HOUSEHOLD COSTS FOR PERSONAL PROTECTIVE MEASURES FOR DENGUE DISEASE

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Abstract: Dengue is a vector-borne disease considered one of the major concerns in public health. Measures can be used to reduce the impact of the mosquito around the houses. In this paper, the main focus is mosquito bites prevention through the use of personal protective measures (PPM), such as skin repellent and bed nets. It is proposed a system with six ordinary differential equations, modeling the interaction human-mosquito. At the same time, a functional, related to the household costs with these measures, is added. The aim is the studying optimal control analysis to understand the best way of applying these measures. It is concluded that the application of skin repellent and treated bed nets have an impact on the reduction of infected people and at the same time contributes to the flattening of dengue cases, which could lead to better health cares for each patient.

Keywords: dengue, personal protection, household costs, optimal control, skin repellent, bed net

1 INTRODUCTION

Dengue affects tropical and subtropical areas, but this disease continues to proliferate in other parts of the world. Rapid unplanned urbanization, changing land-use patterns, and increased international travel and trade bring humans into more frequent contact with vectors, while climate and other environmental changes fuel their spread worldwide [19].

According to World Health Organization [20], over 700000 deaths are caused by vector-borne disease annually, and 17% of the global burden of communicable disease is due to vector-borne diseases.

The costs of a disease can be split into two main folds. Downstream, they are related to the treatment, where the cost can be divided into direct (hospitalization, outpatient, drugs) and indirect (loss of productivity, tourism impact, loss of school days). Upstream, the costs are focused on prevention. All the efforts go to mosquito reduction or, at least, the reduction of mosquito bites. They can be developed by health authorities, through the insecticide or larvicide application, education campaigns to promote preventive behaviors; or by each individual that is in an affected area by applying self-protective measures (such as skin repellent, repellent treated cloths, bed nets for sleeping or bed nets for windows and doors) [7, 13, 17].

In this paper, the focus goes to PPM, especially skin repellent and treated bed nets. The use of repellents is one of the actions accepted as part of integrated mosquito-borne disease control programs. Currently, a variety of repellents are marketed, mainly containing synthetic pyrethroids and DEET as an active ingredient [18]. Insecticide-treated bed nets are effective in preventing nocturnally transmitted vector-borne diseases. A recent study [9] refers that insecticide-treated window curtains can reduce dengue vector densities for low levels and potentially reduce dengue transmission [1].

The organization of the paper is as follows. Section 2 presents the mathematical model that describes the interaction between humans and mosquitoes, as well as the functional used to model the application of the PPM. The main numerical results obtained are exposed in Section 3, and the main conclusions are carried out in Section 4.

2 MATHEMATICAL MODEL

The mathematical model is based on the research paper [2], with the adaptation of the functional for two control measures, as well as the related differential equations.

There are considered six state variables, where the first four are related to humans (s susceptible, p protected, i infected, and r recovered), and the remaining are concerned with mosquitoes (s_m susceptible, and i_m infected). Additionally, there are two control variables related to the willingness to use PPM, namely u_1 skin repellent, and u_2 treated bed net. Even with excellent advertising campaigns, it seems to be impossible persuading everybody to apply PPM, and consequently, the controls were bounded between 0 and $umax = 0.7$. This value, 0.7, means that a maximum of 70% of people are considered to use PPM, which appears to be credible.

After the normalization of the state variables, the epidemiological model is defined by:

$$\begin{cases} \dfrac{ds(t)}{dt} = \mu_h - (6B\beta_{mh}i_m(t) + u_1(t) + u_2(t) + \mu_h)\, s(t) + ((1-\rho_1) + (1-\rho_2))p(t) \\ \dfrac{dp(t)}{dt} = (u_1(t) + u_2(t))\, s(t) - ((1-\rho) + (1-\rho_2) + \mu_h)\, p(t) \\ \dfrac{di(t)}{dt} = 6B\beta_{mh}i_m(t)s(t) - (\eta_h + \mu_h)\, i(t) \\ \dfrac{dr(t)}{dt} = \eta_h i(t) - \mu_h r(t) \end{cases} \tag{1}$$

and

$$\begin{cases} \dfrac{ds_m(t)}{dt} = \mu_m - (B\beta_{hm}i(t) + \mu_m)\, s_m(t) \\ \dfrac{di_m(t)}{dt} = B\beta_{hm}i(t)s_m(t) - \mu_m i_m(t) \end{cases} \tag{2}$$

This set of equations is subject to the initial equations ([15]):

$$s(0) = \frac{11191}{N_h}, p(0) = 0, i(0) = \frac{9}{N_h}, r(0) = 0, s_m(0) = \frac{66200}{N_m}, i_m(0) = \frac{1000}{N_m}. \tag{3}$$

To minimize at the same time, the cumulative number of infected persons and the costs related to the application of control measures, it is proposed the following objective functional:

$$J(u(\cdot)) = r(T) + \int_0^T (\gamma_1 u_1^2(t) + \gamma_2 u_2^2(t))dt \tag{4}$$

where γ_1 and γ_2 are positive constants that represent the cost of taking PPM per day and person, related to skin repellent and bed net, respectively. Each PPM has two factors associated: measure cost for a whole year and durability of the protection per day.

