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Research Report

Vaccinating children against COVID-19 is crucial to protect schools and communities

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Abstract

To evaluate the joint impact of childhood vaccination rates and school masking policies on community transmission and severe outcomes due to COVID-19, we utilized a stochastic, agent-based simulation of North Carolina to test 24 health policy scenarios. In these scenarios, we varied the childhood (ages 5 to 19) vaccination rate relative to the adult's (ages 20 to 64) vaccination rate and the masking relaxation policies in schools. We measured the overall incidence of disease, COVID-19-related hospitalization, and mortality from 2021 July 1 to 2023 July 1. Our simulation estimates that removing all masks in schools in January 2022 could lead to a 31% to 45%, 23% to 35%, and 13% to 19% increase in cumulative infections for ages 5 to 9, 10 to 19, and the total population, respectively, depending on the childhood vaccination rate. Additionally, achieving a childhood vaccine uptake rate of 50% of adults could lead to a 31% to 39% reduction in peak hospitalizations overall masking scenarios compared with not vaccinating this group. Finally, our simulation estimates that increasing vaccination uptake for the entire eligible population can reduce peak hospitalizations in 2022 by an average of 83% and 87% across all masking scenarios compared to the scenarios where no children are vaccinated. Our simulation suggests that high vaccination uptake among both children and adults is necessary to mitigate the increase in infections from mask removal in schools and workplaces.

Keywords: COVID-19, Public Health Policy, School and Community Health, Childhood Vaccination, Agent-Based SEIR Simulation Model

Significance Statement:

This study uses an agent-based, extended SEIR model to evaluate the joint impact of childhood vaccinations and school masking on COVID-19 infections, hospitalizations, and deaths in children and the broader community. Our findings stress the need for high vaccine uptake in all age groups before the removal of masks in schools. Policymakers must consider that public health policies in schools could have an impact on the broader community.

Introduction

Vaccination has shown to be effective in reducing the transmission of SARS-CoV-2 and improving outcomes in those who develop COVID-19 (1). Recently, the CDC Advisory Committee on Immunization Practices (ACIP) extended vaccination recommendations (2) to include children ages 5- to 11-y-old (3), which renewed discussion of what role nonpharmaceutical interventions (NPIs) should continue to play, particularly whether masks should be worn in schools (4). The CDC recommends universal masking for all eligible staff and students regardless of community transmission levels due to the variability of mixing between vaccinated and unvaccinated individuals in school settings (5). Yet, state public health agencies have updated their guidelines and recommend that schools consider levels of community transmission when contemplating the decision to enforce masking in schools (4). One example is that schools can consider removing a mask mandate for vaccinated individuals when community transmission rates are consistently low to moderate (e.g. for seven consecutive days)

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and remove the mandate for everyone when community transmission remains low. As of 2021 November 5th, only 16 states were enforcing a mask mandate in schools regardless of vaccination status (6), with many states, such as Alabama, Georgia, and North Carolina, allowing counties to decide their masking policies (7). Specifically for North Carolina, school boards must meet at least once a month to vote to continue enforcing masking policies on school grounds (8). In contrast, some districts in other states have removed mask requirements completely during the fall of 2021 (9).

Previous work has shown that masks are effective at slowing infection transmission in the community and schools (10), and that increased vaccine uptake is required to reduce infections when NPIs, such as masks, are lifted (11). In the face of slowing vaccination among previously eligible individuals and more transmissible variants, studies need to estimate the impacts of alternate child-facing interventions (NPIs and vaccination) on community transmission and COVID outcomes to inform decision-making. A recent study used an agent-based simulation model of the United States to assess the impact of testing and contact tracing strategies to identify and isolate presymptomatic and asymptomatic infections in children before the emergence of the Delta variant. They describe this as a proxy for their vaccination, as vaccines were not available at the time for children. They found that specific interventions for children were required in addition to adult vaccination to control disease outbreaks in the broader community (12). While this study highlighted the need for targeted intervention strategies for children when vaccines were unavailable, it did not explicitly consider their vaccination status. Another study using an agent-based simulation for Australia concluded that vaccinating ages 5 to 11 and 12 to 17 could significantly reduce COVID-19 cases and hospitalizations under the Delta variant. They found that fully vaccinating 90% of the children and adults is effective at averting all future COVID-19 deaths. However, it did not evaluate the impact of removing or adding masks in schools (13). Round 9 results from the Scenario Modeling Hub ensemble model indicate that if childhood vaccinations follow observed adolescent vaccinations, by March 2022, they could reduce the total COVID-19 deaths by 3.5% or 2% if there is or is not a new, more infectious variant than Delta, respectively (14). However, they do not quantify the impact of varying vaccination rates or the use of masks.

Given the fall/winter 2021 pandemic context in which adult vaccination is leveling out and communities are facing increased infectivity and breakthrough risk of newer variants (Delta and Omicron), we used an agent-based simulation model to project the impact of child and/or adult vaccination uptake in combination with masking policies on COVID-19 outcomes. To the best of our knowledge, this study is the first to consider the joint impact of increasing county-level vaccination rates across specific age ranges, including children, and masking policies in schools and workplaces on community-wide COVID-19 incidence, hospitalizations, and mortality.

