

Research Article

Assessing the Impact of Vaccination on Controlling the Spread of Human Scabies

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Scabies is among the infestations almost forgotten due to its association with poor communities. We formulate a deterministic model to assess the possible impact vaccination will have on scabies control. The Descartes's rule of signs is used to show the nature of the endemic equilibria. Analysis of the reproduction number and numerical simulations suggest that vaccination in addition to treatment will help greatly in reducing the spread of scabies infestation. This suggests there is a strong need for researchers to come up with a possible vaccine in that order to effectively control scabies especially among the disadvantaged communities.

1. Introduction

Scabies is a highly contagious skin infestation caused by skin infestation with the mite *Sarcoptes scabiei* and is spread by direct contact. Its common name is the “itch mite” derived from the severe pruritis it causes [1]. The female mite burrows the skin and lays its eggs which hatch into larvae within 2-3 days [2]. The larvae then burrow to reach the skin surface, then dig burrows where they pass through two further developmental stages (protonymphs and tritonymphs) before moulting into either male or female mites. As a result a result, S-shaped trails accompanied by small insect bites cover infested areas. It is only less than 1% of the eggs laid by female mites that develop into adult mites [3]. Following infection, the mite population increases rapidly up to 25 adult mites after 50 days and upto 500 mites by 100 days [3], and thereafter rapid decrease may be due to scratching as well as host immune's response. However, 10–12 mites are enough to cause a burden in a host [1].

It is estimated that, despite the availability of effective treatment, over 300 million people in the world are scabies infested [6]. Scabies is well described in the historical record with descriptions evident in ancient texts from China, India and the Middle East [7]. Scabies was also a scourge in London during the First World War upto 1920 [8]. Scabies can be

treated with any of the following medications: permethrin (one of the most effective and most expensive), ivermectin (an oral medicine shown in clinical studies to be effective against scabies but not recommended for children), lindane (effective though there are concerns that it can cause neurotoxicity), benzyl benzoate, crotamiton, malathion, and sulphur preparations. Due to low cost, benzyl-benzoate and sulphur ointments are commonly used in developing countries. In general the prevalence of scabies is not well documented especially in Africa [2]. Scabies infestations like other infectious diseases are more common among the poor due to the overcrowded and unhygienic living conditions they are exposed to. However, the issues of associating poverty and scabies are complicated as even in the developed world scabies cases have also being recently reported [9]. In November 2007, the Public Health Service in Amsterdam was notified that the nursing home doctor in Amsterdam had been diagnosed with scabies and that another staff member who worked in the same nursing home had been diagnosed with scabies in September 2007 [9].

Currently, there is no vaccine against scabies; however, the observations that scabies infestation in humans is self limiting and that after the first infestation, significant protective immunity against re-infestation provide theoretical support for the development of a vaccine against scabies

TABLE 1: Number of possible positive roots of $h(\lambda^*) = 0$ for $\mathcal{R}_{P_T} > 1$ and $\mathcal{R}_{P_T} < 1$.

Cases	A	B	C	D	\mathcal{R}_{P_T}	Number of sign changes	Number of possible real roots (endemic equilibrium)
1	+	+	+	+	$\mathcal{R}_{P_T} < 1$	0	0
	+	+	+	-	$\mathcal{R}_{P_T} > 1$	1	1
2	+	-	+	+	$\mathcal{R}_{P_T} < 1$	2	0,2
	+	-	+	-	$\mathcal{R}_{P_T} > 1$	3	1,3
3	+	-	-	+	$\mathcal{R}_{P_T} < 1$	2	0,2
	+	-	-	-	$\mathcal{R}_{P_T} > 1$	1	1
4	+	+	-	+	$\mathcal{R}_{P_T} < 1$	2	0,2
	+	+	-	-	$\mathcal{R}_{P_T} > 1$	1	1

TABLE 2: Effects of different levels of vaccination and vaccine waning rates.

