Optimal Control of Dengue Transmission: A Comparative Study of Vaccination and Treatment Efficacy

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Abstract: Evaluating public health intervention techniques is essential to manage dengue successfully. This study proposes an epidemic model that includes two essential therapeutic interventions: vaccination and treating infected individuals to better understand dengue transmission dynamics. We introduce a seven-state model and investigate the model's endemic and disease-free equilibria. Results show that when vaccination efficacy is low, therapy is a more effective strategy for lowering dengue cases, whereas a highly effective vaccine significantly reduces dengue cases. The study also formulates an optimal control problem, suggesting that combined strategies are more effective in mitigating the disease spread.

Dengue fever, caused by a virus common in tropical and subtropical regions, presents significant health challenges globally, with over 4 million cases reported annually by the WHO [1-2]. The disease's severe manifestation can be fatal, especially without adequate medical care, though supportive treatment can drastically reduce mortality rates. Despite a three-dose vaccine for individuals aged 9 to 45, concerns about its long-term safety for those without prior exposure to the virus remain. The economic burden of dengue and the need for effective intervention strategies underscore ongoing scientific efforts to control the disease.

One can distinguish compartmental models and network epidemiological models. Compartmental models, which use aggregate compartments and differential equations, are advantageous for their simplicity and efficiency in large-scale population studies [3-4]. Network models, on the other hand, represent individual interactions within a network, offering detailed insights into transmission dynamics and the impact of network structures [5-9]. They often rely on centrality measures to identify key nodes in disease spread [10-13]. Our work concerns with the first approach.

Esteva and Vargas initiated the study of dengue transmission using compartmental models for human and mosquito populations [14]. Singh et al. [15]. and Tasman et al. [16]. later considered vaccination effects and the differentiation between primary and secondary infections. Sow et al. [17] developed a model for Zika, similar to dengue, incorporating both vector-borne and human-to-human transmission dynamics. Ndii et al. [18] explored the interaction between media publicity, vaccination, and disease seasonality, highlighting waning immunity as a key factor in dengue infection increases. Chamnan [19] focused on optimal control strategies for vaccinating individuals with documented dengue infection histories. Arquam et al. proposed a Seasonal SIR model incorporating the influence of temperature variations and the heterogeneous structure of the human interaction network on the spreading process of vector-borne diseases [20-21]. Although researchers have formulated numerous mathematical models to investigate dengue transmission dynamics in the context of vaccination, these models have primarily overlooked the potential synergies with treatment. This work examines how therapy and vaccination interact to stop the spread of dengue.

We propose and investigate an epidemic model incorporating vaccination and treatment as two primary therapeutic measures represented through seven state variables in ordinary differential equations [22]. The model diagram (Figure 1) presents a comprehensive schematic representation of the dengue transmission dynamics incorporated in the study. The model's analysis includes both disease-free and endemic equilibria. Stability analysis of the disease-free equilibrium is performed under the condition that the basic reproduction number is less than one.

The numerical simulations in the study evaluate the impact of vaccination and treatment on dengue transmission through various scenarios. Parameter values used in the simulations are based on data from dengue cases in Kaohsiung, Taiwan. The results, illustrated in figures, show that increasing the cure rate leads to a significant reduction in the number of infected individuals (Figure 2). Improved vaccination efficiency also results in fewer infections (Figure 3). The study explores three primary scenarios: vaccination alone, treatment alone, and combined. Treatment alone reduces dengue cases more effectively than vaccination alone, achieving reductions of approximately 74%, 89%, and 98% for vaccination, treatment, and combined strategies, respectively (Figure 4). Despite high vaccination rates, treatment remains more effective due to potential reinfections when vaccine efficacy is low (Figure 5). These findings highlight the critical role of treatment in controlling dengue outbreaks, particularly when vaccines have lower efficacy.

