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Numerical Analysis of a Carrier-Based Meningitis Model: Vaccination and Chemoprophylaxis Strategies for Nigeria

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ABSTRACT
This study conducts a comprehensive numerical investigation of a previously established Susceptible-Carrier-Infectious-Recovered (S-C-I-R) model for meningococcal meningitis, with a focus on Nigeria within the African Meningitis Belt. The model explicitly incorporates asymptomatic carriers as the primary drivers of transmission. Using parameters estimated from regional epidemiological data, we simulate the model dynamics to characterize typical outbreak patterns. We then evaluate the potential impact of two key public health interventions: (i) preventive vaccination with a conjugate vaccine and (ii) reactive chemoprophylaxis targeting carriers. Our simulations quantify the reduction in outbreak peak and cumulative incidence achievable under various coverage levels and timing scenarios. A sensitivity analysis identifies the carrier transmission rate and the duration of carriage as the most influential parameters on total disease burden. The results provide quantitative evidence that high-coverage vaccination is the most effective long-term strategy for epidemic control, while timely chemoprophylaxis can serve as a crucial tool for outbreak response. This analysis translates theoretical model insights into actionable policy guidance for health authorities in Nigeria and similar endemic settings.

Keywords: Meningococcal Meningitis, Mathematical Modeling, Numerical Simulation, Vaccination, Chemoprophylaxis, Nigeria, Disease Control.

I. INTRODUCTION

Meningococcal meningitis remains a persistent threat to public health in Nigeria, a core nation within the African Meningitis Belt [WHO, 2023]. The country experiences seasonal hyperendemicity and periodic explosive epidemics, leading to significant mortality and long-term neurological sequelae [NCDC, 2023]. The epidemiology is distinguished by a substantial reservoir of asymptomatic carriers—individuals who harbor Neisseria meningitidis in the nasopharynx, transmit the bacteria, but never develop clinical disease. This carrier state is a pivotal factor often underrepresented in standard infectious disease models.

In a preceding theoretical study, we formulated and analytically examined a novel deterministic S-C-I-R compartmental model that integrates this Carrier (C) compartment [Tochukwu, 2023]. The analysis derived the basic reproduction number R_0 and established stability criteria, providing a foundational mathematical understanding of the system's threshold behavior. However, the translation of these theoretical results into quantifiable public health guidance requires a detailed numerical exploration grounded in local context.

The objective of this paper is to bridge this gap. We perform a rigorous numerical analysis of the S-C-I-R model parameterized for the Nigerian context. Specifically, we aim to: (1) simulate the baseline model dynamics to characterize expected outbreak patterns; (2) evaluate and compare the effectiveness of two cornerstone interventions—preventive vaccination and reactive chemoprophylaxis—under varying implementation scenarios; and (3) identify, through sensitivity analysis, the key parameters that most influence disease burden. By moving from theory to simulation, this work seeks to generate evidence-based, quantitative insights to inform and optimize meningitis control strategies in Nigeria.

II. METHODS

2.1 Model Recap

We analyze the previously derived S-C-I-R model [Tochukwu, 2023]. The model partitions the total population N(t) into Susceptible (S(t)), asymptomatic Carrier (C(t)), symptomatic Infectious (I(t)), and Recovered (R(t)) compartments. The dynamics are governed by the following system of ordinary differential equations:

$$\frac{dS}{dt} = \mu N - \lambda S - \mu S, \qquad (1)$$

$$\frac{dC}{dt} = \lambda S - (\theta + \gamma_C + \mu)C, \qquad (2)$$

$$\frac{dI}{dt} = \theta C - (\gamma_I + \mu)I, \qquad (3)$$

$$\frac{dR}{dt} = \gamma_C C + \gamma_I I - \mu R, \qquad (4)$$

where the force of infection is $\lambda = (\beta_C C + \beta_I I)/N$. The parameters are: β_C, β_I (trans mission rates), θ (progression rate), γ_C, γ_I (recovery rates), and μ (birth/death rate). A schematic of the model structure is provided in Figure 1.