	$\alpha < \alpha^c$	$\alpha > \alpha^c$
$\rho < \rho^c$	As much as vaccine waning rates are low, the vaccination rates are not high enough to control scabies	Ideal situation where vaccination rates are high and vaccine waning rates are low. In this case, vaccination leads to the control of scabies.
$\rho > \rho^c$	Low vaccination rates with a vaccine which wanes too quickly cannot control scabies in a community	High vaccination rates with a vaccine which wanes too quickly have little effect on scabies control

TABLE 3: Model parameters.

Model parameter	Value (range)	Source
Λ	$0.029 \text{ yr}^{-1} \times 10000$	CSOZ
μ	0.02 yr^{-1}	CSOZ
β	0.043 yr^{-1}	Landwehr et al., 1998 [4]
δ	0.125 (0.0-1.0)	Assumed
σ	0.25 (0.0-1.0)	Assumed
α	0.8 yr^{-1}	Bhunu et al., 2008 [5]
ρ	0.0002 yr^{-1}	Bhunu et al., 2008 [5]
γ	0.75 yr^{-1}	Assumed

where $\lambda^* = 0$ corresponds to the disease-free equilibrium and $h(\lambda^*) = 0$ corresponds to the existence of endemic equilibria where

$$\begin{aligned}
 A &= \frac{\sigma\delta}{\mu(\mu + \gamma)(\mu + \alpha + \rho)}, \\
 B &= \frac{\delta}{\mu(\mu + \alpha + \rho)} + \frac{\sigma(\mu + \rho + \delta(\mu + \alpha - \beta))}{\mu(\mu + \gamma)(\mu + \alpha + \rho)}, \\
 C &= \frac{\mu + \rho + \delta\alpha}{\mu(\mu + \alpha + \rho)} - \frac{\sigma\mathcal{R}_{P_T}}{\mu} + \frac{\sigma}{\mu + \gamma} + \frac{\delta(\mu + \gamma - \beta)}{(\mu + \gamma)(\mu + \alpha + \rho)}, \\
 D &= 1 - \mathcal{R}_{P_T}.
 \end{aligned} \tag{8}$$

Solving for λ^* in $h(\lambda^*) = 0$, the roots of $h(\lambda^*) = 0$ are explored using the Descartes's rule of signs. The various possibilities are tabulated in Table 1.

The analysis of the results in Table 1 results in the following Theorem 2.

Theorem 2. *The scabies model (1)*

- (i) has a unique endemic equilibrium if $\mathcal{R}_{P_T} > 1$ and whenever Cases 1, 2, 3, and 4 are satisfied;
- (ii) could have more than one endemic equilibrium if $\mathcal{R}_{P_T} > 1$ and Case 2 is satisfied;
- (iii) could have two endemic equilibria if $\mathcal{R}_{P_T} < 1$ and cases 2, 3, and 4 are satisfied.

3.2. Analysis of the Reproduction Number \mathcal{R}_{P_T} . In the absence of both vaccination and treatment \mathcal{R}_{P_T} is simply the basic reproduction number \mathcal{R}_0 which is defined as the number of secondary scabies cases produced by one infectious

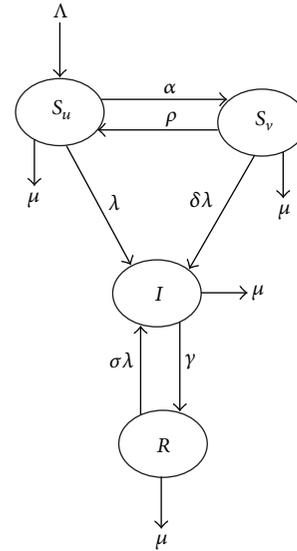


FIGURE 1: Structure of the model.

