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Temporal Associations Between Nonpharmaceutical Interventions and COVID-19 Transmission in Delaware

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Brief Report

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Abstract

Background: Understanding how nonpharmaceutical interventions temporally align with changes in COVID-19 transmission remains important for public health monitoring and evaluation. However, substate-level evidence remains limited. Delaware provides a useful setting for such analyses due to its small population and largely uniform statewide policy implementation during 2020.

Methods: We analyzed COVID-19 transmission dynamics in Delaware and its 3 counties (Kent, New Castle, and Sussex) between March 2020 and March 2023, with policy-focused analyses restricted to major statewide interventions implemented in 2020. Incident infections were reconstructed using a deconvolution-based approach, and the time-varying reproduction number (Rt) was estimated using the *EpiEstim* R package.

Results: Rt estimates varied across policy periods and revealed substantial spatial heterogeneity. The most consistent increases in Rt were associated with the transition to hybrid school reopening, while decreases in Rt were associated with limits on social gatherings, the public mask mandate, and the stay-at-home advisory and overnight curfew. During Phase 1 reopening, Rt changes were small statewide, while Sussex County exhibited a larger increase than other counties.

Conclusions: COVID-19 transmission dynamics in Delaware during 2020 varied across policy periods and counties, illustrating substate heterogeneity under uniform statewide interventions and the use of Rt-based estimates for monitoring epidemic dynamics.

Introduction

In the early phase of the COVID-19 pandemic, state and local governments in the United States (U.S.) relied heavily on nonpharmaceutical interventions (NPIs), e.g., business closures, mask mandates, and limits on social gatherings to mitigate its impact. Evaluating how these measures were associated with changes in transmission remains important for understanding their potential role in future public health responses.

Delaware provides a setting in which statewide policy interventions were implemented within a relatively small population of approximately 1 million residents distributed across 3 counties. Most major NPIs were implemented statewide during 2020. While policies were largely uniform across Delaware, counties differ in population density, demographic composition, and economic activity. These differences provide an opportunity to assess whether transmission patterns and policy-associated changes varied across counties within the state.

Delaware consists of three counties with distinct geographic and demographic characteristics (Figure S1). New Castle County is the most populous and urbanized and includes Wilmington as part of the greater Philadelphia metropolitan area. Kent County contains the state capital of Dover and has a mixed urban–rural character. Sussex County is the largest by area and least densely populated, with an economy largely driven by agriculture and seasonal tourism.

The objectives of this analysis were 3-fold. First, we estimated the time-varying reproduction number (Rt) for Delaware statewide and for each of its 3 counties from March 2020 through March 2023. Second, we quantified changes in Rt associated with 5 major policy interventions implemented during 2020. Third, we examined differences in transmission dynamics and policy-associated patterns in 2020 across counties.

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Methods

Daily confirmed COVID-19 case counts were obtained from the Johns Hopkins University Center for Systems Science and Engineering COVID-19 Data Repository for all 3 Delaware counties from March 11, 2020, through March 1, 2023, and were aggregated to produce statewide totals for analysis.[1] Reported incident case count data contain known reporting artifacts, including negative values resulting from retrospective corrections and zero counts associated with reporting delays. To address these issues, negative daily case counts were imputed using a 7-day centered average, and isolated zero counts inconsistent with surrounding trends were smoothed to reduce artificial variability.

