Assessing the impact of revising MenACWY vaccination schedule for adolescents in the United States: a modelling study

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Summary

Background The current recommendation for MenACWY vaccination against invasive meningococcal disease (IMD) in the United States (US) includes two doses: the first dose at ages 11–12 and a booster dose at age 16. The Advisory Committee on Immunization Practices has proposed options for revising this schedule by either eliminating the first dose or adjusting the timing of the first dose to age 15 and the booster to ages 17–18. The impact of these alternative schedules on IMD incidence remains undetermined.

Methods We developed an age-stratified, agent-based Monte-Carlo simulation model of meningococcal transmission dynamics, parameterised with US age demographics, to assess the impact of the proposed changes to the MenACWY vaccination schedules. Excluding serogroup A, absent in the US for decades, the model included serogroups C, W, and Y for asymptomatic infection (carriage) and vaccine effectiveness against IMD. We calibrated serogroup-specific transmission and IMD development probabilities by fitting the model to reported IMD cases from 1997 to 2004, before vaccine introduction. The calibrated model then simulated the current vaccination schedule (CVS) starting in 2005 and alternative schedules from January 1, 2025 to December 31, 2035, comparing outcomes over the same period.

Findings Switching from the CVS to a single-dose program at age 16 with 61% vaccine uptake (as reported for the booster in 2022) would result in 1062 (95% Uncertainty Range [UR]: 724–1419) additional IMD cases during the 11-year study period. With a case fatality rate of 14.5%, this change could cause an estimated 154 (95% UR: 105–206) additional deaths. Even if vaccine uptake increased to 90% at age 16, the program would still result in 934 (95% UR: 640–1242) additional cases and 135 (95% UR: 93–180) more deaths compared to the CVS. The second alternative schedule (i.e. first dose at age 15, booster at ages 17–18) also increased IMD cases, notably shifting a substantial burden to adolescents aged 11–15 years.

Interpretation Our findings indicate that the current MenACWY vaccination program remains more effective than the proposed alternatives, even with increased vaccine uptake during late adolescence. Improving the uptake rate of the booster at age 16 while maintaining the 11–12-year dose within the existing program would reduce the IMD burden among high-risk adolescents and young adults.

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Keywords: Meningococcal disease; Transmission dynamics; MenACWY vaccination; Simulation

Introduction

In the United States (US), routine adolescent vaccination against invasive meningococcal disease (IMD) caused by *Neisseria meningitidis* (*N. meningitidis*) serogroups A, C, W, and Y began in 2005 with the introduction of the MenACWY conjugate vaccine.

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Research in context

Evidence before this study

In the United States (US), routine adolescent vaccination against invasive meningococcal disease (IMD) caused by *Neisseria meningitidis* serogroups A, C, W, and Y began in 2005 with the introduction of meningococcal quadrivalent conjugate vaccine (MenACWY). Previous research has demonstrated the contribution of vaccination efforts to the declining trend in IMD incidence among adolescents and young adults. The current MenACWY vaccination schedule includes two doses: the first dose is administered at ages 11–12 and the second (booster) dose at 16 years of age. In February 2024, the Advisory Committee on Immunization Practices within the US Centers for Disease Control and Prevention (CDC) proposed alternative vaccination schedules to either (i) replace the current program with a single-dose of the MenACWY vaccine at age 16, or (ii) adjust the age for the first dose to 15 years and the second dose to 17–18 years. We searched MEDLINE and SCOPUS, supplemented with internet searches (Google) between February and September 2024, to identify any studies assessing the proposed schedules in the US for the incidence of IMD in adolescents or other age groups. We found no studies evaluating the potential impact of these alternative schedules compared to the current vaccination program.