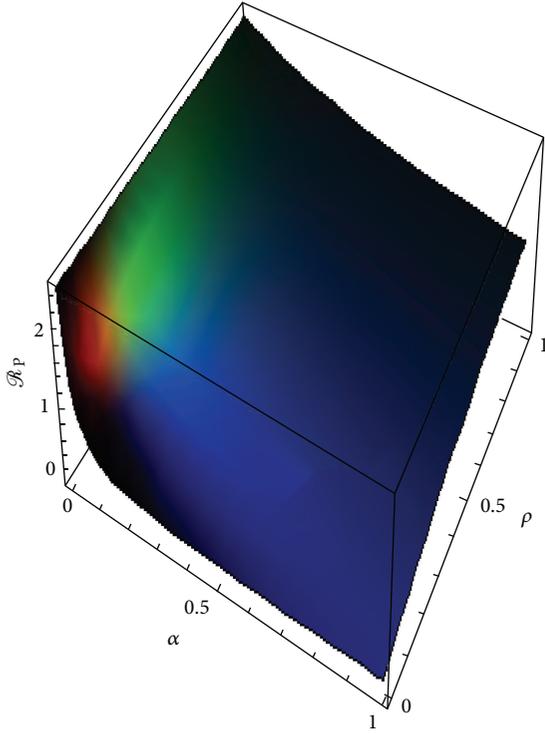


FIGURE 2: Effects of vaccination rate and vaccine waning rate on \mathcal{R}_p .

individual during his/her entire infectious period in the absence of any intervention strategy and is given by

$$\mathcal{R}_0 = \frac{\beta}{\mu}. \quad (9)$$

Now let us analyse what happens when their vaccination is only in the community. In that scenario, \mathcal{R}_{P_T} becomes \mathcal{R}_P which is defined as the number of secondary scabies cases produced by one infected individual during his/her entire infectious period in presence of vaccination and is given by

$$\lim_{\gamma \rightarrow 0} \mathcal{R}_{P_T} = \mathcal{R}_P = \frac{\beta(\mu + \rho + \delta\alpha)}{\mu(\mu + \rho + \alpha)} = \frac{\mu + \rho + \delta\alpha}{\mu + \rho + \alpha} \mathcal{R}_0. \quad (10)$$

Subtracting \mathcal{R}_P from \mathcal{R}_0 , we have

$$\Delta_p = \mathcal{R}_P - \mathcal{R}_0 = \frac{(1 - \delta)\alpha}{\mu + \rho + \alpha} \mathcal{R}_0 > 0. \quad (11)$$

Also, partially differentiating \mathcal{R}_P with respect to α , one gets

$$\frac{\partial \mathcal{R}_P}{\partial \alpha} = -\frac{(\mu + \rho)(1 - \delta)}{(\mu + \rho + \alpha)^2} \mathcal{R}_0 < 0. \quad (12)$$

The fact that (11) is positive and (12) is negative suggests that the increase in the use of the vaccine will increase its benefit to the community. This result suggests more resources should be geared towards the development and deployment of this possible vaccine against scabies. Now we determine the critical vaccination rate necessary for the vaccine to have

a positive impact on its control and this is done by expressing α as a subject of the formula in (10) to obtain

$$\alpha^c = \frac{(\mu + \rho)(1 - \mathcal{R}_P/\mathcal{R}_0)}{\mathcal{R}_P/\mathcal{R}_0 - \delta} \text{ and exists for } \delta < \frac{\mathcal{R}_P}{\mathcal{R}_0} < 1. \quad (13)$$

Thus, as long as $\alpha > \alpha^c$, then vaccination will aid in the control of scabies. However, for $\alpha < \alpha^c$, vaccination levels will not be high enough to make a meaningful impact on scabies control. To effectively determine the effects vaccination has on scabies control, there is a need to know the critical vaccine waning rate which is found by making ρ the subject of formula in the equation of \mathcal{R}_P to obtain

$$\rho^c = \frac{(\mu + \delta\alpha)((\mu + \alpha)\mathcal{R}_P/(\mu + \delta\alpha)\mathcal{R}_0) - 1}{1 - \mathcal{R}_P/\mathcal{R}_0} \quad (14)$$

$$\text{which exists for } \frac{\mu + \delta\alpha}{\mu + \alpha} < \frac{\mathcal{R}_P}{\mathcal{R}_0} < 1.$$

Thus, vaccination will be able to control scabies provided $\rho < \rho^c$. If $\rho > \rho^c$, then the rate at which the vaccine wanes is very high that herd immunity cannot be achieved. Table 2 summarises the effects of vaccination and vaccine waning rates.