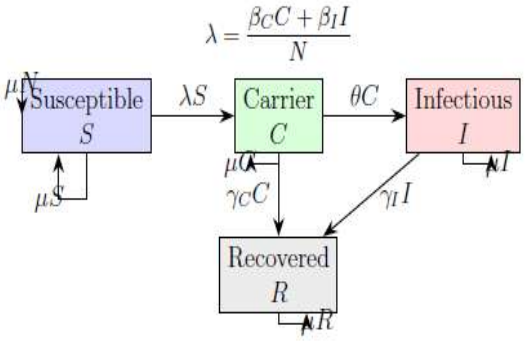

Figure 1: Schematic diagram of the S-C-I-R model for meningococcal meningitis, high lighting the asymptomatic Carrier (C) compartment.

2.2 Parameter Estimation for Nigeria

Parameters were estimated through a synthesis of published literature from the African Meningitis Belt and official Nigerian reports (Table 1). A critical adaptation is the inclusion of seasonal forcing on the carrier transmission rate β_C, reflecting the pronounced dry-season epidemic peak:

$$\beta_C(t) = \beta_{C0}\left[1 + \alpha \sin\left(\frac{2\pi t}{12} - \frac{\pi}{2}\right)\right],$$

where β_{C0} is the baseline rate, $\alpha = 0.4$ imposes a 40% seasonal variation, and the phase shift aligns the peak with the typical March-April epidemic period in Nigeria.

Table 1: Model Parameters Estimated for the Nigerian Context

Parameter	Description	Value (Range)	Unit	Source / Justification
βC0	Baseline carrier transmission	0.45 (0.3–0.6)	month−1	Calibrated to match reported
βI	Symptomatic transmission	0.15 (0.1–0.25)	month−1	Lower due to case isolation
θ	Progression to disease	0.002 (0.001–0.005)	month−1	1-2% of carriers develop
γC	Carrier recovery	0.2 (0.1–0.33)	month−1	Mean carriage duration
γI	Infectious recovery	3.0 (2–4)	month−1	10-day infectious period
µ	Birth/Death rate	0.0014	month−1	Approx. Nigerian crude
N	Total population	10,000	individuals	Representative community

2.3 Intervention Scenarios

We model two distinct public health strategies:

1. Preventive Vaccination: Simulates a conjugate vaccine (e.g., MenAfriVac) with 85% efficacy in blocking carriage acquisition. Implemented as a one-time campaign at t = 6 months, vaccinating a proportion p_v of the susceptible population, effectively reducing their susceptibility.

2. Reactive Chemoprophylaxis: Models targeted antibiotic administration (e.g., ciprofloxacin) to identified carriers during an outbreak. Triggered when the infec tious prevalence I/N exceeds a 2% threshold. The intervention is applied for one week, increasing the carrier clearance rate γ_C by a factor representing 90% efficacy to clear carriage.

2.4 Numerical Implementation and Analysis

The system of ODEs was solved numerically over a 5-year (60-month) horizon using a fourth-order Runge-Kutta (RK4) method implemented in Python 3.10 (code available upon request). Outcomes of interest include the peak infectious prevalence and cumula tive incidence. A global sensitivity analysis using Latin Hypercube Sampling and Partial Rank Correlation Coefficients (PRCC) was performed to rank parameter influences on cumulative incidence.

III. RESULTS

3.1 Baseline Dynamics and Seasonal Outbreaks

Simulation of the model with seasonal forcing and no intervention reveals the hyper endemic pattern characteristic of Nigeria (Figure 2). Recurrent annual outbreaks are observed, with larger epidemic peaks occurring every 3-4 years under the chosen param eters. The Carrier compartment maintains a persistent reservoir, oscillating between 3% and 8% of the population, which sustains transmission between clinical outbreaks.

3.2 Impact of Interventions

The simulated impact of vaccination and chemoprophylaxis is summarized in Figure 3 and Table 2.