Rt, defined as the average number of secondary infections generated by an infected individual at time t, was estimated using a deconvolution-based approach that accounts for delays between infection and case reporting. Incident infections were reconstructed using flexible spline-based models, and uncertainty in the reconstructed infection curves was represented through multiple realizations generated using a Poisson-distributed multiplier of 4. Rt was estimated from March 2020 through March 2023 using the *EpiEstim* R package, which applies a Bayesian framework with a gamma-distributed serial interval.[2] A mean serial interval of 4.6 days and a standard deviation of 5.55 days (based on an early-pandemic serial interval distribution) were specified, and posterior sampling was used to generate 95% credible intervals (CrIs).[3] To assess the robustness of Rt estimates to alternative modeling assumptions, sensitivity analyses were conducted by applying an Omicron-specific serial interval distribution (mean 2.9 days, SD 1.64 days), the underreporting multiplier ($\lambda = 2$ and $\lambda = 6$ versus baseline $\lambda = 4$), and the infection-to-reporting delay distribution (shifted ±2 days).[4]

Analysis of policy-associated changes in Rt was restricted to 2020. Five major policy changes implemented in Delaware between March and December 2020 were included. On April 2, 2020, the state introduced limits on social gatherings and required the closure of nonessential businesses (Policy A). On April 28, 2020, a statewide public mask mandate was established (Policy B). On June 1, 2020, Phase 1 reopening began, including the lifting of the mandatory 14-day quarantine for out-of-state travelers (Policy C). On September 8, 2020, the school year began with hybrid in-person and remote instruction (Policy D). On December 14, 2020, a stay-at-home advisory and overnight curfew was established (Policy E). For each policy transition, analysis windows were defined for periods before and after implementation, and percentage changes in Rt were calculated from the posterior distributions of Rt estimates across consecutive policy periods. Table S1 presents a chronology of NPIs and pharmacological interventions implemented in Delaware in 2020.

All analyses were performed using R statistical software (version 4.5.2). Supplementary File S1 contains the supplementary methods, figures, tables, and references. The complete code for this analysis is provided in Supplementary File S2 (scripts written in R Markdown format) and Supplementary File S3 (custom R functions).

Results

Figure 1 presents reported and deconvolved daily COVID-19 case counts, deconvolved estimates of incident infections, and time-varying Rt estimates for Delaware statewide from March 2020 through March 2023. Multiple waves were observed, including increases in spring 2020, winter 2020-2021, winter 2021-2022, mid-2022, and winter 2022-2023; the largest statewide peak in both reported cases and estimated infections occurred in winter 2021-2022. Deconvolved infection estimates followed the same temporal pattern as reported cases and exhibited higher peaks during major surges. Statewide Rt estimates varied over time and were frequently near 1.0, with periods of increasing estimated infections coinciding with Rt values above 1.0 and periods of declining infections coinciding with Rt values below 1.0. The width of the 95% CrIs was greater early in the epidemic and during periods of rapid change in Rt. Sensitivity analyses yielded Rt trajectories similar to those of the primary analysis (Figures S2-S4).

County-level results are shown in Figures S5-S7. All 3 counties exhibited waves occurring at similar times as statewide trends, with differences in magnitude and variability. New Castle County had the highest reported case counts and estimated infections across waves. Kent County exhibited lower counts with more gradual changes. Sussex County showed relatively sharper increases in estimated infections during several waves, including winter 2020-2021 and winter 2021-2022. Rt trajectories were broadly similar across counties but differed in short-term variability, with larger fluctuations observed in Sussex County, comparatively stable trajectories in Kent County, and patterns in New Castle County closely resembling statewide estimates.

Policy-associated percentage changes in Rt are presented in Figure 2 and Table S2, and Rt estimates within major policy time windows are shown in Figure S8. Early pandemic interventions were associated with substantial decreases in Rt; notably, limits on social gatherings (April 2, 2020) and the public mask mandate (April 28, 2020) were associated with statewide decreases of 9.9% (95% CrI: −19.8% to −3.5%) and 13.2% (95% CrI: −16.6% to −6.9%), respectively. Notably, in Sussex County, with the mask mandate, Rt dropped from 1.12 (95% CrI: 1.06 to 1.16) to 0.89 (95% CrI: 0.86 to 0.93). During Phase 1 reopening (June 1, 2020), median Rt changes were small statewide and in Kent and New Castle counties, while Sussex County exhibited a modest increase distinguishable from 0 (median increase 10.1%; 95% CrI: 4.0% to 15.0%). The most consistent increases across jurisdictions were associated with the transition from phased reopening to hybrid school reopening (September 8, 2020), with median Rt increasing by approximately 8% to 11% statewide and across all 3 counties, and all CrIs excluding 0. Finally, the stay-at-home advisory and overnight curfew (December 14, 2020) were associated with a statewide decrease in median Rt of 10.9% (95% CrI: −20.1% to −0.3%), with CrIs also excluding 0 in Kent and New Castle counties.

