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The impact of bed-net use on malaria prevalence

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HIGHLIGHTS

- ► The existence of backward bifurcation is presented.
- ► Bed-net usage has a positive impact in reducing the reproduction number $\mathcal{R}$.
- ► Malaria could be eliminated if 75% of the population were to use bed-nets.

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ABSTRACT

Malaria infection continues to be a major problem in many parts of the world including the Americas, Asia, and Africa. Insecticide-treated bed-nets have shown to reduce malaria cases by 50%; however, improper handling and human behavior can diminish their effectiveness. We formulate and analyze a mathematical model that considers the transmission dynamics of malaria infection in mosquito and human populations and investigate the impact of bed-nets on its control. The effective reproduction number is derived and existence of backward bifurcation is presented. The backward bifurcation implies that the reduction of $\mathcal{R}$ below unity alone is not enough to eradicate malaria, except when the initial cases of infection in both populations are small. Our analysis demonstrate that bed-net usage has a positive impact in reducing the reproduction number $\mathcal{R}$. The results show that if 75% of the population were to use bed-nets, malaria could be eliminated. We conclude that more data on the impact of human and mosquito behavior on malaria spread is needed to develop more realistic models and better predictions.

1. Introduction

Malaria is a disease that can be transmitted to people through the bites of infected mosquitoes. It is one of the leading causes of morbidity and mortality in some of the poorest tropical and subtropical regions in the world including the Americas, Asia, and Africa. Malaria is particularly a major public health problem in Africa, where 20% of children under the age of 5 die as a result of infection. The World Health Organization (WHO) estimates that every year 250 million people become infected and nearly one million die.

Malaria was successfully eliminated from many parts of the world including Europe, North America, the Caribbean, and parts of Asia and South-Central America in the early 20th century. Dichlorodiphenyltrichloroethane (DDT) was one of the main intervention strategies used to eradicate malaria in these countries. However, these efforts were abandoned but have gradually been revived by different organizations including the WHO and the Bill & Melinda Gates Foundation. There are several new interventions that are currently being used in the fight against malaria including insecticide-treated bed-nets (ITNs).

ITNs are mosquito nets treated with insecticides that protect individuals by diverting mosquitos and killing those who come in contact with the net. A review of 22 randomized control trials of ITNs (Lengeler, 2004) found that they can reduce malaria cases by 50% and deaths in children by one-fifth. Although the cost-effectiveness

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of ITNs has been demonstrated in numerous studies (Goodman and Mills, 1999), there are many challenges due to improper handling and human behavior (e.g., lack of use due to hot weather). Moreover, insecticide on nets usually lasts between 3 and 5 years due to frequent washing, type of soap used, and exposure to direct sunlight, which can deteriorate the effectiveness of the insecticide sprayed on it.

Mathematical models of the transmission of infectious agents can be useful tools in understanding disease dynamics and assessing the effect of different interventions (Hethcote, 2000). Although several articles have investigated the impact of various intervention strategies including ITNs (Chitnis et al., 2010; Killeen and Smith, 2007; Smith et al., 2008; White et al., 2009), none of them have incorporated human behavior. Killeen and Smith (2007) used a deterministic model to investigate the impact of mosquito behavior in response to ITN usage. Smith et al. (2008) used an individual-based stochastic simulation of malaria to estimate the impacts of various intervention strategies including ITNs on the spread of malaria, response activities, and cost. White et al. (2009) used a simple deterministic model and compared it to more sophisticated models to evaluate the impact of different intervention strategies. They concluded that a combined intervention strategy could achieve elimination through a sustained control strategy. Chitnis et al. (2010) used a system of difference equations to analyze the impact of ITNs and indoor residual spraying (IRS) on malaria-control programs. They showed that people that use only ITNs are better protected than those with only IRS.

Therefore, understanding the impact of human behavior (Del Valle et al., 2005) can help us develop optimal intervention strategies and devise more realistic predictions to control malaria spread. In this paper, we identify a threshold needed to reduce malaria cases through the use of ITNs and the impact of human behavior on ITNs' effectiveness.

2. Model formulation

We formulate the basic model for the effects of bed-net on the transmission dynamics of malaria infection consisting of mosquito (also referred as vector) and human populations (also referred as host). The host population is grouped into two compartments, susceptible and infectious, which are denoted by S_h, I_h, respectively, with a total population given by $N_h = S_h + I_h$. The vector population is similarly grouped into two compartments, susceptible and infectious with sizes S_v, I_v, respectively, and the total population size is given by $N_v = S_v + I_v$. All newborn individuals are assumed to be susceptible and no infected individuals are assumed to come from outside of the community.

