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Enhancing Dengue Control: Vaccination, Treatment, and Integrated Strategies

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1 Abstract

This paper presents a mathematical model to explore the interplay between vaccination and treatment strategies to control dengue fever, a significant public health concern in tropical and subtropical regions. The study employs an SVITR compartmental model (Susceptible, Vaccination, Infectious, Treatment, Recovered) to analyze dengue transmission dynamics and assess the effectiveness of various intervention strategies. Key findings indicate that while a highly effective vaccine can significantly reduce dengue cases, treatment becomes more critical when the efficacy of the vaccine is low. The results show the advantages of combining vaccination and treatment to optimize disease control, providing valuable information for public health policy.

2 Introduction

Dengue fever, caused by the dengue virus and transmitted primarily by Aedes mosquitoes, poses a considerable health threat globally, particularly in tropical and subtropical regions. The increasing frequency of dengue outbreaks requires effective intervention strategies to manage its transmission. This study develops a mathematical framework that captures the dynamics of dengue transmission while assessing the combined effects of vaccination and treatment. Realistic numerical analyses validate the model and explore the effects of vaccine efficacy and treatment rate on epidemic growth. Figure 1 illustrates the SVITR (Susceptible, Vaccination, Infectious, Treatment, Recovered) compartmental model, providing a visual representation of the different states in the model and how human (h) and vector (v) transition between them . The model assumes a single serotype dengue without secondary infections, granting lifelong immunity to recovered individuals. Transmission occurs through mosquito bites.

This work departs from previous research by uniquely focusing on the combined impact of vaccination and treatment. Unlike earlier works that primarily analyzed these interventions separately, it demonstrates that combining them significantly outperforms single approaches in mitigating disease spread [1–3]. The study introduces global sensitivity and optimal control analyses to identify key parameters influencing transmission

and optimize intervention strategies over time. Additionally, it addresses the underexplored scenario of low vaccine efficacy, highlighting the critical role of treatment in such cases. By validating the model with real dengue data from Kaohsiung, Taiwan, it bridges theoretical insights with practical outcomes, providing a comprehensive framework for understanding the interplay of vaccination and treatment in dengue management [4].

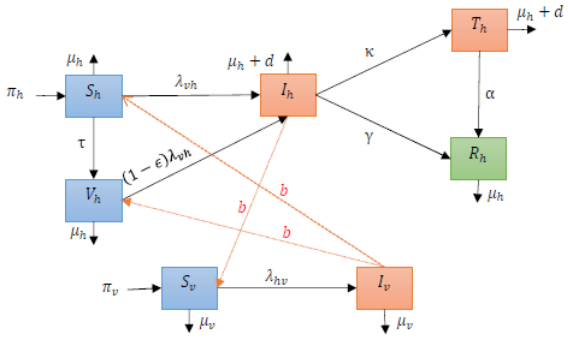


Fig. 1. The host population is either Susceptible (S_h), Vaccinated (V_h), Infectious (I_h), under Treatement (T_h) and Recovered (R_h).The vector population is either Susceptible (S_v) or Infectious (I_v). Dashed arrows show direction of transmission between humans and mosquitoes.π_h is the Recruitment rate of human. b is the Mosquito biting rate. β_{vh} represents the probability of infection of a susceptible human per bite by an infected mosquito. γ is the human rate recovery.τ is the vaccination rate.μ_h is the human natural mortality rate. ϵ is the vaccine efficacy;κ is the Infectious humans treatement rate. α is the Recovery rate of hospitalized individuals. d is the human Disease-induced mortality rate. π_v is the Recruitment rate of vector. μ_v is the natural mortality rate of adult mosquitoes.

3 Results

The simulations use ordinary differential equations to capture dengue virus transmission dynamics. Weekly dengue case data from the 2014–2015 outbreak in Kaohsiung, Taiwan, were used to validate the model, with parameters either estimated through least squares regression or derived from literature. Initial conditions reflected Kaohsiung's population (1,768,000), with ten initial infections. Figure 2 presents the dengue reduction with three scenarios: Vaccination, Treatment, and both vaccination and Treatment. It appears that Treatment alone significantly reduces dengue cases more than the vaccine. Specifically, using vaccination alone, treatment alone, and a combination of both strategies can reduce the number of dengue cases by approximately 20%, 42%, and 60%, respectively. These results illustrate that relying solely on Treatment is insufficient to reduce dengue cases when the vaccine efficacy is sufficiently low.

In general, the study provides several critical insights into the effectiveness of vaccination and treatment strategies. Firstly, a highly effective vaccine can significantly

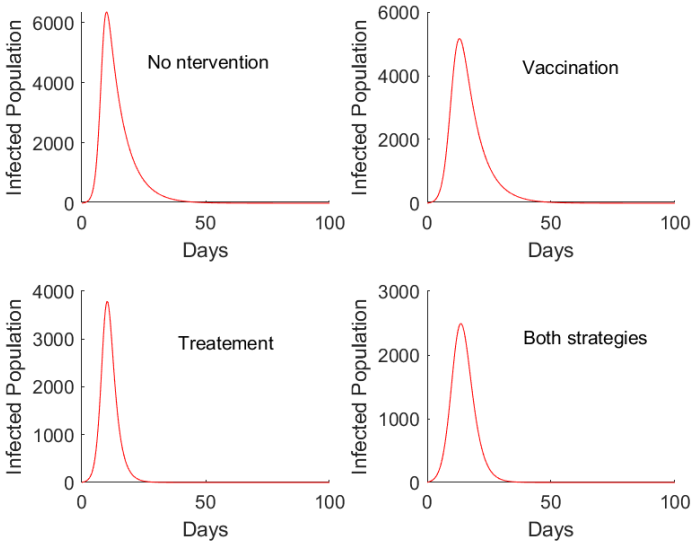


Fig. 2. Numerical simulations of the model with no intervention, vaccine only, Treatement only, and both vaccine and Treatement. The vaccine efficacy is 0.536 and the vaccination rate is 0.2.

reduce the incidence of dengue cases; however, when the vaccine efficacy is low, treatment emerges as a more effective strategy to control the disease. One can establish a critical vaccination level necessary to achieve population protection, indicating that complete vaccination is not required to effectively control dengue transmission.

The sensitivity analysis identifies the key parameters influencing dengue transmission and control strategies, focusing on their impact on the basic reproduction number. Using Latin Hypercube Sampling and Partial Rank Correlation Coefficients, the analysis reveals that transmission probability, mosquito biting rate, vaccine efficacy, treatment rate, human recovery rate, and mosquito mortality rate are the most influential factors. Transmission probability and biting rate exhibit negative correlations, meaning reducing these factors decreases infections, while parameters like vaccine efficacy and treatment rate show positive correlations, emphasizing their importance in controlling the epidemic. The results highlight that combining high vaccine efficacy with effective treatment strategies creates a synergistic effect, significantly reducing the basic reproduction number and disease spread.

Our model has certain limitations that will be addressed in future research. One significant limitation is the absence of seasonality effects, which are known to play a critical role in vector-borne disease transmission by influencing mosquito population dynamics and human exposure patterns [5, 6]. Furthermore, future work could investigate the interaction between dengue and other diseases, such as vector-borne infections like Zika [7], or person-to-person transmissible diseases like COVID-19 [8, 9]. Such investigations could uncover potential interactions and co-infections, shedding light on

how these dynamics might alter disease outcomes and complicate control efforts. Finally, research aimed at developing integrated control strategies that simultaneously address multiple aspects of epidemic transmission could optimize resource allocation and enhance the effectiveness of public health responses during outbreaks [10–19].

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