Added value of this study

Using an age-stratified transmission dynamic model, we estimated the burden of IMD that would occur if these alternative vaccination schedules were implemented beginning in 2025 compared to the current program, while considering vaccine uptake scenarios that match those reported in 2022 for the first and second doses. We found that both alternative options would lead to an increase in the overall incidence of IMD compared to the current MenACWY vaccination schedule, even if vaccine uptake increased to 90%. The single-dose vaccination program at 16 years of age would generate a substantial burden on population health, with mean estimates of 1062 and 934 cases, respectively, for vaccine uptake rates of 61% and 90% over the 11-year study period from 2025 to 2035. The highest burden of disease was observed among adolescents aged 11–15 years, accounting for at least 52% of the increased IMD cases and 33% of the additional deaths in the population. Similarly, the other alternative schedule, in which the first dose was moved to age 15 years, resulted in overall increases in IMD cases compared to the CVS regardless of the uptake rate for the second dose of vaccine at 17–18 years of age, with over 49% of additional IMD cases occurring among adolescents aged 11–15 years.

Implications of all the available evidence

Our study demonstrates that the current MenACWY vaccination program outperforms the proposed alternative schedules. Eliminating the 11–12-year dose from the MenACWY vaccination program would lead to many more cases and deaths compared with the CVS. Maintaining CVS and improving the uptake of the booster dose at age 16 to match the 90% uptake rate of the first dose could further enhance the program's effectiveness by extending protection during the high-risk period of late adolescence and young adulthood.

Initially, a single dose of MenACWY was recommended for adolescents aged 11–12 years.[1,2] Subsequent studies on bactericidal antibody persistence and vaccine effectiveness indicated that vaccine-induced protection could wane within five years, potentially dropping below protective levels against IMD.[3–5] To ensure continued protection during the high-risk period of late adolescence and young adulthood, the initial recommendation was updated in 2010 to include a booster dose at age of 16.[3]

Vaccination has accelerated the decline in meningococcal disease in the US that began in the late 1990s,[6] reducing the incidence from a peak of 1.2 IMD cases per 100,000 population in 1996 to 0.09 in 2022.[7] The lowest rates of IMD have been observed among adolescents aged 11–15 years, remaining under 0.05 cases per 100,000 population since 2017.[7,8] In February 2024, the Advisory Committee on Immunization Practices of the Centers for Disease Control and Prevention (CDC) presented options for revising the MenACWY vaccination schedule, aiming to optimise protection among college students who are at high risk of IMD, while maintaining harmonisation with existing adolescent vaccination programs.[7] Proposed options include (i) changing the recommendation to a single dose of MenACWY vaccine administered at 16 years of age, and (ii) moving the recommended age for the first dose to 15 years and the second dose to 17–18 years.[7] While the currently low rates of disease among young adolescents 11–15 years and the increased risk of IMD and severe outcomes seen in young adults may appear to support these options, eliminating the first dose or administering it later in adolescence could result in lower vaccine uptake and a reduction in overall herd immunity, potentially leading to an increase in disease incidence.

To assess the impact of these proposed changes to the MenACWY vaccination schedule, we developed an age-stratified, agent-based model to simulate the transmission dynamics of *N. meningitidis* with serogroups C, W, and Y as observed in IMD cases in the US since 1997.[8] The model incorporated vaccination rates and the natural history of meningococcal disease to compare the outcomes of each proposed option with the current vaccination schedule over an 11-year period beginning January 1, 2025, and extending through December 31, 2035.

Methods

We developed an agent-based, Monte-Carlo model to simulate the transmission dynamics of meningococcal disease, caused by *N. meningitidis* serogroups C, W, and Y, within a population of 100,000 individuals reflecting the demographic distribution of the US. The population was stratified into age groups: <1, 1–4, 5–10, 11–15, 16–23, 24–49, 50–64, and ≥65 years. Interactions among individuals were determined using an empirically established contact network,[9–12] with the weekly number of contacts for each individual sampled from an age-specific Negative Binomial distribution (Appendix Table A1). We considered only direct physical contacts for meningococcal transmission[13] and used a distribution matrix for the proportion of such interactions occurring within and between different age groups (Appendix Tables A2–A3).