The global sensitivity analysis evaluates the impact of uncertainty in the model's parameters on the numerical simulation results. This analysis uses Latin Hypercube Sampling (LHS) and Partial Rank Correlation Coefficient (PRCC) to determine the most influential parameters. The analysis reveals that transmission probability, biting rates, vaccine efficacy, human recovery rate, and mosquito mortality rates significantly influence the model outcomes. Transmission probability and biting rates exhibit negative correlations, while the other parameters show positive correlations, indicating that higher values of these parameters result in fewer infections. The sensitivity analysis underscores the importance of targeting these critical parameters through control measures like vaccination and treatment to effectively reduce dengue transmission.

We introduce an optimal control problem to mitigate dengue transmission. The model examines the temporal variations of these controls and their influence on disease dynamics. The objective functional aims to minimize the number of infected individuals and the cost of implementing controls. The simulations explore two strategies: using a single control and combining both controls. Results show that vaccination alone reduces the incidence of infection more effectively than treatment alone. However, combining both controls leads to the most significant reduction in infected individuals. The results highlight that while individual controls are beneficial, the combined strategy offers the most substantial impact on reducing dengue cases.

The epidemic model presented in this study underscores the critical role of combined vaccination and treatment strategies in managing dengue transmission. By demonstrating the global stability of the disease-free equilibrium and the effectiveness of combined therapeutic measures, the study provides valuable insights for developing comprehensive public health intervention strategies against dengue.

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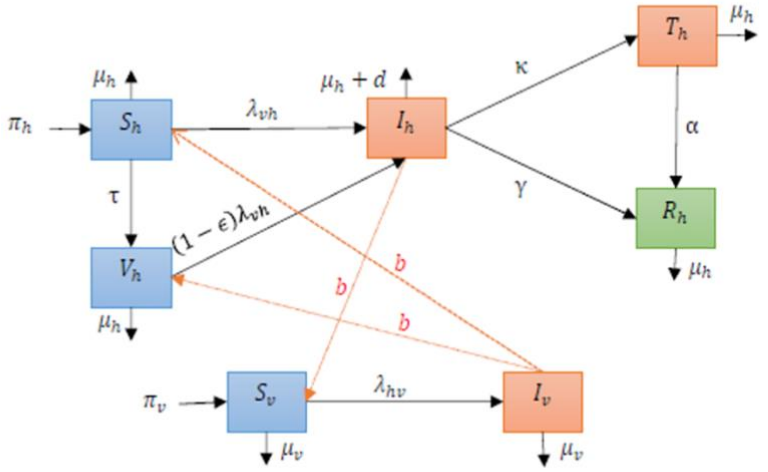

Parameter	Definition
π_h	Recruitment rate of human
b	Mosquito biting rate
β_{vh}	Probability of mosquito infectiousness
β_{hv}	Probability of mosquito infection
γ	Recovery rate for humans rate
τ	Vaccination rate
μ_h	Natural mortality rate of humans
ϵ	Vaccine efficacy
κ	treatement rate of Infectious humans
α	Recovery rate of hospitalized individuals
d	Disease-induced mortality rate of humans
π_v	Recruitment rate of vector
μ_v	Natural mortality rate of adult mosquitoes

Figure 1: The model diagram of the dengue transmission dynamics incorporated in the study. It depicts the various compartments used to categorize the human population into distinct health states: susceptible (S_h), vaccinated (V_h), infected (I_h), treatment (T_h), and recovered (R_h). The arrows between these compartments illustrate the transitions individuals make due to disease progression, vaccination, and treatment interventions. The diagram also includes the role of mosquito vectors in the transmission cycle, highlighting the interactions between human and susceptible (Sv), and Infected (Iv), mosquitos.