Methodology

Model structure

We used a stochastic agent-based, Susceptible–Exposed–Infected–Recovered simulation model (11, 15) (Figure S2, Supplementary Material) with an embedded household, peer group, and community interaction network (Figure S1, Supplementary Material) to evaluate the joint impact of mask compliance in schools and rates of vaccination for children (5 to 19), adults (20 to 64), and 65+ on community transmission, as measured by infections and severe cases requiring hospitalization or resulting mortality. The model was populated with 1,017,720 agents using census tract level data for the 10.5 million population of North Carolina. Each agent was assigned to one of five age groups (0 to 4, 5 to 9, 10 to 19, 20 to 64, or 65+), one of four race/ethnicity groups (non-Hispanic White, non-Hispanic Black, Hispanic, and non-Hispanic other), a school or workplace peer group if applicable (i.e. 5 to 19, "school-age" or 20 to 64, "working-age"), a household group where the size is dependent on age and race/ethnicity, and a mask wearing attribute, which is age-based and scenario dependent. We assumed that mask wearing reduces an agent's infectivity and susceptibility by 50% (16). A subset of adult agents was assigned a high-risk medical condition based on the statewide age- and race-specific prevalence of diabetes. We used commuting pattern data (33) to incorporate individuals who live in one census tract and work in another census tract. Finally, we incorporated census tract-specific case importation to simulate infections generated from outside the interaction network.

Using a stochastic agent-based simulation model allowed us to model individuals' different behaviors (e.g. masking and vaccination) over time and construct a stochastic interaction network to model human interactions. The stochastic interaction network captures structural differences (i.e. household size and composition), which vary geographically, and captures the spatiotemporal disease spread caused by agents' interactions and behaviors. At this level of granularity, modeling behaviors and interactions approximate the complexity of real-world disease spread. In addition, multiple stochastic realizations of the simulation allowed us to assess the various trajectories the pandemic can take due to the randomness of human behavior under the same parameterization.

Vaccination and masking scenarios

We evaluated the impact of six vaccination uptake settings and four mask compliance settings within schools, 24 total scenarios, on community transmission of COVID-19. For age groups 5 to 9 years and 10 to 19 years, we tested vaccination levels that are a percentage (50%, 75%, and 100%) of the 20 to 64 year age group's observed vaccination at the county level. We forecasted county-specific vaccination demand for 12 months for age groups 20 to 64 and 65+ using the average vaccination rate for each age group observed in July 2021 (17). The new age group's (5 to 11 years) vaccine eligibility begins 2021 November 15. Additionally, we simulated a 50% and 75% increase in uptake from the forecast for the 20+ eligible population, with children's and adolescents vaccine uptake equal to the adult level. Finally, we simulated no vaccine uptake in the 5 to 9 year age group as a control. Figure 1 shows the mean, maximum, and minimum simulated vaccine uptake over all ages across the 100 counties in North Carolina over time. Figure S6 (Supplementary Material) shows observed vaccine uptake by age through 2022 April 14, for reference. Simultaneously, we tested four masking scenarios, in which masks either remain in place (100% adherence in schools and 70%, 60%, and 50% adherence in workplaces in urban, suburban, and rural census tracts, respectively) (18) or are removed in schools (retained in workplaces) on either: 2022 January 1, 2022 March 8 (∼3/4 between January 1 and April 1), or incrementally between January and April. In the incremental removal scenario, 50% of current mask wearers in schools stop wearing their masks each month from 2022 January 1 through 2022 April 1, leaving approximately 5% of the school-aged population wearing masks.