Stronger associations between Rt changes and policy changes were observed in Sussex County than in New Castle County. Limits on social gatherings and the public mask mandate were associated with substantial Rt reduction (−12.9%, 95% CrI: −23.3% to −5.0%; and −20.5%, 95% CrI: −24.9% to −15.0% respectively) in Sussex County, whereas Rt reductions in New Castle County were modest and statistically not significant (−6.8%, 95% CrI: −17.5% to 0.1%; and −7.2%, 95% CrI: −11.8% to 0.3% respectively). Meanwhile, Phase 1 reopening was associated with a 10.1% (95% CrI: 4.0% to 15.0%) increase in Rt in Sussex County, whereas Rt change was minimal and statistically not significant (−1.4%, 95% CrI: −7.9% to 3.1%) in New Castle County.

Discussion

This analysis examined COVID-19 transmission dynamics in Delaware in 2020-2023, with a focused analysis in 2020 within the context of statewide NPIs implemented across a relatively small,

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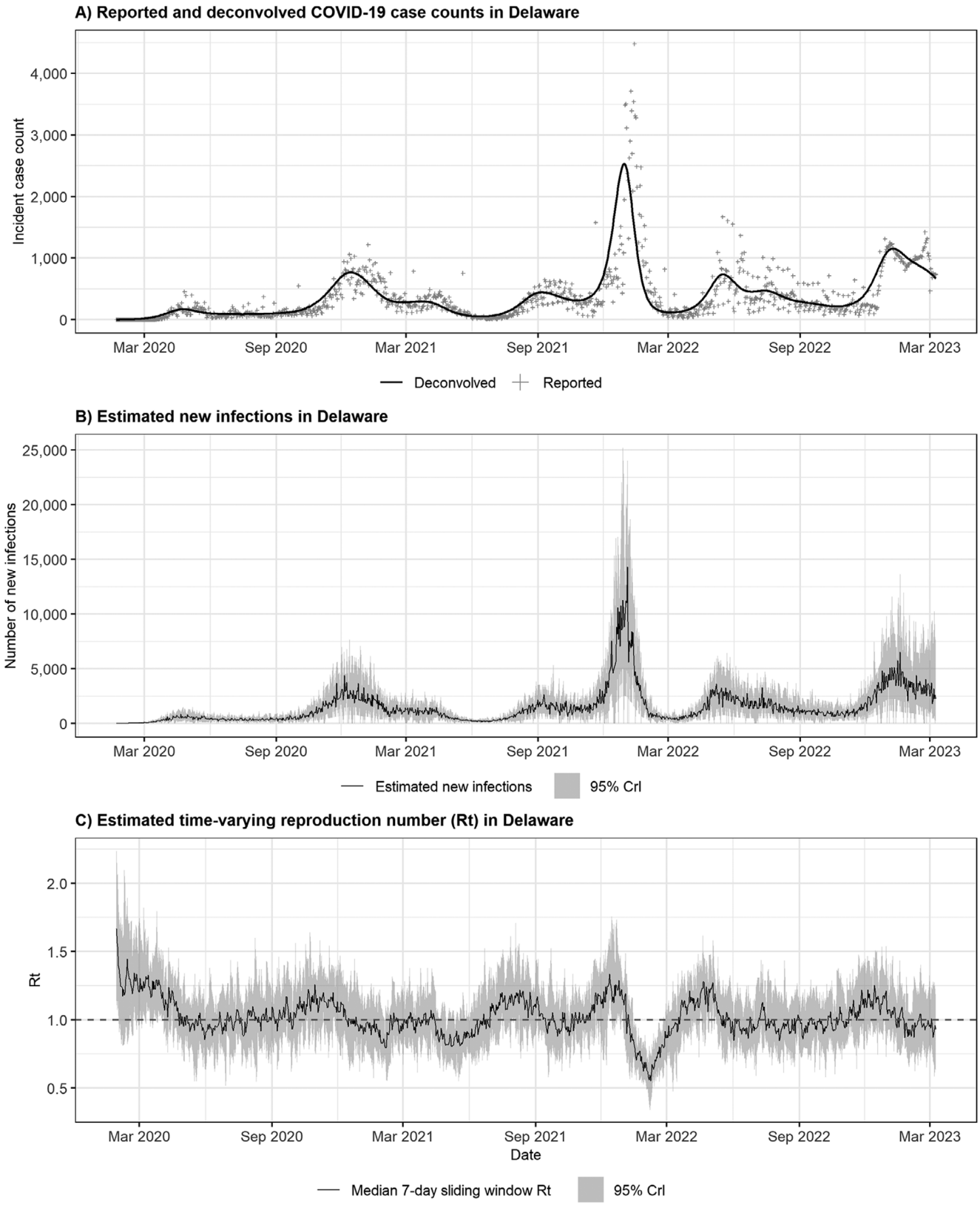