Results from Table 2 show that an ideal situation for a vaccine to achieve herd immunity is when vaccination coverage rates are high and vaccine waning rates are low ($\alpha > \alpha^c$, $\rho < \rho^c$). This result is further illustrated in Figure 2 which shows that high vaccination rates accompanied by low vaccine waning rates are ideal to make the reproduction number \mathcal{R}_P small. A reduction in the size of the reproduction number translates to a reduction in the number of new infections.

Since we are talking about vaccination and its potential impact of scabies control, there is a need to find the critical protective factor for a vaccine to be effective. This requires making δ the subject of the formulae in \mathcal{R}_P and doing so one gets

$$\delta^c = \frac{\mu + \rho}{\alpha} \left(\frac{(\mu + \rho + \alpha)\mathcal{R}_P}{(\mu + \rho)\mathcal{R}_0} - 1 \right) \quad (15)$$

$$\text{which exists for } \frac{\mu + \rho}{\mu + \rho + \alpha} < \frac{\mathcal{R}_P}{\mathcal{R}_0} < 1.$$

If $\delta < \delta^c$, then the vaccine will be effective enough to control scabies infection. However, when $\delta > \delta^c$, then vaccination will not contribute meaningfully to the reduction of scabies. Looking at the nature of \mathcal{R}_{P_T} shows that it is a decreasing function of γ suggesting the benefits the community gets by increasing levels of treatment. Is vaccination necessary in a community where treatment is there? To answer this question, we partially differentiate \mathcal{R}_{P_T} with respect to α and we obtain

$$\frac{\partial \mathcal{R}_{P_T}}{\partial \alpha} = -\frac{\mu\mathcal{R}_0(\mu + \rho)(1 - \delta)}{(\mu + \gamma)(\mu + \rho + \alpha)^2} < 0. \quad (16)$$

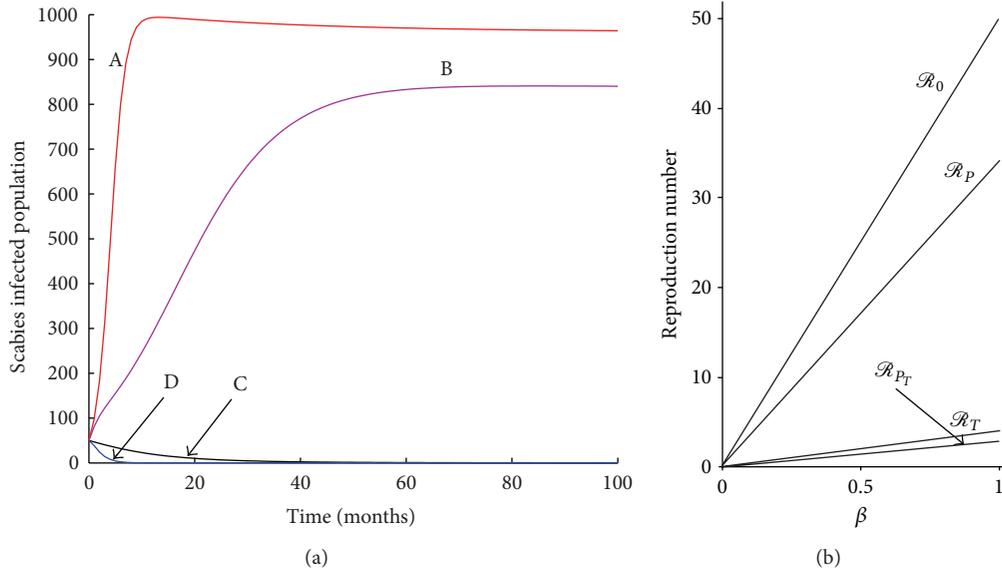


FIGURE 3: Effects of vaccination and treatment. A denotes when there is no intervention, B denotes when vaccination is the only intervention strategy to fight scabies, C denotes when scabies treatment is the only intervention, and D denotes when vaccination and treatment are both used to control scabies. Parameter values used are in Table 3.