Transmission dynamics

At any given time, individuals were classified into one of four health states: susceptible, asymptomatic carriers (carriage), invasive meningococcal disease (IMD), and recovered (immune) (Appendix, Figure A1). We modelled transmission only through contacts with individuals in the carriage state, assuming that those who develop IMD from carriage would be isolated. Transmission was serogroup-specific and occurred probabilistically.

Newly infected individuals transition to the carriage state with a risk of developing IMD. The median duration of meningococcal carriage was 42 weeks (corresponding to an estimated 9.6 months),[14] and this duration was sampled for each infected individual from a Poisson distribution (Table 1). Recovery from carriage or IMD provided transient protection against the same serogroup, lasting on average 245 weeks (approximately 4.7 years),[15] which was sampled for each individual from a Poisson distribution. Natural protection from one serogroup was assumed to also confer 20% cross-protection against infection with other serogroups.[16,17] Based on prior estimates for serogroup C,[18] we assumed that individuals could be infected with any serogroup at most twice in their lifetime.

Vaccination schedules

We implemented the current vaccination schedule (CVS) of MenACWY in the model, with the first dose administered at ages 11–12 and a second (booster) dose given at age 16. The annual vaccine uptake for the first dose increased from 13% in 2005 to 90% in 2022.[8,19] For the second dose, vaccine uptake rose from 6% in 2010 to 61% in 2022 among adolescents aged 17 years.[8,19] We maintained the uptake rates reported in 2022 for simulating the CVS forward in time, and restricted booster dose eligibility to individuals who received their first dose at ages 11–12.

For the first proposed revision to the vaccination schedule (RVS1), the model was updated to eliminate the provision of the first dose of MenACWY at 11–12 years of age but include the administration of a single dose of MenACWY vaccine at age 16 beginning in 2025, with a 61% uptake rate (RVS1-61), matching the reported uptake in 2022 for the second dose in the CVS. Additionally, we simulated this revised schedule with a higher uptake of 90% (RVS1-90), corresponding to the vaccine uptake reported for the first dose in the CVS.

To implement the second proposed revision to the vaccination schedule (RVS2), the model adjusted the age for the first dose of MenACWY to 15, with the second dose being administered at age 17. This proposed schedule began in 2025 and was adopted for those who were under 11 years of age in 2024. Those who had received their first dose of the vaccine at age 11 prior to 2025 were offered the second dose at age 16, following the CVS with 61% uptake. In RVS2, the vaccine uptake for the first dose at age 15 was set to 90%, consistent with the uptake observed in the CVS at ages 11–12. For the second dose at age 17, we simulated two uptake rates, one of 61% (RVS2-61) and another of 90% (RVS2-90).

Parameter Description	Mean Estimate	Distribution	Source
Duration of carriage	42 weeks	Poisson (42)	14
Duration of protection after recovery	245 weeks	Poisson (245)	15
VE against carriage	41%	Beta (1148.6, 1654.3)	20,21
MenACWY-TT VE against IMD			
ACWY	94%	Beta (18.7240, 1.2464)	22,23
MenACWY-DT VE against IMD			
serogroup C	77.0%	Beta (18.6884, 5.5822)	5
serogroup W	71.5%	Beta (5.5250, 2.1869)	Derived[a]
serogroup Y	51.0%	Beta (2.5293, 2.4301)	5
Duration of vaccine protection	261 weeks	Poisson (261)	5

VE: vaccine effectiveness. [a]See the derivation of vaccine effectiveness against serogroup W in Appendix.

Table 1: **Description of the parameter values and their associated distributions.**

Vaccine effectiveness

Prior to the approval of the MenACWY-TT (tetanus toxoid) vaccine in 2020, the MenACWY-DT (diphtheria toxoid) vaccine was used in US vaccination programs. We therefore incorporated both vaccines in our main analysis: MenACWY-DT was used for the period from 2005 through 2019, transitioning to MenACWY-TT in 2020 and thereafter. As a secondary analysis, we examined scenarios where only MenACWY-DT was utilised.