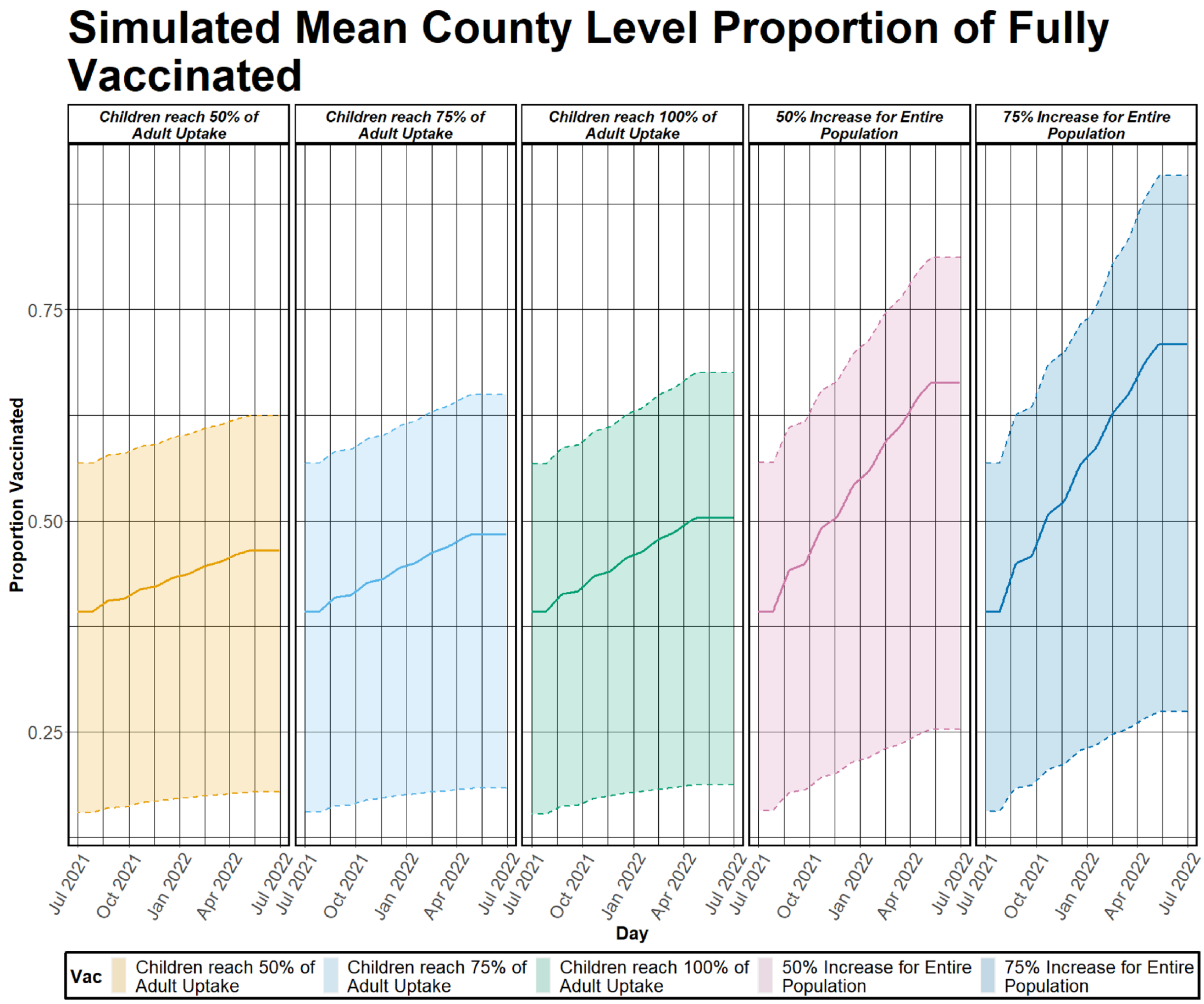

Fig. 1. County-level proportion of total population fully vaccinated over time. Values presented correspond to simulation values, where solid lines reflect the mean vaccine uptake. Dashed lines correspond to the minimum and maximum vaccine uptake across the 100 counties of North Carolina, and the shaded area represents the corresponding range.

Additional modeling considerations

Scenarios were seeded with aggregate county-level infections, aggregate hospitalizations, age-based deaths, and age-based vaccination rates as of 2021 July 1. We incorporated the Delta variant by increasing transmissibility based on the percentage of circulating cases in North Carolina (19). We integrated immunity loss from both previous infection and vaccination by including age-based immunity loss upon seeding, which was dependent on the time each age group was first eligible to receive vaccines in North Carolina (20) and throughout the simulation with a base immunity of 6 months (21, 22), similar to Round 8 of the Scenario Modeling Hub (14). Immunity loss is greater with a previous infection than vaccine (23). Reinfected agents had a 56% lower probability of being symptomatic during infection compared to the population with no immunity from vaccination or infection (24).

Outcomes of interest

The outcomes studied are the cumulative rate of infection per 100,000 by age group, and the current number of people hospitalized. The infection rate is the primary disease metric that can be compared across age groups due to the low hospitalization and mortality rates of children ages 5 to 19. The current number of people hospitalized, emphasizing peak hospitalizations, provides insight into the stress applied to the medical system. If the hospital systems become overwhelmed, it can result in reductions in quality of care and excess mortality (31). NPI and pharmaceutical interventions aim to slow the spread of COVID-19 to prevent hospitalizations from exceeding hospital capacity (32).

Validation

We validated the model on cumulative infections and deaths and current hospitalizations associated with COVID-19 from NCDHHS (17). We use a calibrated ascertainment rate of 36% to estimate the true infections (34, 35). Figures 2 and 3 include estimated true infections and current hospitalizations, respectively, to demonstrate the validation. See the supplement for an extended methodology, additional validation (Figures S3–S5, Supplementary Material), and model parameters (Tables S1 and S2, Supplementary Material).

Data availability

Data used to construct the simulation is publicly available and referenced throughout the text and supplemental material. The