Figure 1. Statewide COVID-19 transmission dynamics in Delaware, March 2020-March 2023. (A) Daily incident case counts (points) compared with the smoothed, deconvolved case trajectory (solid line). (B) Estimated daily number of new infections. (C) Estimated time-varying reproduction number (Rt). In (B) and (C), solid lines represent median estimates, and shaded ribbons indicate 95% credible intervals (CrI). The dashed horizontal line in (C) denotes the epidemic threshold (Rt = 1.0).

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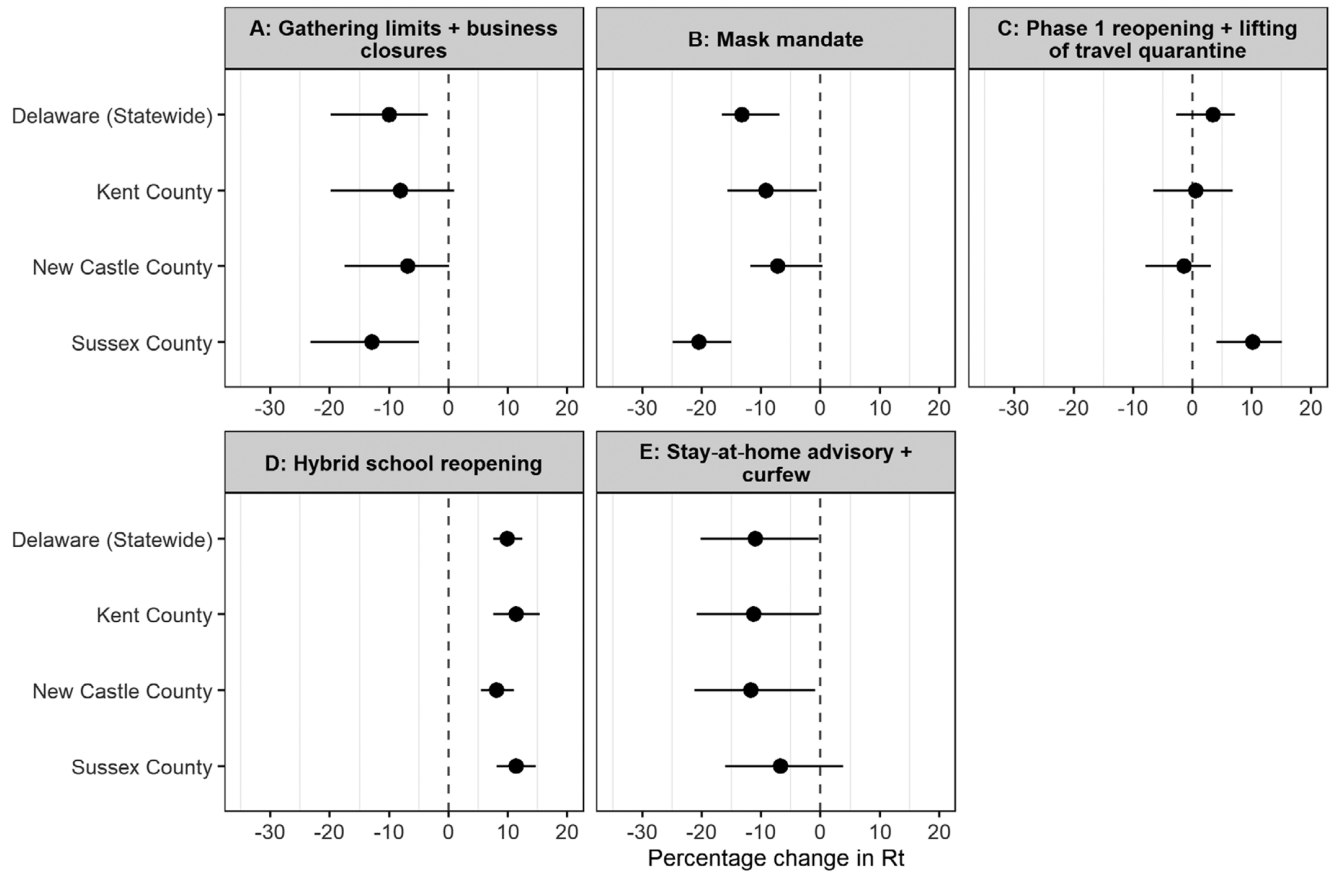


