Journal of Theoretical Biology 388 (2016) 119–130

Contents lists available at ScienceDirect

Journal of Theoretical Biology

journal homepage: www.elsevier.com/locate/yjtbi

Effects of adaptive protective behavior on the dynamics of sexually transmitted infections

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HIGHLIGHTS

- Behavior change over time is an important determinant of STI dynamics.
- We built a game theoretic STI transmission model with adaptive contact behavior.
- Behavioral-transmission feedback yields a wide range of dynamics.
- Extinction is possible for $\mathcal{R}_0 > 1$, due to behavior change.
- However, endemic prevalence is also possible for arbitrarily low R0.

ARTICLE INFO

Article history:
Received 16 March 2015
Received in revised form
19 August 2015
Accepted 20 August 2015
Available online 8 September 2015

Keywords:
Transmission model
Behavioral dynamics
Game theory
Sexually transmitted infections

ABSTRACT

Sexually transmitted infections (STIs) continue to present a complex and costly challenge to public health programs. The preferences and social dynamics of a population can have a large impact on the course of an outbreak as well as the effectiveness of interventions intended to influence individual behavior. In addition, individuals may alter their sexual behavior in response to the presence of STIs, creating a feedback loop between transmission and behavior. We investigate the consequences of modeling the interaction between STI transmission and prophylactic use with a model that links a Susceptible-Infectious-Susceptible (SIS) system to evolutionary game dynamics that determine the effective contact rate. The combined model framework allows us to address protective behavior by both infected and susceptible individuals. Feedback between behavioral adaptation and prevalence creates a wide range of dynamic behaviors in the combined model, including damped and sustained oscillations as well as bistability, depending on the behavioral parameters and disease growth rate. We found that disease extinction is possible for multiple regions where $\mathcal{R}_0 > 1$, due to behavior adaptation driving the epidemic downward, although conversely endemic prevalence for arbitrarily low $\mathcal{R}_0$ is also possible if contact rates are sufficiently high. We also tested how model misspecification might affect disease forecasting and estimation of the model parameters and $\mathcal{R}_0$. We found that alternative models that neglect the behavioral feedback or only consider behavior adaptation by susceptible individuals can potentially yield misleading parameter estimates or omit significant features of the disease trajectory.

1. Introduction

In spite of advances in treatment and prevention, sexually transmitted infections (STIs) remain endemic worldwide. The CDC estimates that 20 million new cases occur annually in the United States alone (National Center for HIV/AIDS, 2013), incurring a total cost of (16 billion for treatment and care. Globally, treatable STIs are responsible for approximately 500 million new cases per year (World Health Organization Media Centre, 2013), while an estimated 35 million individuals currently live with HIV. These statistics underscore the importance of understanding the dynamics that drive and sustain STI transmission. To this end, mathematical epidemiology has made substantial progress investigating the role of contact patterns such as age-structure, sexual networks, and levels of sexual activity (Anderson and Garnett, 2000; Eames and Keeling, 2002). However, many open questions remain in understanding the feedback relationship between behavioral change and disease dynamics.

From a behavioral standpoint, sexually transmitted diseases are noteworthy as they require a direct and intimate interaction

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http://dx.doi.org/10.1016/j.jtbi.2015.08.022
0022-5193/

between individuals. As a result, many common preventative measures, such as condom use, are not determined unilaterally (Lam et al., 2004; Peasant et al., 2014). In addition, assuming individuals form preferences over protective behaviors based on the associated costs and benefits, we would expect these behaviors to respond to the risk of infection as an outbreak progresses (Des Jarlais et al., 1996; SteelFisher et al., 2009; Rubin et al.,). While changes in risky or protective behavior can amplify or suppress outbreaks, adoption of these behaviors can in turn be driven by the spread of disease, as demonstrated by increased testing and condom use among men who have sex with men in response to the HIV outbreak in the US (Fisher and Fisher, 1992; Gregson et al., 2006).