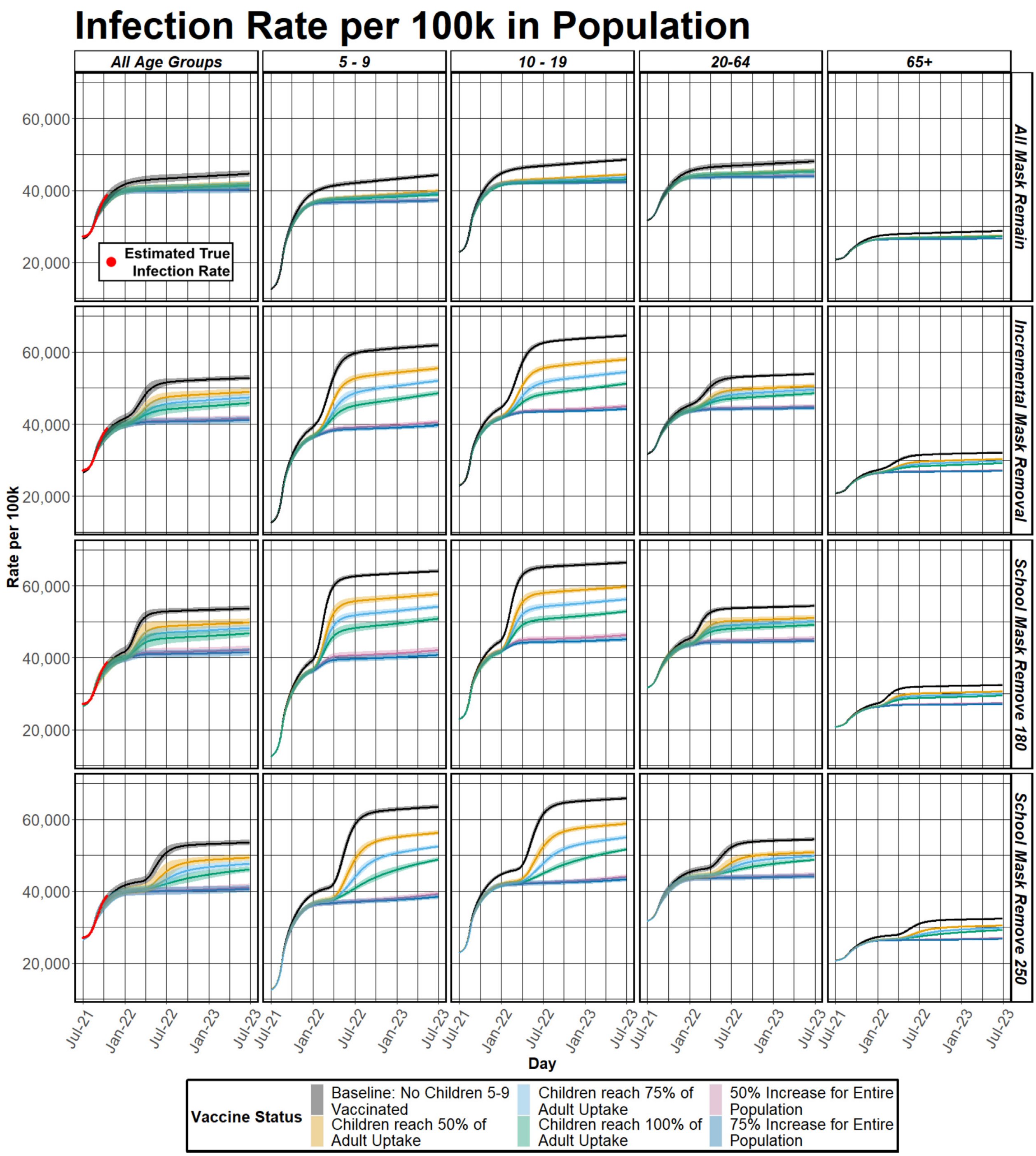

Fig. 2. Cumulative infections per 100,000 population. Columns disaggregate the infection rate by age group, where "All Age Groups" reports the state-level infection rate. Rows separate scenarios by masking status. Each subgraph presents six vaccine uptake settings. The red dotted line corresponds to the estimated true infection rates for validation. Each scenario is accompanied by a 95% CI (shaded band).

simulation code and output can be made available via a request to the corresponding author, Dr. Julie Swann.

Results

Figure 2 shows the cumulative infection rate at the state level and by age group for all masking and vaccination scenarios. If masks were removed in schools on 2022 January 1, the infection rate for age group 5 to 9 would increase by 45%, 38%, and 31% when vaccine uptake among children and adolescents is 50%, 75%, and 100% of the adult vaccination uptake compared with masks remaining, respectively. Similarly, we observed the infection rate increased by 35%, 28%, and 23% for the age group 10 to 19 when vaccine uptake among children and adolescents was 50%, 75%, and 100% of the adult vaccination uptake when masks were removed in January. If masks were removed 66 days later on 2022 March 8, we observed an average 3.5% lower cumulative infection rate in children 5 to 19 than compared to removing masks on 2022 January 1, over all vaccination scenarios. Additionally, we observed that if masks were removed in schools on

