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Voluntary vaccination strategy and the spread of sexually transmitted diseases

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ABSTRACT

In this work, we investigate the spread and control of sexually transmitted diseases when a game-theory based vaccination strategy is involved. An individual's decision on vaccination uptake may follow a cost-benefit analysis since the individual obtains immunity against the disease from the vaccination and, at the same time, may have some perceived side effects. Evolutionary game theory is integrated into the epidemic model to reveal the relationship between individuals' voluntary decisions on vaccination uptake and the spread and control of such diseases. We show that decreasing the perceived cost of taking vaccine or increasing the payoff from social obligation is beneficial to controlling the disease. It is also shown how the "degree of rationality" of males and females affects the disease spread through the net payoff of the game. In particular, individual awareness of the consequences of the disease on the infectives also contributes to slowing down the disease spread. By analyzing an asymmetric version of our evolutionary game, it is shown that the disease is better controlled when individuals are more sensitive to fitness differences when net payoff is positive than when it is negative.

1. Introduction

The development of effective vaccines against some sexually transmitted diseases enables susceptible individuals to protect themselves from infection. The wide applications of such vaccines have the potential to eliminate the spread of these diseases [1]. However, even though the immediate monetary cost of some vaccines is becoming lower, there is often no significant increase in the rate of voluntary vaccination and, in fact, the rate of taking vaccines is decreasing in some locations [2–4]. Of course, besides the monetary cost, taking a vaccine has some potential risk from its side-effects. However, although most vaccines used in clinics are safe for the majority of the population (i.e. there is low risk of side-effects), the perceived (or "fictional") risk of taking the vaccination still remains high [4,5]. A susceptible individual may also refuse to take the vaccine due to cultural reasons [5]. From these observations, it is clear that individuals are making vaccination decisions based on complex interrelated factors, a situation where, as we will see, a game-theoretic perspective is important.

As a public health problem, the prevalence of sexually transmitted diseases (STDs) is becoming a major health concern [6]. Recent investigations indicate that over a million adolescents and young adults annually suffer from one or more STDs in the United States [7]. The consequences of such diseases might be severe. For example, the human papilloma virus (HPV) can cause cervical cancer for women [8] and males infected with HPV have the potential to develop penis carcinomas [9]. In 1998, 12,800 women were diagnosed with uterine carcinoma in the United States [8]. Though the use of condoms has proved to be effective in lowering the chance of getting infected with many types of STDs, it does not provide sufficient protection from infection by other types [10]. Vaccination against STDs has been introduced as an intervention approach to control the spread of such diseases and this approach has been demonstrated to be effective [1,11]. Vaccines against many STDs are available for both male and female individuals [10,12–14]. However, some vaccines may have potential adverse side effects and risks, which are the significant barriers that compromise the vaccine uptake [15,16].

When making a decision on vaccine uptake, an individual may consider the potential payoff and perceived cost of the vaccine. This benefit-cost analysis may lead to a "rational" decision/behavior for the individual. An individual's rational behavior can be modeled using game theory. In fact, game theory has even been used to successfully predict the population dynamics of ecological systems where each species is assumed to behave rationally to increase their per capita growth rates [17,18]. Von Neumann and Morgenstern performed a thorough study on a variety of economic

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models using game theory [19]. They presented a discussion on rational decision making and investigated the effects such decisions have on economic and sociological direction. Kahneman and Tversky [20] developed prospect theory to model an individual's decision making process under perceived risks, using an asymmetric hypothetical value function that incorporates risk aversion.

Game theory based behavioral dynamics have also been integrated into disease models to study the effects that individuals' rational decisions have on disease transmission [21–26]. In particular, game-theoretic epidemic models have been introduced to study disease transmission in multi-group populations. For example, Reluga [27] investigated disease transmission between two interacting subpopulations, in which an epidemiology game was integrated to address the relation between decision making and the epidemic status. The author proved the existence of multiple Nash equilibria and discussed, in terms of their stability, which were good predictors of the epidemic outcome. Galeotti and Rogers [28] constructed a mathematical model with strategic immunization to investigate disease transmission between two groups, thereby revealing the relationship between disease control and resource allocation. Game theory has also been used to study the effects of vaccination decisions on HPV transmission. For example, Basu et al. [29] designed a game-theoretic epidemic model to investigate these effects when public perceptions and economic incentives are taken into account.