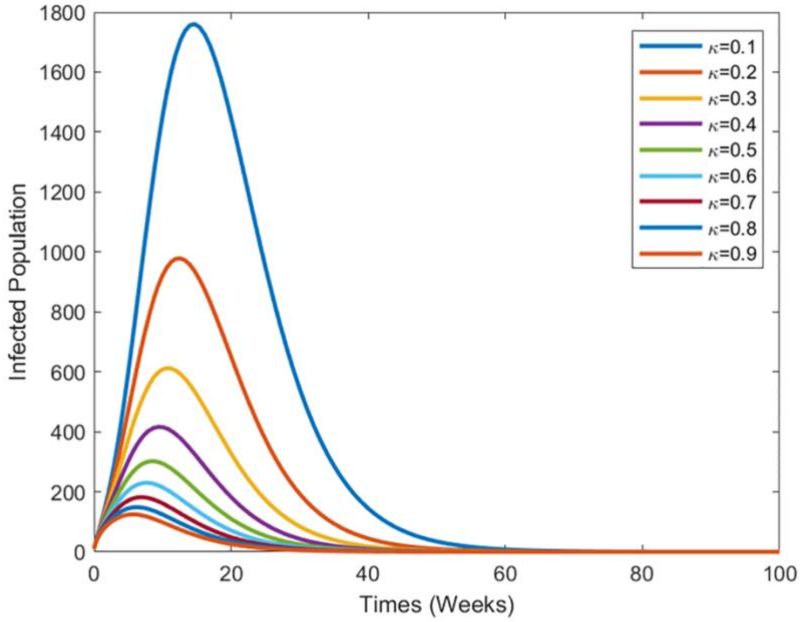

Figure 2 illustrates the effect of varying cure rates on the number of infected individuals in the population. The simulations show that the number of infected individuals significantly decreases as the cure rate increases. The model parameters are based on data from dengue cases in Kaohsiung, Taiwan, highlighting the critical role of effective treatment in controlling the spread of dengue.

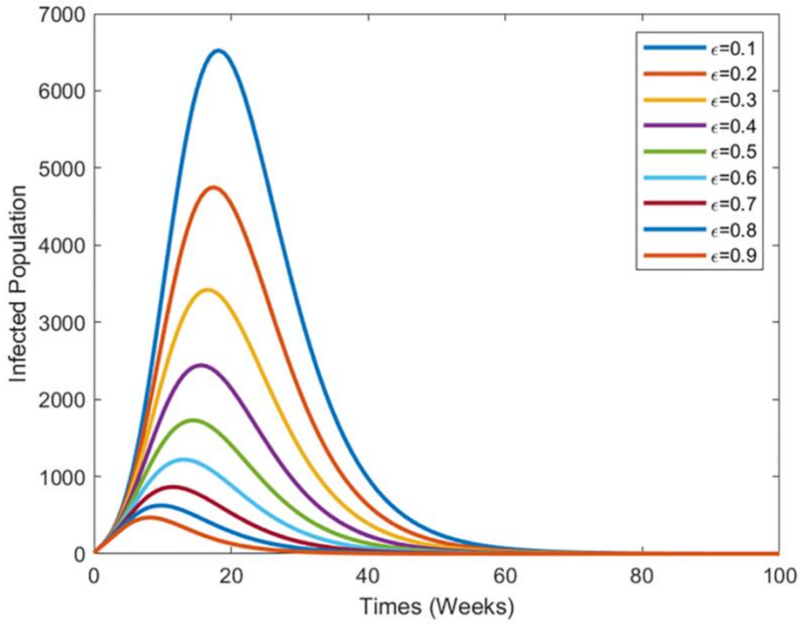

Figure 3 illustrates the effect of varying vaccine efficacy on the number of infected individuals in the population. The simulations show that the number of infected individuals significantly decreases as the vaccine efficacy increases. The model parameters are based on data from dengue cases in Kaohsiung, Taiwan, highlighting the critical role of effective vaccine in controlling the spread of dengue.