Figure 2. Policy-associated percentage changes in the time-varying reproduction number (Rt) for Delaware and its counties. Points show median percentage changes and horizontal lines show 95% credible intervals (CrI) across transitions between consecutive policy periods. The vertical dashed line indicates no change (0%). Values to the right of the vertical dashed line indicate an increase in Rt, and values to the left indicate a decrease. Policy levels correspond to: (A) Social gathering limits and nonessential business closures (April 2, 2020); (B) Public mask mandate (April 28, 2020); (C) Phase 1 reopening and lifting of out-of-state travel quarantine (June 1, 2020); (D) Hybrid school reopening (September 8, 2020); (E) Stay-at-home advisory and overnight curfew (December 14, 2020).

administratively centralized jurisdiction. In some U.S. states (e.g., South Carolina), counties or municipalities independently determine the timing and adoption of measures such as mask mandates or business restrictions.[5] In Delaware, most major interventions were enacted at the state level and implemented with similar timing across counties, allowing examination of temporal associations between policy changes and transmission dynamics with reduced within-state policy heterogeneity.

The observed patterns are broadly consistent with prior evidence showing that some NPIs have been temporally associated with changes in COVID-19 transmission, while reported changes in Rt vary substantially across settings and analytic approaches. Previous reviews and multi-country analyses documented associations between combinations of interventions, including restrictions on gatherings, business closures, mask mandates, and stay-at-home measures, and changes in Rt, though estimates differed widely depending on context and method.[6,7] Methodological reviews have further emphasized that accurate Rt estimation requires careful consideration of observation delays, generation interval uncertainty, and analytic choices, including assumptions about delays between infection and case reporting and specification of the serial interval, all of which can influence estimates of transmission dynamics and their temporal alignment with policy changes.[8]

County-level differences observed in this study are consistent with prior research showing that Rt can vary across substate geographies within a state, even when interventions are implemented at the state level and evaluated across policy-defined periods.[5,9] Within Delaware, counties differ in population density, economic structure, and mobility patterns, factors that may contribute to variation in observed transmission dynamics despite shared policy timing. Similar heterogeneity has been reported in other U.S. studies evaluating policy-associated changes in transmission at substate levels.[10] As more than half of Delawareans live in the urban New Castle County, its Rt trajectory was less subject to random fluctuations than those of the other two counties and more resembling the statewide trajectory.

