million savings in direct healthcare costs.

For the pediatric population, we estimated that the high-uptake scenario of bivalent booster vaccination could avert a total of 103,585 (95% CI: 90,814–116,872) days of isolation in NYC. Among children aged 5–17 years, the scenario could also prevent as many as 72,879 (95% CI: 63,894–82,228) days of school absenteeism that would occur in the base case scenario due to COVID-19 illness. In addition, we estimated that the high-uptake booster scenario could prevent 215 (95% CI: 181–249) hospitalizations among the NYC pediatric population, of which 47 (95% CI: 34–59) would be ICU admissions.

We performed additional analysis assuming that only 50% of mildly symptomatic patients followed guidelines for 5-day self-isolation. Comparing the base case and counterfactual scenarios, the estimated outcomes averted and their associated savings under the high-uptake booster were higher than those obtained when all mildly symptomatic patients practiced 5-day isolation (Supplementary Table A6).

Discussion

The historic vaccination campaign implemented in NYC has been instrumental in mitigating the COVID-19 pandemic. The scale of investment in the "Vaccine for All Campaign" was associated with a comparatively more rapid pace of vaccine delivery for primary series in NYC. In a previous work,[7] we demonstrated that this campaign reduced the COVID-19 burden substantially and suppressed a surge of cases attributable to more transmissible variants in 2021. With additional investment towards the booster campaign, we further evaluated the return on investment of the COVID-19 vaccination in NYC, and found that the campaign averted substantial economic losses from high costs of healthcare.[3]

As population-level immunity wanes and is concomitantly challenged by the emergence of immune-evasive and highly transmissible variants of SARS-CoV-2, NYC has utilized booster campaigns to combat COVID-19.[31] In September 2022, NYC began rolling out Omicron-specific bivalent boosters,[32] but uptake remained modest among eligible residents. Building on previous work,[3,7] our simulation model quantified the benefits of improving the coverage of booster vaccination, demonstrating a substantial impact on reducing severe health outcomes and preventing millions of direct healthcare costs, while supporting school attendance.

The bivalent booster provides additional protection against symptomatic and severe COVID-19 illness for people who were previously infected or vaccinated with monovalent vaccines.[33] However, despite high rates of hospitalization and deaths in the US during fall 2022 and winter 2023, uptake of bivalent booster doses remained low at the national level, with only 17% of the US population having received them as of May 10, 2023.[34] A recent CDC survey found that the most common reasons to forego the bivalent booster vaccination included a lack of awareness about vaccine availability and eligibility criteria, combined with an inflated perception of personal immunity against infection.[35] Understanding these barriers to vaccine uptake is vital to effective policy making. In NYC, bivalent booster coverage has varied widely demographically as well as geographically.[6] For example, By February 2023, bivalent coverage among children below the age of 17 in NYC was under 7% and improved gradually with age to 28.7% among adults 65–74 years of age.[6] Across various boroughs of the city, bivalent booster uptake was highest in Manhattan (26.5%). Black and Hispanic residents who comprise almost half of the NYC population had the lowest uptake of only 7.9%. Therefore, targeted outreach programs that address these vaccination disparities are critical for improving the overall bivalent booster uptake in NYC[36–38] Extensive strategies that have been implemented by the city included offering in-home vaccination, nursing home outreach and co-location of clinics, partnerships with pharmacies and Federally Qualified Health Centers, pop-up vaccination sites, digital marketing and media campaigns and public service announcements. To facilitate vaccine uptake among the elderly, more than 2 million texts, emails and reminder calls were utilized (DOHMH internal data). Similarly, to mitigate disparities, non-English language media strategies and community outreach programs were implemented.

The importance of vaccination in reducing or eliminating pandemic-related restrictions on movement, businesses, schools and in-person learning is undeniable. Going forward, vaccination would still play a central role in maintaining high levels of population immunity to minimize the burden of disease and ensure that normal socio–economic activities can continue. Although we have not quantified the broader societal benefits of vaccination, our study shows the indirect benefits of vaccination, especially for protecting young children under 5 years of age. This protection provides additional indirect benefits which may be difficult to quantify due to the lower rates of severe COVID-19 in children than adults. For instance, by reducing the risk of infection, vaccination would lower the rates of long-covid and other sequelae, and thus reduce short- and long-term costs associated with such outcomes. Furthermore, reduced acute illness and outcomes would avert substantial loss of quality-adjusted life-year and societal values which may be quantified in future research.

Limitations

While our model is highly detailed and includes myriad aspects of realism informed by data provided by NYC DOHMH, there are nonetheless limitations. First, our model used reported confirmed and probable cases for calibration instead of actual number of infections. Reported cases undercount SARS-CoV-2 for several reasons including testing patterns that have varied over time, and often prioritizing symptomatic and severe cases, potentially missing a significant portion of SARS-CoV-2 infections that may experience asymptomatic infection. Second, we set the daily vaccination rate of the base case scenario to the average observed during December 2022. Despite a transient acceleration in the vaccination rate shortly after the introduction of bivalent booster vaccines, daily rates of vaccine administration have steadily declined in NYC.[6] Given the declining trend of vaccination rates in NYC, our findings for the impact of a high-uptake scenario for booster vaccination are likely an underestimate. Third, we did not consider the effect of other measures (e.g., testing) that would likely increase isolation days and school absenteeism. For example, individuals with a positive test during asymptomatic infection are expected to isolate; however, our estimates of isolation days and absenteeism rely only on projected symptomatic cases. Fourth, our study does not quantify the indirect benefits of vaccination such as reduced loss of productivity, averted loss of quality-adjusted life-year and other health outcomes including long-covid. Quantification of these benefits merits further investigation. Finally, we did not consider the costs associated with implementing high-uptake booster campaigns or possible adverse outcomes of vaccination.

Conclusion

Our results demonstrate that improving booster coverage among NYC residents will not only prevent many severe health outcomes, but it could also save substantial direct healthcare costs that could be used for the benefit of other patients. The findings underscore the role of improved booster uptake on uninterrupted functioning of schools, and on continuous socioeconomic activities.

Contributors

SMM and TNV had full access to all of the data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis.

Concept and design: All authors.

Acquisition, analysis, or interpretation of data: AP, MCF, SMM, TNV, CK.

Drafting of the manuscript: All authors.

Statistical analysis: SMM, TNV.

Obtained funding: MCF, SMM, APG.

Data sharing agreement

All data are publicly available at https://github.com/nychealth, and computational model is available at https://github.com/thomasvilches/NYC_twoyears_estimation.

Declaration of interests

Authors declare that they have no competing interests.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.lana.2023.100555.

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