Vaccine effectiveness (VE) against nasopharyngeal carriage for all serogroups was sampled from a Beta distribution (Appendix) for each individual, with a mean of 41%.[20,21] This effectiveness was applied for both MenACWY-DT and MenACWY-TT vaccines, and was implemented as a reduction factor in disease transmission. We assumed that VE against carriage would last for an average of 261 weeks (approximately 5 years), which was also sampled for each vaccinated individual from a Poisson distribution (Table 1).

For MenACWY-DT, VE against IMD was serogroup specific, with mean values of 77%, 71.5%, and 51.0% for serogroups C, W, and Y, respectively (Table 1),[5] sampled from their respective Beta distributions for each vaccinated individual. Given the wide uncertainty intervals regarding the VE of MenACWY-TT against IMD for individual serogroups,[22] we relied on the overall VE of 94% (Table 1),[22,23] sampled from the corresponding Beta distribution for each vaccinated individual. The duration of vaccine-induced protection against IMD after each dose was sampled from a Poisson distribution, lasting for an average of 5 years (Table 1).[5]

Model implementation and calibration

We implemented the model using the Julia programming language and employed a two-stage calibration process to determine transmission parameters used for simulating vaccination scenarios. In the first stage of calibration, we initialised the model with the estimates of carriage prevalence rates in different age groups[24] and serogroup-specific transmission probabilities per contact to achieve a steady state over a 30-year time horizon, thereby establishing herd immunity and stabilising the stochastic effects. After achieving the steady state, we fitted the model to IMD case data across all serogroups over the eight-year period from 1997 to 2004 (Fig. 1). An optimisation process—minimizing the squared error loss between the observed and simulated IMD cases—was employed to derive the optimal serogroup-specific transmission probabilities and estimate the probability of developing IMD. While capturing the temporal decline in IMD cases, the calibrated model produced a peak carriage prevalence of 11.3% in the population, distributed as 42.7% for serogroup C, 4.4% for W, and 52.9% for Y at the peak in 1997, reflecting the average proportions observed in IMD data. In subsequent simulations, the probability of developing IMD was applied to unvaccinated individuals who contracted infection. For vaccinated individuals, this probability was reduced based on the serogroup-specific VE if infection occurred during the vaccine protection period.

Following the calibration process (Fig. 1), the model was simulated from 2005 through 2035 under various vaccination schedules, successfully replicating the trend for each serogroup (Appendix Figure A4). For each alternative schedule beginning in 2025, we assessed the difference in cumulative IMD cases by comparing with the CVS across different age groups and the overall population. To account for stochasticity and sensitivity of parameter values, we performed 500 independent Monte-Carlo simulations, each involving the sampling of individual–level parameters from relevant distributions (Table 1). Pairwise simulations were then used to calculate the mean and 95% uncertainty range of estimates over the 11-year study period from January 1, 2025 through December 31, 2035. This analysis period was selected to account for the average five-year duration of vaccine-induced protection for each dose administered five years apart. The computational model is available at http://github.com/affans/imd_abm.

Ethics

Data provided by the CDC had no identifiable personal information, and thus no ethical approval or informed consent was required in accordance with York University research ethics guidelines for program evaluation activities relying on secondary use of anonymous data.

Role of the funding source

Thomas Shin is an employee of Sanofi and participated in formulating research questions, interpreting the results, and reviewing the manuscript. The funders had no role in the study design, methods, data analysis, or decision to submit for publication.

Results

We estimated that continuing with the CVS using MenACWY-TT would result in a mean total of 2821 (95% Uncertainty Range [UR]: 2293–3882; standard deviation [SD] = 402) cases of IMD caused by serogroups C, W, and Y from 2025 to 2035.