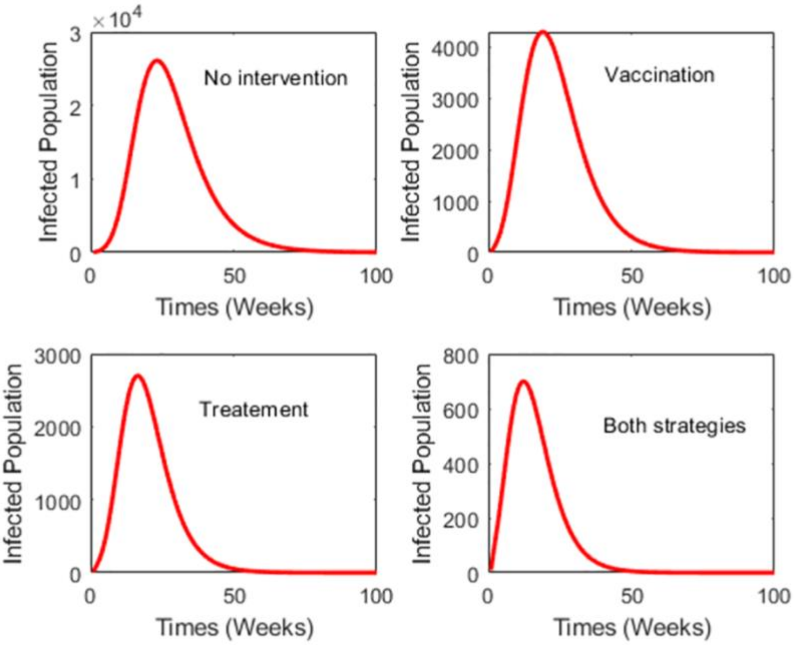

Figure 4 reports the numerical solutions of the model with a vaccination rate of 0.2 and a vaccine efficacy of 0.536. In this case, the vaccine's 0.536 efficacy indicates how well it works on seronegative people. The results show that therapy alone, as opposed to vaccination, dramatically lowers dengue cases. Specifically, dengue cases can be reduced by roughly 74%, 89%, and 98%, respectively, by employing vaccination alone, treatment alone, and combining both strategies. It emphasizes that in situations where vaccine efficacy is low, treating patients alone is adequate to minimize the number of episodes of dengue.

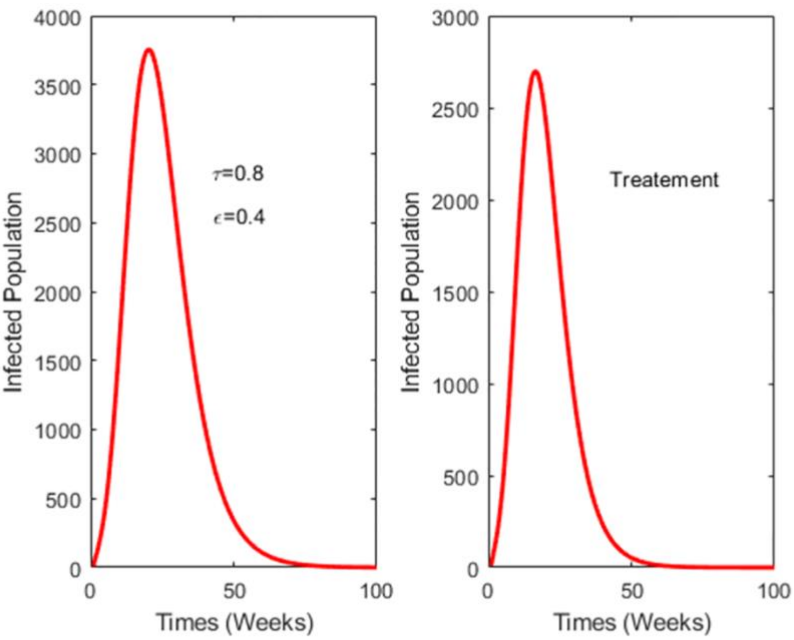

Figure 5 illustrates that despite a high vaccination rate, the effectiveness of treatment surpasses that of the vaccine. This outcome could potentially be influenced by a low vaccine efficacy, resulting in the reinfection of vaccinated individuals.