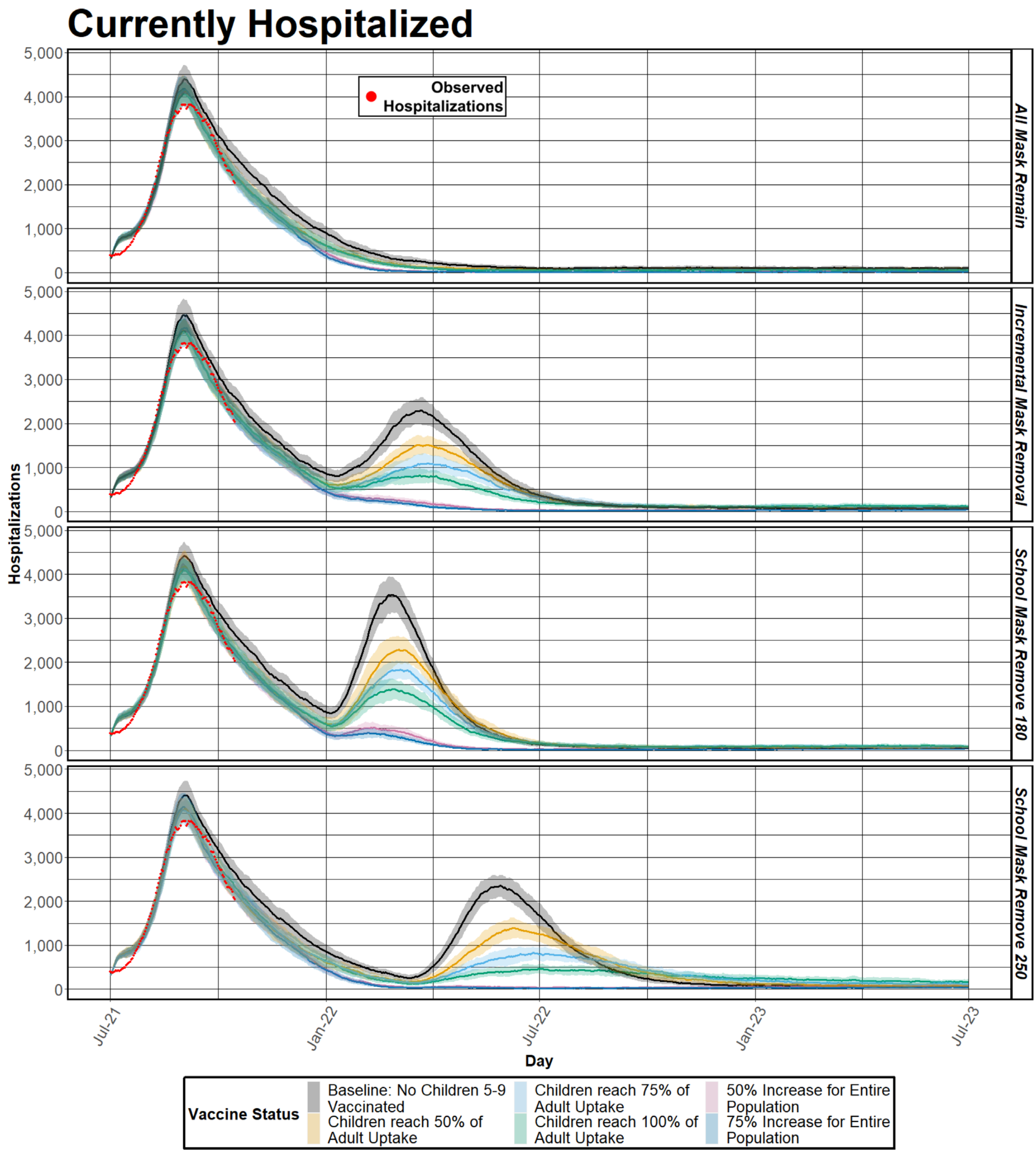

Fig. 3. A. Number of individuals currently hospitalized. Rows separate scenarios by masking status. Each subgraph presents six vaccine uptake settings. The red dotted line corresponds to the observed hospitalizations for validation. Each scenario is accompanied by a 95% CI (shaded band).

2021 January 1, the infection rate increased by 9% to 12%, 8% to 12%, and 13% to 19% for 20 to 64, 65+, and the total population, respectively, depending on the rate of vaccination uptake in children.

When the vaccine uptake was increased by 50% and 75%, we observed 13% and 9%, 9% and 6%, 5% and 3% increases in infection rate when masks were removed in January 2022 for age groups 5 to 9, 10 to 19, and the total population, respectively. When children ages 5 to 9 have vaccination uptake that is 50% of adults, we observed an average reduction of 7% for the cumulative infection rate for the total population overall masking scenarios compared with no childhood vaccination.

Figure 2 also shows the cumulative infection rate at the state level and by age group for scenarios with incremental mask removal in schools. We observed that under the incremental mask removal, the infection rate for age group 5 to 9 increased by 39%, 32%, and 26% when vaccine uptake among children and adolescents was 50%, 75%, and 100% of the adult vaccination uptake compared with masks remaining, respectively. Similarly, we observed the infection rate for 10 to 19 increased 30%, 24%, and 19% when vaccine uptake among children and adolescents was 50%, 75%, and 100% of the adult vaccination uptake. Additionally, we observed that the infection rate increased by 7% to 11%, 7% to 10%, and 11% to 17% for 20 to 64, 65+, and the total population, respectively, depending on the rate of vaccination uptake in children, compared to when masks remained. When the vaccine uptake for everyone was increased by 50% and 75%, we observed 9% and 6%, 6% and 4%, and 3% and 2% increases in infection rate when masks were removed for age group 5 to 9, 10 to 19, and the total population, respectively. Incremental mask removal led to an average 3.2% and 1.5% reduction in infections for children ages 5 to 19 and the total population compared with universal mask removal on 2022 January 1, overall vaccination scenarios.