At the same time, it is relevant that this functional also has a payoff term: the number of humans recovered by disease at the final time, $r(T)$. In this research, the final time was considered one year, meaning $T = 365$.

Table 1: Parameters of the epidemiological model

Parameter	Description	Range	Used values	Source
N_h	Human population		112000	[15]
$\frac{1}{\mu_h}$	Average lifespan of humans (in days)		79×365	[8]
B	Average number of bites on an unprotected person (per day)		$\frac{1}{3}$	[14, 15]
β_{mh}	Transmission probability from I_m (per bite)	$[0.25, 0.33]$	0.25	[4]
$\frac{1}{\eta_h}$	Average infection period on humans (per day)	$[4, 15]$	7	[3]
$\frac{1}{\mu_m}$	Average lifespan of adult mosquitoes (in days)	$[8, 45]$	15	[5, 6, 11]
N_m	Mosquito population		$6 \times N_h$	[16]
β_{hm}	Transmission probability from I_h (per bite)	$[0.25, 0.33]$	0.25	[4]
ρ_1	Insect repellent protection (per day)		$\frac{1}{6}$	
γ_1	Insect repellent cost (per person and day)		$\frac{10 \times 12}{365 \times 11200}$	
ρ_2	Bed net protection (per day)		$\frac{1}{3}$	
γ_2	Bed net cost (per person and day)		$\frac{20}{365 \times 11200}$	

As expected, these systems depict the interactions of the disease between humans to mosquitoes and vice-versa. Parameters of the model are presented in Table 1.

The following section shows several simulations to understand the trade-off between costs with PPM and the number of infected persons.

3 NUMERICAL RESULTS

The Pontryagin's Maximum Principle [12] was used to solve the optimal control problem, whose objective function is (4) subject to the constraints (1), (2) and (3). Numerically, the problem was solved in MATLAB, version R2017b, under de ODE45 routine, and evaluated using a forward-backward fourth-order Runge–Kutta method with a variable time step for efficient computation (see [10] for more details).

To perceive the impact on dengue cases five strategies were tested. The first one was done without any control ($u_1 = u_2 = 0$). The second and third scenarios consider only a single control. Finally, the last two strategies were drawn using combined controls: one applying both controls allowing them to reach the optimal control strategy, and the other using the implementation of the maximum control ($u_1 = u_2 = 0.7$). Figures 1 and 2 represent the first four strategies previously defined; the last one has similar behavior of the combined optimal control scenario. The main conclusion is that these measures, alone or combined, have effects on a dengue outbreak.

Through the graphics of the infected (Figure 1, left) is possible to observe the impact of PPM on the peak of the disease. With PPM, it is possible to decrease the number of infected individuals and at the same time flatten the curve, allowing each person have better health

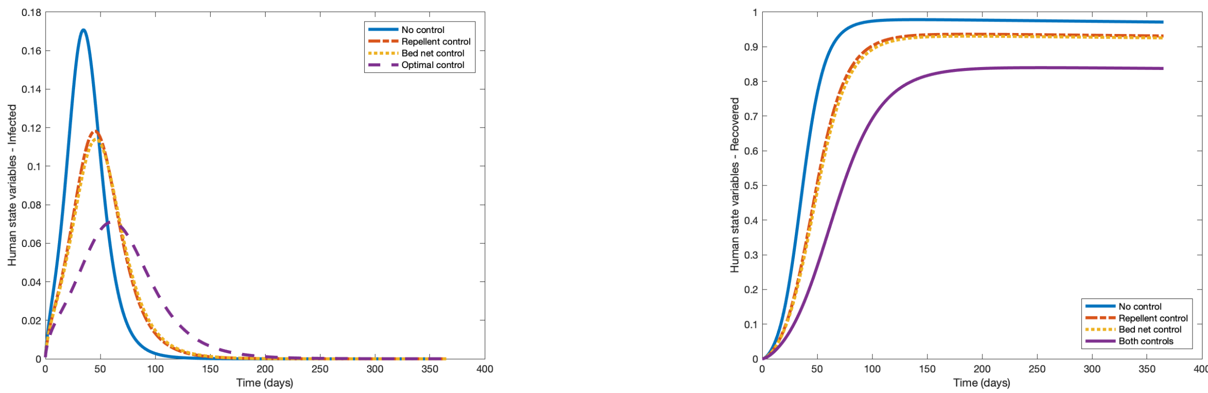

Figure 1: State variables, infected (i) and recovered (r), for the multiple strategies

care. At the same time, the total number of infected individuals (and then recovered) is approximately 20% lower when the combined strategy is applied (Figure 1, right).