The aim of this article is to investigate the effects individual rational decisions have on vaccine uptake for STDs and the corresponding consequences of such behaviors on the disease spread. Since the majority of male individuals get STD infections from female individuals and vice versa [30], when making a decision about the vaccination uptake, an individual may consider the epidemic status of the population of the opposite gender. On the other hand, male and female individuals may suffer from an STD in different ways and the treatment of such a disease for men and women might also be different. For instance, the probability that the STD occurs for males might not be the same as for females. Men and women may also have different STD related death rates. Thus, the cost-benefit analysis and their corresponding decision making process for male and female individuals are different, which leads to complex behavioral and epidemic dynamics. In this article, we construct an epidemic model with game theory-based behavioral strategies integrated into the decision-making process of male and female individuals concerning their vaccination uptake and the resulting consequences on the transmission and control of STDs. The rest of this paper is organized as follows: In Section 2, we develop the game theory based sexually transmitted disease model with vaccination strategy involved. Then, in Section 3, we obtain the disease-free equilibrium of the model and calculate the basic reproduction number. Section 4 generalizes the analysis of Sections 2 and 3 to the model that includes asymmetric decision making. In Section 5, we present numerical simulation results and discuss them in terms of the control and spread of the STDs.

2. The sexually transmitted disease model with vaccination strategy

2.1. The sexually transmitted disease model

In the literature, mathematical models have been introduced to consider the impact of mass vaccination on the spread and control of STDs. For example, the deterministic model of Alsaleh and Gumel [31] examines this impact on the transmission dynamics of HPV type viruses that have the potential to cause tumors and warts . The authors performed stability and bifurcation analysis to examine the effectiveness of two currently available anti-HPV vaccines with constant vaccination rate.

In this section, we introduce our epidemic model where the above constant vaccination rates are replaced with a game-theoretic vaccination strategy. In our model, the population of male individuals is divided into susceptible, infectious, and vaccinated classes, denoted by S_M, I_M and V_M respectively. Similarly, the population of female individuals contains susceptible, infectious, and vaccinated classes, which are, respectively, denoted by S_F, I_F and V_F. The epidemic model is given by the following differential equation system.

$$
\begin{aligned}
\dot{S}_M &= A_M - \mu_M S_M - \frac{\beta_F S_M I_F}{(S_F + I_F + V_F)^p} + r_M I_M \\
&\quad - \phi_M S_M s_M(\Delta W_M) + \eta_M V_M, \\
\dot{I}_M &= \frac{\beta_F S_M I_F}{(S_F + I_F + V_F)^p} - r_M I_M - \mu_M I_M - d_M I_M, \\
\dot{V}_M &= -\mu_M V_M + \phi_M S_M s_M(\Delta W_M) - \eta_M V_M, \\
\dot{S}_F &= A_F - \mu_F S_F - \frac{\beta_M S_F I_M}{(S_M + I_M + V_M)^q} + r_F I_F - \phi_F S_F s_F(\Delta W_F) + \eta_F V_F, \\
\dot{I}_F &= \frac{\beta_M S_F I_M}{(S_M + I_M + V_M)^q} - r_F I_F - \mu_F I_F - d_F I_F, \\
\dot{V}_F &= -\mu_F V_F + \phi_F S_F s_F(\Delta W_F) - \eta_F V_F,
\end{aligned} \tag{1}
$$

where A_M and A_F denote the recruitment rates of male and female individuals into the population. Here μ_M and μ_F respectively represent the death rates for males and females (and so $\frac{1}{\mu_M}$ and $\frac{1}{\mu_F}$ can also be interpreted as the expected sexual activity durations of male and female individuals respectively [31]).

System (1) models STDs that are typically transmitted from female individuals to male individuals or vice versa. The effect of disease transmission among men who have sex with men and women who have sex with women is beyond the scope of this article. In system (1), the susceptible male individuals get infected from infected female individuals at incidence rate

$$\frac{\beta_F I_F}{(S_F + I_F + V_F)^p},$$

where β_F is a positive constant and $p \in [0, 1]$. On the other hand, the susceptible female individuals get infected from infected male individuals at incidence rate

$$\frac{\beta_M I_M}{(S_M + I_M + V_M)^q},$$

where β_M takes a positive value and $q \in [0, 1]$, which may be different from β_F and p respectively. Obviously, the widely used [32] standard incidence rate and bilinear incidence rate correspond to $p = q = 1$ and $p = q = 0$, respectively. We also assume that the infected male and female individuals have different recovery rates, given by r_M and r_F, respectively.

Vaccination is an effective approach to control or slow down the spread of STDs. An individual's decision on vaccination uptake follows his or her benefit-cost analysis. In model (1), ϕ_M is the rate that susceptible male individuals take the vaccination and ϕ_F denotes the vaccination rate of female individuals when the benefit of taking the vaccination is infinite and the cost is zero. When the cost and benefit of taking vaccination is taken into account, using a game-theoretic strategy, the vaccination rates of the male and female individuals become $\phi_M s_M(\Delta W_M)$ and $\phi_F s_F(\Delta W_F)$, respectively, where $s_M(\cdot)$ and $s_F(\cdot)$ are functions of fitness differences of susceptible male individuals ΔW_M and susceptible female individuals ΔW_F, respectively. Model (1) assumes that the immunity obtained from the vaccination is not permanent. Vaccinated male individuals lose immunity and move into compartment S_M at rate η_M. For vaccinated female individuals, the rate of losing their immunity and moving into compartment S_F is η_F.