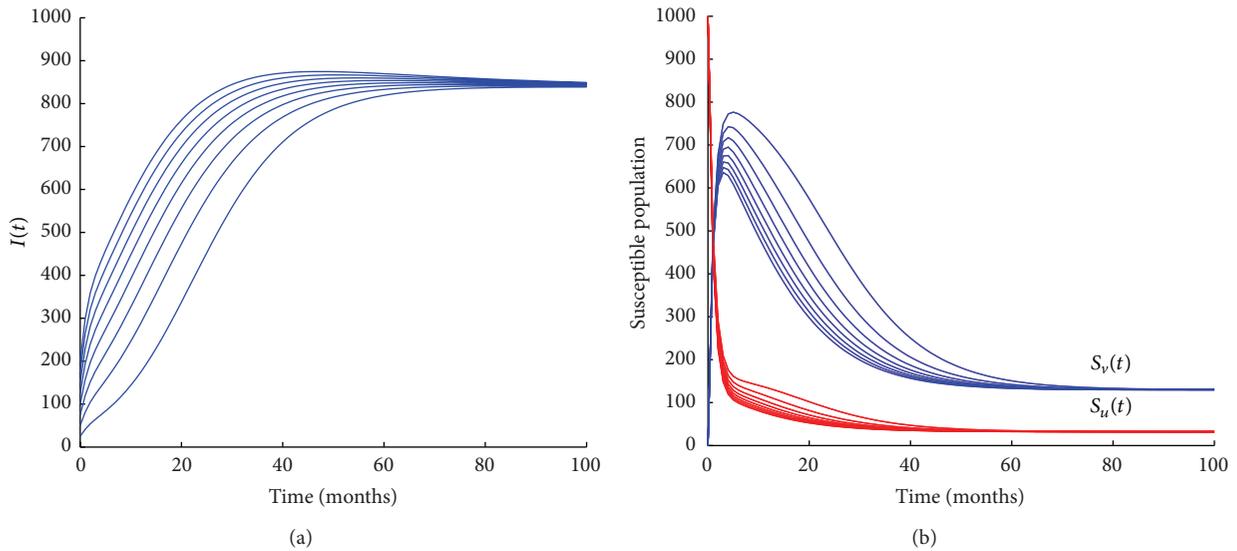


FIGURE 4: Simulations of model system (1) showing plots of the susceptibles and scabies infected as a function of time with various initial conditions when $R_p > 1$ ($R_p = 1.545$). Parameter values used are in Table 3.

The fact that (16) is negative suggests that even in communities where treatment of scabies is already available the community will also benefit scabies vaccination.

4. Numerical Simulations

In this section, we carry out detailed numerical simulations using MATLAB programming language to assess the possible effects intervention strategies will have on scabies control. The parameter values that we use for numerical simulations are in Table 3. In Table 3, CSOZ denotes Central Statistical Office of Zimbabwe. For vaccination and vaccine waning rates, we used estimates used in possible TB vaccines by Bhunu et al. [5], just for illustration purposes.

Figure 3 shows the effect of vaccination and treatment on the actual scabies cases and on the reproduction numbers obtained for different scenarios. This in a way allows comparison of vaccination and treatment as intervention strategies to control scabies. Figure 3(a) is graphical representation of scabies infected population under different intervention strategies. It shows that in the absence of any intervention strategy the scabies infected population increases from the onset and reaches a state where it remains constant. In the presence of vaccination, only the number of scabies increases from the onset until it reaches its asymptotic state where it remains more or less constant. It is worth mentioning here that trend A is always greater than trend B apart from