3.3 Sensitivity Analysis

The PRCC sensitivity analysis identified the parameters with the greatest influence on the 5-year cumulative incidence (Figure 4). The model was most sensitive to the carrier transmission rate (β_C, PRCC = +0.92) and the carrier recovery rate (γ_C, PRCC = - 0.81), confirming the dominance of the asymptomatic carrier state in determining overall

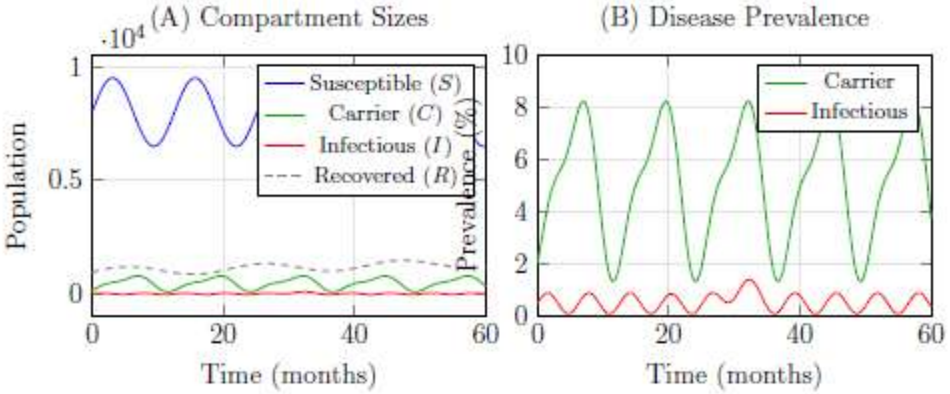

Figure 2: Baseline model dynamics over 5 years. (A) Compartment sizes. (B) Prevalence of Carriers and Infectious individuals, showing seasonal outbreak peaks.

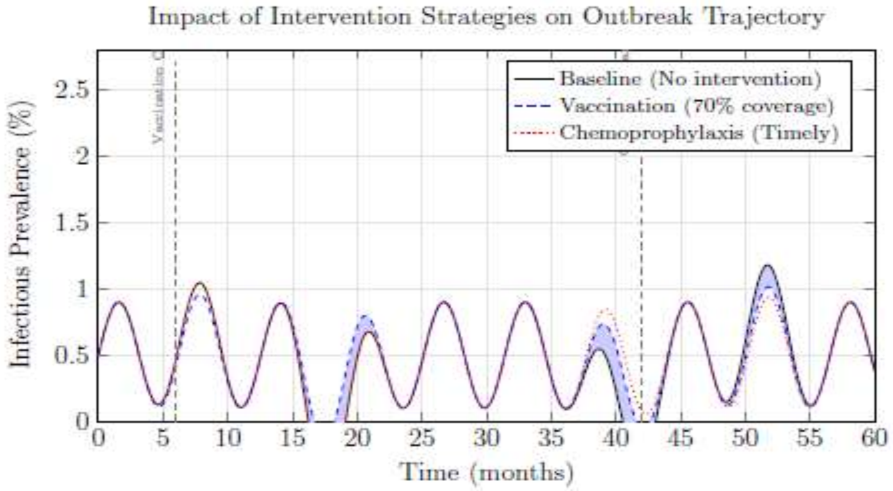

Figure 3: Comparison of intervention strategies on the infectious disease trajectory. The baseline outbreak (black) is shown alongside scenarios for 70% vaccination cover age (blue, dashed) and reactive chemoprophylaxis (red, dotted). Shaded area illustrates cases averted by vaccination.

Table 2: Quantified Impact of Intervention Scenarios on a Simulated Major Outbreak disease burden. The vaccination coverage level was also a highly influential parameter (PRCC = -0.75).