Figure 3 shows the number of people requiring hospitalization with COVID-19 overtime for all masking and vaccination scenarios. By removing masks on 2022 March 8, 66 days after 2022 January 1, the 2022 peak hospitalizations were reduced by an average of 60% across all vaccination scenarios. Similarly, under incremental removal of masks, peak hospitalizations were reduced by an average of 39% across all vaccination scenarios compared with universal removal on 2022 January 1. When children ages 5 to 9 have vaccination uptake, that is 50% of adults, we observed an average 35% reduction in peak hospitalizations overall masking scenarios compared with not vaccinating this group. Additionally, without increased vaccination uptake in the adult population, a 25% increase in child vaccination uptake from 50% to 75% uptake and from 75% to 100% uptake relative to the adult population led to a 27% and 20% or 42% and 46% decrease in peak hospitalizations in 2022 across scenarios when masks were removed 2022 January 1 or 2022 March 8, respectively. Further increasing vaccine uptake can lead to an average decrease of 83% and 87% in peak hospitalization when vaccination uptake is increased by 150% and 175% for the entire eligible population, respectively, across all masking scenarios compared to scenarios where no children are vaccinated. Sensitivity analysis of masking efficacy, adherence rates, and transmissibility of the delta variant is available in Table S3 and Figures S7–S9 (Supplementary Material).

Discussion

As of December 2021, much of the United States is still in the midst of the COVID-19 wave associated with the increased infectivity of the Delta variant; simultaneously, children ages 5 to 11 have become a new eligible population for vaccination. This work estimated the impact of the vaccine uptake in children and mask policy in schools, indicating that high vaccine uptake rates in children must occur to reduce the impact of mask removal. If masks are removed in schools, we expect to see increased infections and hospitalizations in school-aged populations and the community regardless of how long mask wearing in schools is retained (up to March 8th days). Under all three mask removal strategies, we observe similar cumulative infection rates in each age group (Fig. 2). Therefore, vaccine uptake in children and adolescents equivalent to adults must be achieved to reduce the impact of mask removal and avoid triggering new spikes with associated surges in hospitalization. Increasing vaccination uptake among child populations (age 5 to 11) leads to reductions in infections and hospitalizations for all age groups in the community. Increasing vaccine uptake among all populations can still further reduce the COVID-19 burden.

Achieving high vaccine uptake in children may be challenging as COVID-19 has disrupted other routine childhood vaccinations (25). School survey studies have shown hesitancy within child and adolescent populations to get the COVID-19 vaccine, highlighting possible disparities between already under-vaccinated populations and the need for specific interventions to increase uptake (26). Survey results in the United States from October 2021 indicate that roughly 3 in 10 parents are "definitely not" going to vaccinate their children 5 to 11 or adolescents 12 to 17 (27). Similarly, survey results indicate adults still face similar vaccine hesitancy issues, with roughly 14% indicating they will "definitely not" take the COVID-19 vaccine (27). This work supports increasing vaccine uptake in children and adults as it could avert cases, hospitalizations, and deaths within the community. Given these challenges in increasing uptake in children and adults, this work supports masks remaining in place in schools.

With many states regularly evaluating the public health policies in schools during the last months of 2021, this analysis is directly relevant to local county health departments and school boards to inform policy decision-making. Policymakers need to consider the impact public health policy in schools can have on not only the students but the broader community. Removal of masks in schools without sufficiently high vaccine uptake in schools could lead to additional surges of cases, hospitalizations, and deaths for all age groups in the community. Policymakers should maintain NPI policies in schools and support initiatives to increase vaccine uptake in schools and the broader community.

Our modeling work was scenario-based as opposed to forecasting, meaning we aimed to quantify the long-term impact of population-wide behavioral decisions rather than project short-term COVID-19 outcomes. Our model is limited due to the large age grouping of the adult population. As a result, we are unable to differentiate age-related differences in behavior, such as an extensive social network and active lifestyle associated with the younger adult population (e.g. 20 to 30), or in characteristics, such as the increased prevalence of high-risk medical conditions associated with the older adult population (e.g. 50 to 64). Similarly, we do not model adults 65+ as having a workplace peer group (i.e. they are retired), which may not be representative of the populations given a geographic location. As a result, we may be underestimating cases, hospitalizations, and deaths for this age group. Additionally, we only illustrate the effect of high-risk chronic conditions within the population with diabetes, which again may lead to underestimating hospitalizations and deaths. Finally, we do not account for the impact of future variants, which may be more infectious or resistant to vaccination, such as the emergence of the Omicron variant in South Africa. The introduction of a more infectious or immunity escaping variant would increase the impact of mask removal in schools and lower vaccine uptake. If variants escape natural and vaccine immunity, NPIs would be critical for controlling transmission, similar to what was observed at the beginning of the pandemic (15, 28). While only North Carolina was modeled here, the findings are generalizable as the underlying model structure can apply to any state. Additionally, North Carolina is representative of the United States with similar demographic characteristics (29), major industry activity (30), and representative population urbanicity (29).

Our model projected the impact of childhood vaccination rates and masking in schools on children, adolescents, and the broader community. We found that increasing vaccine uptake in children and maintaining masks in schools will avert a large number of cases, hospitalizations, and deaths compared with the removal of masks in schools. Policymakers must consider that public health policies in schools could have an impact on the broader community. Our findings stress the need for high vaccine uptake in all age groups before the removal of masks in schools.