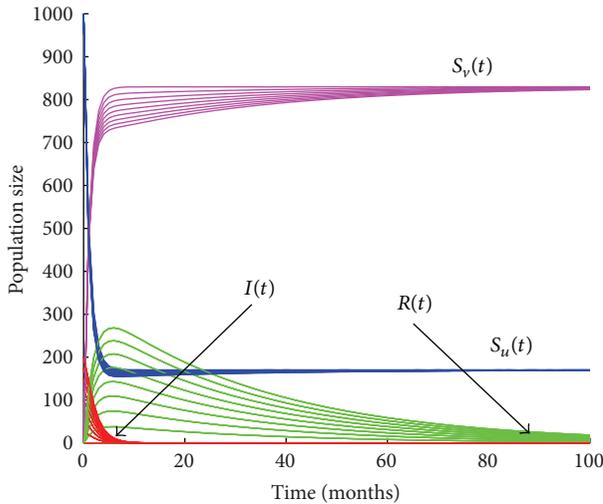


FIGURE 5: Simulations of model system (1) showing plots of the susceptibles and scabies infected as a function of time for various initial conditions when $\mathcal{R}_{P_T} < 1$ ($\mathcal{R}_{P_T} = 0.875$). Parameter values used are in Table 3.

the starting point. This suggests that vaccination will partially reduce scabies infection. However, the situation is different when treatment is involved as the only intervention strategy, and the number of scabies case declines to asymptotically low levels, suggesting that treatment alone can control scabies infections. In the case where vaccination of susceptibles is coupled with treatment infectives, the scabies infected population falls off more rapidly to asymptotically low levels than when treatment is used as the only intervention strategy. Vaccination reduces the rate at which individuals are infected and treatment kills off scabies causing mites. Figure 3(b) illustrates relationship and behavior of \mathcal{R}_0 , \mathcal{R}_P , \mathcal{R}_T , \mathcal{R}_{P_T} for varying rate of acquiring scabies infection. It shows that $\mathcal{R}_0 > \mathcal{R}_P > \mathcal{R}_T > \mathcal{R}_{P_T}$ for the given parameter values and when there is one scabies infected individual in a pool of exclusively susceptible individuals. This implies that vaccination coupled with treatment is the most effective way of combating scabies in a community. Comparing results in Figure 3(a) with those in Figure 3(b), we conclude that vaccination coupled with treatment is the best approach to control scabies as evidenced by the depletion of scabies infected cases in Figure 3(a) and a very small reproduction number in Figure 3(a). By looking at trends C and D (Figure 3(a)) and \mathcal{R}_T and \mathcal{R}_{P_T} (Figure 3(b)), we safely also conclude that treatment alone is also effective in scabies control.

In Figure 4, effects of varying initial conditions when the vaccination induced reproduction is greater than unity are illustrated. It shows that the susceptibles and scabies infected converge to their corresponding endemic equilibrium states. It is worth mentioning that there is no recovered population in this case as once an individual has been infected, he/she remains so in the absence of treatment.

Figure 5 graphically shows what happens when $\mathcal{R}_{P_T} < 1$ for various initial conditions. It shows that all the sub-populations of people converge to their respective disease-free equilibrium states. This signifies that making

the reproduction number less than unity is necessary for disease eradication.

5. Discussion

A mathematical model for the transmission dynamics of scabies has been proposed and investigated. The potential of a possible preexposure vaccine and treatment have been analysed and compared in an effort to understand the best possible scabies control strategies. The disease-free equilibrium is shown to be locally asymptotically stable when the corresponding reproduction number is less than unity. The possible endemic equilibria states of the model have been explored using the Descartes' rule of signs. Analysis of the reproduction number has shown that vaccination has some potential to control the scabies epidemic. Additionally, it has been shown that, in communities where scabies treatment is available, adding vaccination into that community will increase the potential to control scabies. It has been shown that to effectively control scabies through vaccination alone there should be high vaccination coverage rates with a vaccine which does not wane too quickly. Numerical simulations also support the analytical results obtained that is vaccination coupled with treatment is the best possible approach to successfully fight scabies in a given community. Furthermore, numerical simulations show that treatment alone is able to control scabies as noted by the depletion of scabies cases and low reproduction number when it is used as the only intervention strategy. This is good news considering that currently there is no preexposure vaccine against scabies. However, given the fact that the most effective medications for scabies are beyond the reach of many, a development and deployment of a "new" vaccine will help in controlling the spread of scabies especially among the disadvantaged communities.

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