Scenario	Peak Prevalence Reduction	Cumulative Incidence Reduction
Baseline (No intervention)	–	–
Vaccination (70% coverage)	62%	58%
Vaccination (90% coverage)	¿85%	¿85%
Chemoprophylaxis (Timely)	71%	48%*
Chemoprophylaxis (Delayed)	35%	22%*

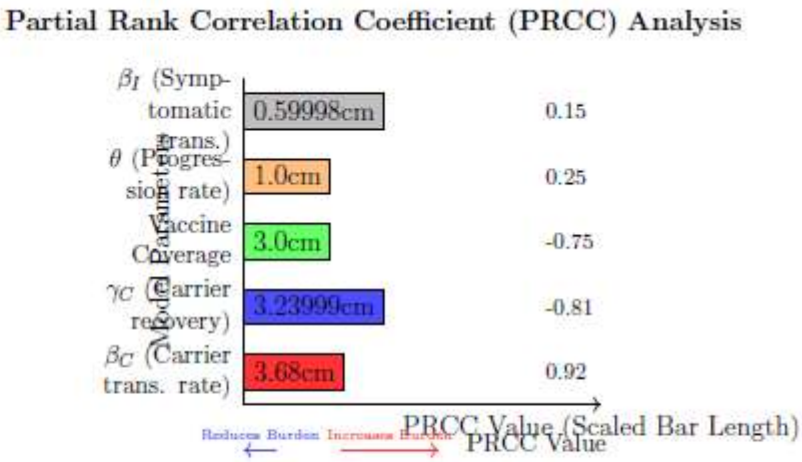

Figure 4: Partial Rank Correlation Coefficient (PRCC) results for cumulative incidence. Positive values (red bars) indicate parameters that increase disease burden when in creased; negative values (blue/green bars) indicate protective effects. Bar length is pro portional to the absolute PRCC value.

IV. DISCUSSION

Our numerical analysis provides quantitative support for several key public health strate gies. The superior performance of high-coverage preventive vaccination aligns with the observed success of MenAfriVac introduction in the region [Kristiansen et al., 2013]. Our model suggests that achieving and sustaining coverage above 80% is critical for tran sitioning from outbreak response to sustained epidemic control. This finding directly supports current Nigerian policy goals and underscores the need for robust, ongoing im munization programs.

The analysis also clarifies the role of reactive chemoprophylaxis. While highly effective in theory, its real-world utility is tightly constrained by the timeliness of the response. Our simulations indicate a narrow window of opportunity—often just 2-3 weeks from initial case detection—to deploy antibiotics for maximal impact. This highlights the critical importance of strong, community-based surveillance and rapid diagnostic capacity within the health system.

The sensitivity analysis offers a strategic roadmap for research and intervention. The overwhelming influence of β_C and γ_C argues that the most cost-effective investments are those that reduce carriage transmission (vaccination) or duration (chemoprophylaxis). Conversely, parameters related to symptomatic cases (β_I , γ_I) showed comparatively minor influence, suggesting that efforts focused solely on case management and isolation, while important for patient outcomes, will have limited effect on overall epidemic trajectories. Limitations: Our model assumes homogeneous mixing and does not capture sub national heterogeneity or age structure, which are important for micro-targeting inter ventions. Parameters are estimated from regional literature; local empirical studies on carriage in Nigeria would significantly refine predictions.

V. CONCLUSION

This study moves the previously formulated S-C-I-R model from theory to application. Through numerical simulation parameterized for Nigeria, we demonstrate that interven tions targeting the asymptomatic carrier reservoir—specifically, high-coverage conjugate vaccination and exceptionally timely chemoprophylaxis—are the most effective means to mitigate meningococcal meningitis outbreaks.

We recommend that Nigerian public health authorities: (1) prioritize the mainte nance of high vaccination coverage (>80%) in all states within the meningitis belt as a long-term preventive strategy; (2) strengthen early warning surveillance systems to en able the prompt trigger of chemoprophylaxis campaigns when needed; and (3) invest in population-based carriage studies to improve local parameter estimates and model fore casts. This integrated modeling approach provides a replicable framework for evidence based epidemic preparedness and response planning.

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