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The sponsors 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; and decision to submit the manuscript for publication.

Disclaimer

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Supplementary Material

Supplementary material is available at *PNAS Nexus* online.

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Authors' Contributions

E.T.R. contributed to the conceptualization and design, acquisition, statistical analysis, and interpretation of data, drafting of the manuscript, and critical revision of the manuscript for important intellectual content; J.M. contributed to the conceptualization and design, acquisition, statistical analysis, and interpretation of data, drafting of the manuscript, and critical revision of the manuscript for important intellectual content; J.S.I. contributed to the conceptualization and design, interpretation of data, critical revision of the manuscript for important intellectual content, acquisition of funding, and general supervision; M.E.M. contributed to the conceptualization and design, interpretation of data, critical revision of the manuscript for important intellectual content, acquisition of funding, and general supervision; M.D.P. contributed to the conceptualization and design, interpretation of data, critical revision of the manuscript for important intellectual content, and acquisition of funding; K.H.L. contributed to the conceptualization and design, interpretation of data, critical revision of the manuscript for important intellectual content, and acquisition of funding; P.D. contributed to the conceptualization and design, and critical revision of the manuscript for important intellectual content; R.L.S.-III contributed to the conceptualization and design, and critical revision of the manuscript for important intellectual content; and J.L.S. contributed to the conceptualization and design, interpretation of data, drafting of the manuscript, critical revision of the manuscript for important intellectual content, acquisition of funding, and general supervision. All authors approved the final manuscript as submitted and agree to be accountable for all aspects of the work.

References

1. CDC. Science brief: COVID-19 vaccines and vaccination. https://www.cdc.gov/coronavirus/2019-ncov/science/science-briefs/fully-vaccinated-people.html. (accessed 2021 Oct 3).
2. CDC. CDC recommends pediatric COVID-19 vaccine for children 5 to 11 years. https://www.cdc.gov/media/releases/2021/s1102-PediatricCOVID-19Vaccine.html#:~:text = CDC%20Recommends%20Pediatric%20COVID%2D19%20Vaccine%20for%20Children%205%20to%2011%20Years,-Media%20Statement&text = Today%2C%20CDC%20Director%20Rochelle%20P,the%20Pfizer%2DBioNTech%20pediatric%20vaccine. (accessed 2021 Nov).
3. FDA. Vaccines and related biological products advisory committee. https://www.fda.gov/advisory-committees/advisory-committee-calendar/vaccines-and-related-biological-products-advisory-committee-october-26-2021-meeting-announcement. (accessed 2021 Oct 28).
4. NCDHHS. StrongSchoolsNC Public Health Toolkit (K-12) frequently asked questions. North Carolina Department of Health and Human Services. https://covid19.ncdhhs.gov/media/401/download?attachment. (accessed 2021 Oct 28).
5. CDC. Guidance for COVID-19 prevention in K-12 schools. https://www.cdc.gov/coronavirus/2019-ncov/community/schools-childcare/k-12-guidance.html. (accessed 2021 Nov 6).
6. Center for Dignity in Healthcare for People wD. State-by-state school mask mandates. Center for Dignity in Healthcare for People with Disabilities. https://centerfordignity.com/state-by-state-school-mask-mandates/. (accessed 2021 Dec 1).
7. Zalaznick M. 2021. School mask tracker: who is and isn't loosening the rules. https://districtadministration.com/track-school-mask-rules-requirements-state-by-state/. (accessed 2021 Dec 8).
8. K - 12 COVID-19 Provisions. 2021. 654, North Carolina General Assembly. https://www.ncleg.gov/Sessions/2021/Bills/Senate/PDF/S654v7.pdf. (accessed 2021 Aug 31).
9. Gewertz C. 2021. Some schools are dropping mask mandates. Should yours?. https://www.edweek.org/leadership/some-schools-are-dropping-mask-mandates-should-yours/2021/11. (accessed 2021 Nov 15).
10. Zhang Y, Johnson K, Yu Z, *et al.* 2021. COVID-19 projections for K12 schools in fall. Significant transmission without interventions. medRxiv. 8. doi: 10.1101/2021.08.10.21261726.
11. Patel MD, Rosenstrom E, Ivy JS, *et al.* 2021. Association of simulated COVID-19 vaccination and nonpharmaceutical interventions with infections, hospitalizations, and mortality. JAMA Netw Open. 4(6):e2110782–e2110782. doi: 10.1001/jamanetworkopen.2021.10782.
12. Moghadas SM, Fitzpatrick MC, Shoukat A, Zhang K, Galvani AP. 2021. Simulated identification of silent COVID-19 infections among children and estimated future infection rates with vaccination. JAMA Netw Open. 4(4):e217097–e217097. doi: 10.1001/jamanetworkopen.2021.7097
13. Milne GJ *et al.*, 2022. Mitigating the SARS-CoV-2 Delta disease burden in Australia by non-pharmaceutical interventions and vaccinating children: a modelling analysis. BMC Medicine. 20, 1–13.
14. Covid Scenario Modeling Hub. https://covid19scenariomodelinghub.org/viz.html. (accessed 2021 Oct 2).
15. Rosenstrom ET, *et al.* 2021. High-quality masks reduce COVID-19 infections and death in the US. Proceedings of the 2021 Winter Simulation Conference (WSC). 1–11. Phoenix (AZ). doi: 10.1109/WSC52266.2021.9715379.
16. Liang M, Gao L, Cheng C, *et al.* 2020. Efficacy of face mask in preventing respiratory virus transmission: a systematic review and meta-analysis. Trav Med Infect Dis. 36:101751–101751. doi: 10.1016/j.tmaid.2020.101751.