Eliminating the first dose (RVS1)

We estimated that RVS1-61 would lead to a mean increase of 1062 (95% UR: 724–1419; SD = 175) additional cases of IMD compared to the CVS over the 11-year time horizon (Table 2). Maximum incidence was projected to occur at the end of the simulation time frame, with a mean of 390 (95% UR: 270–484; SD = 51) IMD cases (Fig. 1A). Among age groups, the largest number of cases was estimated among adolescents aged 11–15 years, with a mean of 557 (95% UR: 441–645, SD = 46) during the simulated time period. Considering case fatality rates of 9.1% and 11.6% previously derived from

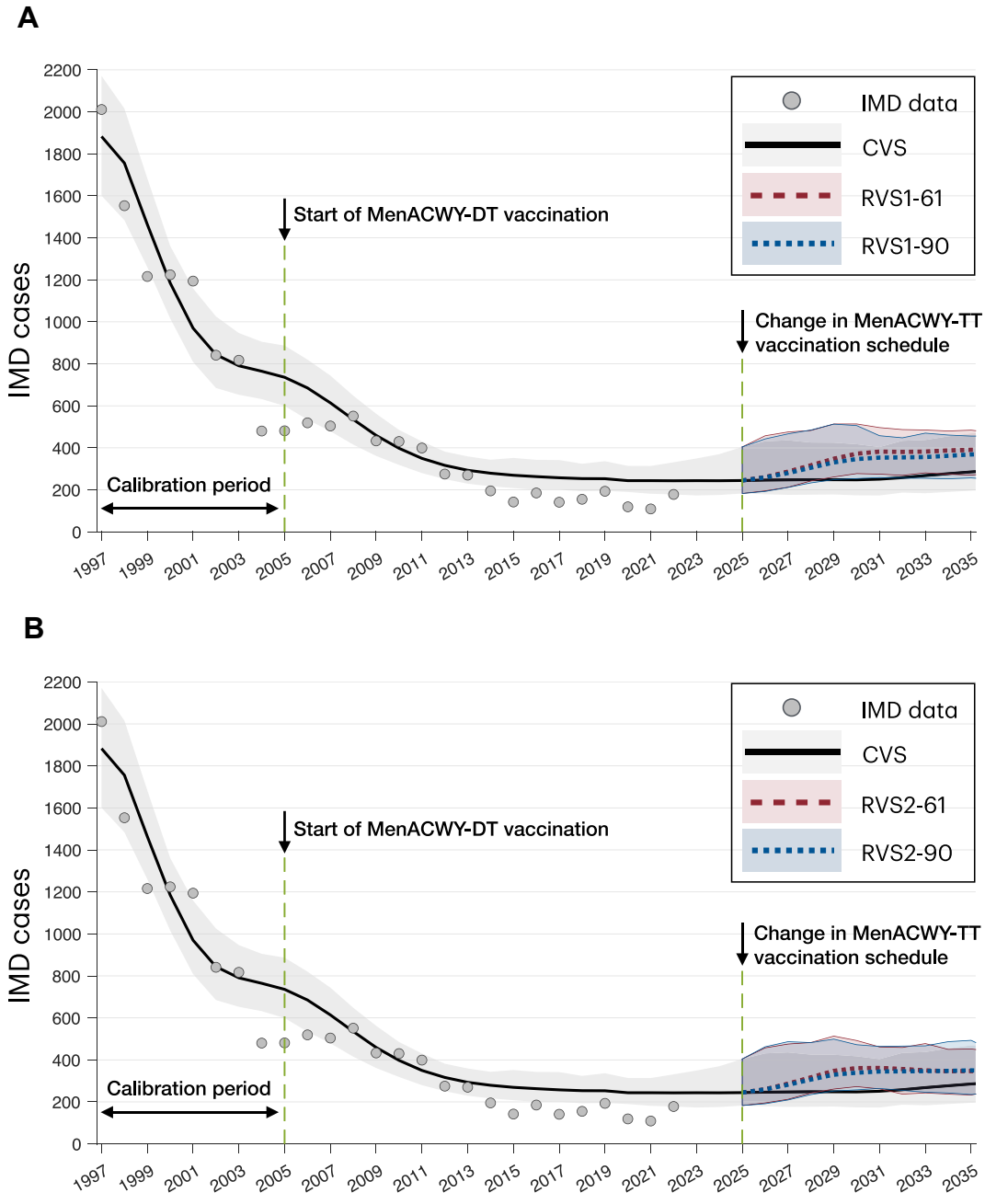

Fig. 1: Comparison of simulated IMD cases under the current vaccination schedule (CVS) and revised schedules of (A) a single-dose program administered at age 16 (RVS1), and (B) adjusting the age for the first dose to 15 and the second dose to 17–18 (RVS2). The simulation assumes the use of MenACWY-DT from 2005 through 2019, transitioning to MenACWY-TT from 2020 onward.

data for the age groups 11–15 and 16–23 years[8] respectively, we estimated means of 51 (95% UR: 40–59; SD = 4) and 15 (95% UR: 9–20; SD = 3) additional deaths, compared to CVS. At the population level, using an overall case fatality rate of 14.5%,[8] we estimated a mean total of 153 (95% UR: 105–206; SD = 25) additional deaths.

RVS1-90 also resulted in a higher incidence of IMD than the CVS, with an estimated mean of 934 (95% UR: 640–1242; SD = 170) additional cases over the 11 years (Table 2) and a maximum incidence of 368 (95% UR: 257–456; SD = 50) cases occurring in 2035 (Fig. 1A). The largest number of IMD cases occurred among those aged 11–15 years, with a mean of 550 (95% UR:

Revised vaccine schedule	IMD cases by age, years (95% uncertainty range)					
	0–10	11–15	16–23	24–49	≥50	Overall
RVS1-61	186 (23–363)	557 (441–645)	126 (80–175)	130 (58–206)	63 (27–102)	1062 (724–1419)
RVS1-90	186 (31–397)	550 (452–622)	18 (1–54)	123 (55–206)	57 (21–94)	934 (640–1242)
RVS2-61	172 (23–356)	545 (438–625)	29 (3–69)	113 (50–184)	57 (22–93)	916 (620–1242)