Several limitations should be considered. This ecological, observational study cannot establish causal relationships between specific policies and changes in transmission. There is the possibility of ecological fallacy, as associations observed at the aggregate level may not apply at the individual level. Policy changes occurred alongside shifts in individual behavior, testing practices, and risk perception that are not fully captured in reported case data. In addition, county-level estimates are subject to greater uncertainty due to smaller population sizes and lower case counts, as reflected in wider CrIs. Short intervals between some policy transitions further limit our method's ability to isolate the effects of individual policy changes. In addition, overlapping timing of policy measures complicates attribution of observed changes in Rt to specific interventions, as multiple policies and concurrent behavioral changes often

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occurred in close succession. Our choice of a Poisson-distributed multiplier with a fixed mean of 4 throughout the study period assumes a constant underreporting rate; however, underreporting may vary over time. We also used the default time lag distribution from infection to report provided in the *incidental* package, which was derived from a Florida 2020 dataset; the assumption that this distribution applies to Delaware over time may not hold.

Despite these limitations, this study contributes to the literature by providing a focused examination of transmission dynamics in a small U.S. state with relatively uniform policy implementation and meaningful substate heterogeneity. By situating Delaware's experience within the broader evidence on NPIs, the findings highlight the presence of substate variability in transmission dynamics during periods of statewide policy change and demonstrate the utility of Rt-based approaches for monitoring epidemic trends over time.

Conclusions

This study examined COVID-19 transmission dynamics in Delaware during 2020 using Rt estimates to evaluate temporal alignment with major statewide NPIs. Statewide and county-level Rt estimates from March 2020 through March 2023 identified multiple epidemic waves with broadly similar timing but meaningful differences in short-term variability across counties. In 2020, Rt patterns varied across major statewide NPIs and between counties. These findings illustrate substate heterogeneity during periods of statewide policy change and demonstrate how Rt-based estimates can be used to track epidemic dynamics in a U.S. state with a small population.

Supplementary material. The supplementary material for this article can be found at http://doi.org/10.1017/dmp.2026.10451.

Data availability statement. Our data are publicly available from the data source described in the Methods. The R code used to replicate the results reported in this paper is included in the supplementary materials.

Author contribution

- ISTL: Conceptualization, study design, R code writing, data analysis, manuscript writing and editing.
- CAO: Conceptualization, study design, R code writing, data analysis, manuscript writing and editing.
- CRB: Conceptualization, study design, R code writing, data analysis, manuscript writing.
- CMT: Conceptualization, study design, R code writing, data analysis, manuscript writing.
- HMM: Conceptualization, study design, R code writing, data analysis, manuscript writing.
- KOK: Statistical consultation, manuscript editing.
- JXK: Statistical consultation, R code writing, manuscript editing.
- XH: Statistical consultation, R code writing, manuscript editing.
- ANMK: Statistical consultation, manuscript editing.
- GC: Statistical consultation, mentoring, manuscript editing.
- ICHF: Conceptualization, study design, R code writing, project oversight, mentoring, and manuscript writing and editing.

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Competing interests. I. C. H. Fung consulted for Merck & Co., Inc. I. S. T. Lee previously completed an internship at Pfizer, Inc.

Disclaimer. The opinions expressed in this manuscript are those of the authors and do not represent the opinions of the Gates Foundation.

Institutional Review Board Statement. The Georgia Southern University's Institutional Review Board gave this study a nonhuman subjects determination (IRB #H20364, date of approval: 26 February 2020) under the G8 exemption category of Title 45, Part 46 of the Code of Federal Regulations.

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