17. NCDHHS. COVID-19 North Carolina Dashboard. N. C. Department of Health and Human Services. https://covid19.ncdhhs.gov/dashboard. (accessed 2021 Oct 8).
18. Delphi Epidata API. 2021. https://github.com/cmu-delphi/delphi-epidata. (accessed 2021 Nov 15).
19. COVID Data Tracker. Centers for Disease Control and Prevention. https://covid.cdc.gov/covid-data-tracker/#variant-proportions. (accessed 2021 Nov 1).
20. NCDHHS. NCDHHS shares updated rollout plan for COVID-19 vaccinations. 2021. https://www.ncdhhs.gov/news/press-releases/2020/12/30/ncdhhs-shares-updated-rollout-plan-covid-19-vaccinations. (accessed 2021 Oct 3).
21. Gaebler C, Wang Z, Lorenzi JCC, *et al.* 2021. Evolution of antibody immunity to SARS-CoV-2. Nature. 591(7851):639–644. doi: 10.1038/s41586-021-03207-w.
22. Hansen CH, Michlmayr D, Gubbels SM, Mølbak K, Ethelberg S. 2021. Assessment of protection against reinfection with SARS-CoV-2 among 4 million PCR-tested individuals in Denmark in 2020: a population-level observational study. Lancet North Am Ed. 397(10280):1204–1212. doi: 10.1016/S0140-6736(21)00575-4.
23. Bertollini R, Chemaitelly H, Yassine HM, Al-Thani MH, Al-Khal A, Abu-Raddad LJ. 2021. Associations of vaccination and of prior infection with positive PCR test results for SARS-CoV-2 in airline passengers arriving in Qatar. JAMA. 326(2):185–188. doi: 10.1001/jama.2021.9970.
24. Lopez Bernal J, Andrews N, Gower C, *et al.* 2021. Effectiveness of the Pfizer-BioNTech and Oxford-AstraZeneca vaccines on covid-19 related symptoms, hospital admissions, and mortality in older adults in England: test negative case-control study. BMJ. 373:n1088. doi: 10.1136/bmj.n1088.
25. DeSilva MB, Haapala J, Vazquez-Benitez G, *et al.* 2021. Association of the COVID-19 pandemic with routine childhood vaccination rates and proportion up to date with vaccinations across 8 US health systems in the vaccine safety datalink. JAMA Pediatr. 176:68. doi: 10.1001/jamapediatrics.2021.4251.
26. Fazel M, Puntis S, White SR, *et al.* 2021. Willingness of children and adolescents to have a COVID-19 vaccination: results of a large whole schools survey in England. EClinicalMedicine. 40:101144–101144. doi: 10.1016/j.eclinm.2021.101144.
27. Kaiser Family F. 2021. Does the public want to get a COVID-19 vaccine? When?. https://www.kff.org/coronavirus-covid-19/dashboard/kff-covid-19-vaccine-monitor-dashboard/. (accessed 2021 Dec 1).
28. Bo Y, Guo C, Lin C, *et al.* 2021. Effectiveness of non-pharmaceutical interventions on COVID-19 transmission in 190 countries from 23 January to 13 April 2020. Int J Infect Dis. 102:247–253. doi: 10.1016/j.ijid.2020.10.066
29. United States Census Bureau. American community survey 5-year estimates 2017. data.census.gov. (accessed 2021 Jan 10).
30. Agriculture NCDo, Consumer S. North Carolina Agricultural Statistics. N. C. Department of Agriculture and Consumer Services. https://www.nass.usda.gov/Statistics_by_State/North_Carolina/Publications/Annual_Statistical_Bulletin/AgStat/NCAgStatBook.pdf. (accessed 2021 Oct 2).
31. Eriksson CO, Stoner RC, Eden KB, Newgard CD, Guise JM. 2017. The association between hospital capacity strain and inpatient outcomes in highly developed countries: a systematic review. J Gen Intern Med. 32(6):686–696. doi: 10.1007/s11606-016-3936-3.
32. CDC. How to protect yourself and others. https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/prevention.html. (accessed 2021 Nov 6).
33. U.S. Census Bureau. Census transportation planning products, 5-year data (2012-2016). data5.ctpp.transportation.org.2021. (accessed 2021 Jan 10).
34. Pei S., Yamana T.K., Kandula S., *et al.* 2021. Burden and characteristics of COVID-19 in the United States during 2020. Nature. 598:338–341. doi: 10.1038/s41586-021-03914-4
35. CDC. Estimated COVID-19 burden. https://www.cdc.gov/coronavirus/2019-ncov/cases-updates/burden.html. (accessed 2021 Feb 1).