RVS2-90	167 (18–386)	536 (433–615)	5 (0–13)	103 (34–189)	50 (16–88)	861 (506–1198)

Table 2: **Estimated mean and 95% uncertainty range of additional cases of IMD under revised MenACWY-TT vaccination schedules of RVS1 and RVS2 compared to the current vaccination schedule (CVS) over the 11-year period from 2025 to 2035.**

452–622; SD = 42). However, the additional burden of IMD was significantly lower (by 86%) among those aged 16–23 years, decreasing from 126 (95% UR: 80–175; SD = 24) under RVS1-61 to 18 (95% UR: 1–54; SD = 14) under RVS1-90. Compared to the CVS, we estimated means of 50 (95% UR: 41–57; SD = 4) and 2 (95% UR: 0–6; SD = 2) additional deaths would occur among age groups 11–15 and 16–23 years, respectively. At the population level, the mean additional deaths under RVS1-90 was estimated to be 135 (95% UR: 93–180; SD = 25).

Assessing the temporal trend in IMD incidence over the simulated time horizon, we observed an annual increase in additional cases following the implementation of RVS1, with a peak occurring within five to seven years. Under both scenarios of 61% and 90% vaccine coverage among adolescents aged 16 years, additional cases exceeded an average of 100 across all age groups at their peak compared to the CVS (Fig. 2).

Changing the age for two-dose vaccination (RVS2)

Similar to what was observed in the RVS1 scenarios, we found that RVS2 resulted in additional cases of IMD compared to the CVS (Table 2). We estimated that RVS2-61 would result in a mean of 916 (95% UR: 620–1242; SD = 162) additional IMD cases, approximately 14% lower than that with RVS1-61. This reduction is primarily due to a more than 77% decrease in IMD cases among those aged 16–23 years that would directly benefit from this two-dose schedule. The peak incidence was projected to occur in 2031 with a mean of 362 (95% UR: 262–462; SD = 49) cases (Fig. 1B). The increased mortality in the population, if RVS2-61 is implemented, was estimated at mean of 133 (95% UR: 90–180; SD = 23) deaths, with over 37% of them occurring among adolescents aged 11–15 years.