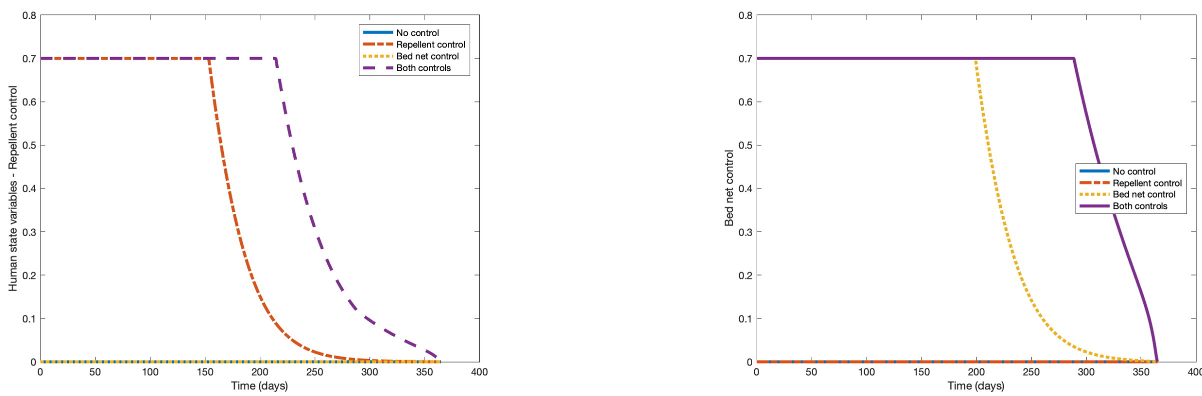

Figure 2: Control variables, u_1 and u_2, for the multiple strategies

Despite every single control have a similar impact on the disease, due to their costs, the application of them has distinct behavior, as Figure 2 exposed. The skin repellent has its optimal application in the 170 days approximately, where the treated bed net should be used longer, more than 200 days. As expected, the strategy of adopting combined controls is recommended to extend in time because it has a significant impact on the number of dengue cases.

However, the cost of using these PPM is different, as Table 2 presents. Not using any control leads to a higher number of infected persons (10878), the peak of the infection is short (35 days). This could be harmful to the preparation of human and logistical resources in an outbreak scenario.

Due to its short duration of any can/bottle of skin repellent, this PPM is very expensive when compared to the use of a bed net. Because of this feature, in the optimal control solution, the application of this measure is shorter when compared with the second control that is 5 times less expensive.

The analysis of the epidemic's end is a meaningful resource, due to the forecasting possibility of the end of the outbreak. The use of the combined strategy of both controls leads to a widening of the outbreak's end. However, when the quality of health service is considered, the spread of the patients per the time could be seen as an advantage.

Another relevant feature of this table is the cost associated with optimal control and maximum control strategies: although having similar behavior in terms of infected and recovered curves, the application of the controls at their maximum leads to an increase of 37% of costs.

Table 2: Summary of the simulations

Strategy	Peak of infected persons	Peak's day	Epidemic's end (day)	r(T)	Cost
No control	1912	35	120	10878	0
Only Repellent	863	58	202	9571	42.3
Only Bed net	710	63	223	9083	8.9
Optimal control	510	72	260	8177	71.5
Maximum control	510	72	261	8176	98

4 CONCLUSIONS

The main conclusion is that the use of controls produces very different results in the spread of the disease. Without the application of any control, the peak of infected people is much higher and earlier, which does not allow health authorities to adapt measures in a timely manner. In this situation, although there are no PPM costs, in the case of an outbreak there will be other types of disadvantages such as hospitalization or absenteeism costs.

Combining the application of the 2 PPM controls, results in a smaller, later and more flattened peak. In the event of an outbreak, congestion in health units (health professionals, beds, medicines) is avoided. When both controls are applied, the repellent should start to be discontinued before the 250th day and the bed net later, after the 300th day. This guideline makes sense, since it is intended to minimize the number of recovered in the final instant but simultaneously the costs. Also, when the controls are applied alone, the repellent should start to be reduced earlier when compared to the bed net. As the repellent is more expensive than the bed net it makes sense to stop applying it sooner.

The strategies of optimal control and maximum control yielded very similar results in terms of the peak of infected, peak's day, epidemic's day and $r(T)$ but significantly different in terms of costs. This relevant guideline denotes that it is not necessary to use the controls at their maximum value (most expensive solution) because no better results are obtained.

Acknowledgements

This work is supported by The Center for Research and Development in Mathematics and Applications (CIDMA) through the Portuguese Foundation for Science and Technology (FCT - Fundação para a Ciência e a Tecnologia), references UIDB/04106/2020 and UIDP/04106/2020 (Brito da Cruz and Rodrigues); and UIDB/00319/2020 (Monteiro).

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