One of the basic forms of protections against the transmission of malaria is the usage of pesticide-treated bed-nets. According to reports (Kayedi et al., 2008; Vanlerberghe et al., 2010), the pesticide treatment on the bed-nets could fade out due to frequent washing with certain soap and exposure to direct sunlight. Despite these problems, bed-nets are among the most important and affordable means of defense against malaria transmissions. Accordingly, we assume that malaria transmission reduces as a function of bed-net usage. We denote the contact rate of mosquitoes and humans by $\beta(b)$. This rate is assumed to be the same for the human and mosquito populations. However, the probability of effective transmission from human to mosquito, which we denote by p_1, is different from the probability of effective transmission from mosquito to humans, denoted by p_2. Normally, the transmission rate is the product of the contact rate and the probability of passing infection. Following the general results obtained as a result of treated bed-net usage in reducing

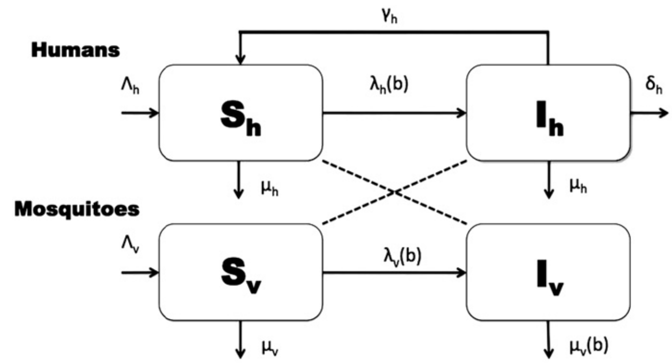

Fig. 1. Flow-chart showing movements of humans and mosquitoes between the susceptible and infectious compartments and the flow of the malaria disease from humans to mosquitoes and from mosquitoes to humans. At time, t, the total human population is $N_h(t) = S_h(t) + I_h(t)$ and the total mosquito population is $N_v(t) = S_v(t) + I_v(t)$.

malaria transmission, we model the average number of bites per mosquito per unit time (contact rate) by a linearly decreasing function of treated bed-net usage, b:

$$\beta(b) = \beta_{max} - b(\beta_{max} - \beta_{min}), \quad 0 \le b \le 1. \tag{1}$$

Note that the parameters β_{max} and β_{min} are the maximum and the minimum transmission rates, respectively, and b is the proportion of bed-net usage that could reduce the mosquito–human contact rate to a minimum level β_{min}.

Bed-nets are typically used at night, thus, we assume that even if the entire host population used bed-nets ($b = 1$), the transmission can only be reduced to a minimum value (β_{min}). Similarly, if no one uses bed-nets ($b = 0$), transmission would be at its maximum level (β_{max}).

A drastic decline in relative exposure to mosquitoes as a result of ITN usage is observed in some parts of Africa (Govella et al., 2010). This leads to a significant reduction of disease transmission. This reduction could be well described by either exponentially decreasing or linearly decreasing function of ITN usage. To simplify the model, we choose the transmission to be a linearly decreasing function of b.

The model is constructed by making some basic assumptions: all new arrivals into the human population are susceptible with recruitment rates as Λ_h and Λ_v for human beings and mosquitoes respectively, the disease is fast progressing so that the exposed stage is minimal and is not considered, infectious humans could die from the disease or become susceptible after recovery, the mosquito population does not recover from infection, insecticide-treated bed-nets contribute to the mortality rate of mosquitoes.

Following the approaches in Blayneh et al. (2009), Bowman et al. (2005) and Teboh-Ewungkem et al. (2010) the value of $\beta(b)$ is the same for each population, so the average number of bites per human per unit time is $\beta(b)N_v/N_h$. Thus, the force of infection for susceptible humans is given by

$$\lambda_h(b) = p_1 \frac{\beta(b)N_v}{N_h}\frac{I_v}{N_v} = \frac{p_1\beta(b)I_v}{N_h},$$

where p_1 is the transmission probability per bite from infectious mosquitoes to humans. The force of infection for susceptible vectors is

$$\lambda_v(b) = \frac{p_2\beta(b)I_h}{N_h},$$

where p_2 is the transmission probability per bite from infectious humans to mosquitoes.

Due to insecticide treatment of bed-nets, female mosquitoes questing for blood meal could die when they become in contact