With the increased vaccine uptake assumed for scenario RVS2-90, the overall burden of IMD compared to the CVS was estimated to result in a mean of 861 (95% UR: 506–1198; SD = 177) additional cases and 118 (95% UR: 73–174; SD = 26) more deaths (Table 2). The incidence of IMD in the 16–23-year age group decreased by 83% in RVS2-90 compared to RVS2-61. Adolescents aged 11–15 years accounted for 62% of estimated cases and 39% of deaths over the study period. The peak incidence in RVS2-90 was projected to occur in 2035 with a mean of 350 (95% UR: 235–493; SD = 51) cases (Fig. 1B).

Secondary analyses

We simulated the model using reduced VE against IMD, reflecting serogroup-specific estimates for the MenACWY-DT vaccine over the entire analysis period (Appendix Figure A5). Comparing the CVS with the

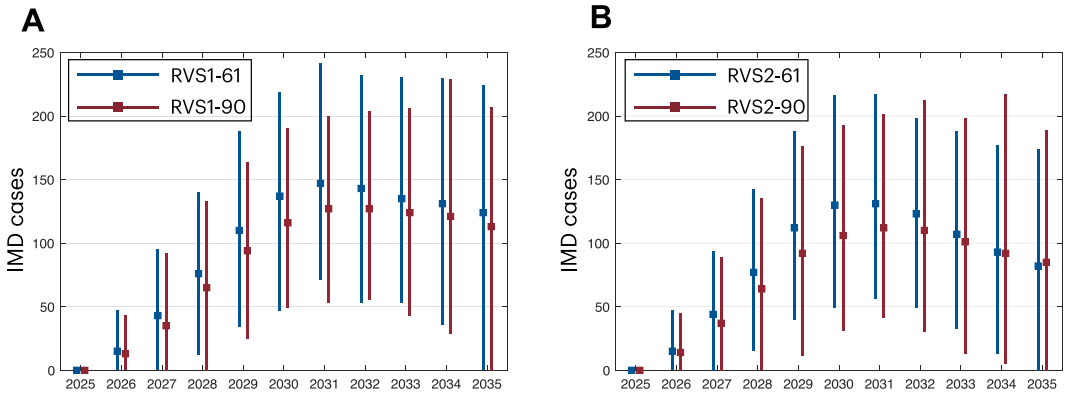

Fig. 2: Estimated annual increase in the number of IMD cases with 95% uncertainty range, comparing the revised vaccination schedules in RVS1 (A) and RVS2 (B) with the current vaccination schedule (CVS) using the MenACWT-TT vaccine.

revised schedules, we obtained similar estimates for additional IMD cases and deaths that would occur over the 11-year period across different age groups (Appendix Table A4). The temporal trends in additional IMD cases mirrored those observed under RVS1 and RVS2 with the MenACWY-TT vaccine during the same period (Appendix Figure A6).

For comparison, we used the model to simulate a situation in which the age for the second dose was adjusted to either 15 or 17 years. Both scenarios resulted in higher IMD cases throughout the study period, indicating that administering the booster dose at age 16 as done in the CVS is optimal. We further assessed the model's outcomes if the CVS maintained, but the uptake for the booster dose of MenACWY-TT at age 16 was increased to 90%. Over the 11-year study period, we estimated that a mean of 413 (95% UR: 148–1198; SD = 272) cases of IMD and 60 (95% UR: 21–174; SD = 39) deaths would be averted compared to the current situation in which the uptake for the second dose at 16 is 61% (Appendix Table A5). Similar results were obtained for the MenACWY-DT vaccine.

Discussion

Our study, which utilised a dynamic transmission model, demonstrates that the proposed alternative schedules for routine adolescent MenACWY vaccination would lead to a higher incidence of IMD and an associated increase in mortality compared to the current schedule. Initially, the annual increase in IMD cases would be minimal, largely attributable to residual protection from prior vaccination or natural infection. However, we observed a peak in IMD incidence within 5–10 years after implementing alternative schedules. Revised schedules would notably shift a substantial burden of meningococcal disease to adolescents aged 11–15 years, a group that currently experiences the lowest IMD rates under the existing vaccination program. These findings indicate that the current schedule is more effective than the proposed alternatives, even if the vaccine uptake rates can be maintained at a high level or increased during late adolescence.

In addition to increasing the burden of IMD, alternative vaccination schedules evaluated here would likely face logistical challenges for program implementation. Historically, as evidenced by the significant drop in uptake rates for the second dose of MenACWY, vaccines administered in later adolescence have lower uptake rates compared to those offered at younger ages.[2,25] If alternative schedules result in uptake rates lower than those observed for the first or second dose in the current MenACWY program, the burden of IMD could be even higher than those estimated in our analysis. Additionally, this burden may be exacerbated by uneven vaccine uptake among different geographic regions and racial groups,[19,26,27] potentially disproportionately affecting those with lower vaccination uptake rates. These factors necessitate further analysis to evaluate equity concerns and optimise protection across age and demographic groups.

Limitations

Although our study uses a dynamic model to account for both the direct and indirect (herd) effects of vaccination, it has several limitations. First, we assumed equivalent levels and durations of protection for both first and second vaccine doses due to limited evidence differentiating their effectiveness. This assumption may underestimate the added protection potentially offered by a prime-boost schedule in RVS2. Second, we treated vaccine effectiveness for each individual as a constant over the sampled duration of protection; however, evidence indicates that protection wanes over time, typically declining between 3 and 8 years.[5] In our model, this decline over time is captured at the population-level as we sample the duration of protection at the individual level. Third, we modelled the durations of immune protection following vaccination and natural infection using Poisson distributions, which are slightly right-skewed. Our estimates may vary if the skewness of these distributions increases significantly. Fourth, we assumed that individuals who recover from natural infection are fully protected against reinfection by the same serogroup for a sampled duration of immunity. Fifth, our study focused on vaccine-targeted serogroups to assess the impact of changes in vaccination schedules; however, immunisation with other vaccines (e.g., MenB) or infection caused by other serogroups may provide some cross-protection against serogroups ACWY, potentially influencing our estimates.[28] Sixth, we assumed a single probability of developing IMD in our analysis, although this probability may differ between serogroups and across age groups. Lastly, we excluded the possibility of rare co-infections with multiple serogroups occurring simultaneously.

Conclusion

Our findings indicate that the proposed revisions to the current MenACWY vaccination schedule would lead to a higher incidence of IMD and increased mortality. The alternative schedules disproportionately increase the disease burden among adolescents aged 11–15 years. Thus, maintaining the existing schedules is recommended as the more effective vaccination program.

Contributors

SMM and AS 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. SMM and APG were responsible for the decision to submit the manuscript.

Study conceptualisation and design: SMM, TS, APG.
Model framework design: SMM, AS, CRW.
Data curation and input parameters: LP-S, CRW, SMM.

Computational model: AS.
Statistical analysis: AS, CWR, SMM.
Analysis and interpretation of the results: All authors.
Drafting of the manuscript: All authors.
Obtaine funding: SMM, APG.

Data sharing statement

The computational model is available at http://github.com/affans/imd_abm.

Declaration of interests

SM Moghadas previously had advisory roles for Janssen Canada and Sanofi for cost-effectiveness of their products. A Shoukat, SM Moghadas and AP Galvani have received consulting fees from Sanofi for evaluation of vaccine products. T Shin is an employee of Sanofi. Other 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.2025.101033.

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