Methods from game theory provide a framework with which to capture this feedback, grounded in well-established mathematical and economic theory. The resulting economic- epidemiological models can explicitly represent the decision process of individuals either in direct interactions (e.g. sexual encounters) or population interactions (e.g. vaccination behavior) (Fenichel et al., 2011; Schroeder and Rojas, 2002; Bauch, 2005; Bauch and Bauch, 2004; Reluga and Galvani, 2011; Reluga et al., 2006; Reluga, 2010). Including the effects of behavioral change on STI dynamics has been primarily motivated by the HIV epidemic among men who have sex with men (MSM) in the 1980s and 1990s, but this modeling approach is relevant for the study of other pathogens and communities as well. Indeed, in 2013 the WHO highlighted the need to study behavioral change in order to design effective interventions (World Health Organization Media Centre, 2013).

Many economic-epidemiological models rely on two behavioral assumptions that are worth consideration. The traditional game theoretic framework assumes that all actors are fully rational, responding optimally at every stage of play (Fudenberg and Tirole, 1991). While convenient, the rationality assumption remains a subject of debate in economic literature. Empirical studies note circumstances in which individual behavior appears to depart from a strict payoff maximization foundation (Selten, 1990; Kahneman, 1994; Bazerman, 1983). In addition, most models (e.g. Chen, 2004 and Geoffard and Philipson, 1996) assume that only susceptible individuals make choices regarding protective behavior. This assumption is the result of representing the cost–benefit calculus of individuals as a tradeoff between various private costs of protective behavior and the risk of infection. However, infected individuals may have incentives to reduce contact or use protection as well, motivated by altruism, self interest, or other factors (Wolitski et al., 2003; O'Leary,). This has been the focus of several intervention strategies in practice (Kennedy et al., 2010; de Rosa and Marks, 1998).

In this paper, we propose a model of combined behavioral and disease transmission dynamics that uses the outcome of sexual interactions between susceptible and infected individuals to determine the effective contact rate for a mass action model of disease transmission. The combined model bears some similarity to the behavior-disease model proposed in Schroeder and Rojas (2002). There are, however, several critical distinctions. We use a deterministic ODE framework, while our game-theoretic model collapses the protection-use game to a single interaction instead of a multi-stage negotiation. In addition, similar to Bauch (2005) and Reluga et al. (2006) we use evolutionary dynamics to represent the process of behavioral change over time, allowing for non-optimal but potentially more realistic behaviors. Unlike the inductive reasoning game developed by Breban and Vardavas (2007), our behavioral dynamics only explicitly consider the current state instead of a history of actions. While this approach loses some realistic features, it still allows us to relax the assumption of full rationality while also providing a convenient mathematical formulation for the combined model (Smith, 1982; Hofbauer and Sigmund, 2003).

2. Model

The Susceptible-Infectious-Susceptible (SIS) model has been studied extensively as a simplified representation of bacterial sexually transmitted diseases (Anderson, 1982; Anderson and May, 1991; Yorke et al., 1978). The model equations are

$$\begin{aligned}\dot{S} &= \gamma I - \beta SI, \\ \dot{I} &= \beta SI - \gamma I,\end{aligned} \tag{1}$$

where S is the fraction of the population which is susceptible, I is the fraction infected, β is the effective contact rate; the product of the rate of sexual partner acquisition and the probability of disease transmission from an infected to a susceptible partner, and γ is the rate of recovery or treatment. The basic reproductive ratio is

$$\mathcal{R}_0 = \frac{\beta}{\gamma}. \tag{2}$$

The disease free equilibrium (DFE) occurs if $\mathcal{R}_0 < 1$. Otherwise the endemic prevalence is

$$I^* = 1 - \frac{\gamma}{\beta}. \tag{3}$$

In order to capture the potential for individuals to adapt their protective behaviors over the course of an outbreak, we define a Bayesian game (Harsanyi, 1967) between a pair of players. In Appendix A, we give a brief overview of the definitions and structure of Bayesian games, with more complete treatments given in Fudenberg and Tirole (1991), Tadelis (2013), Harsanyi (1967). The payoffs for the game depend on the disease states of both players, which are considered private information. Players must infer the type of their partner, reflecting realistic uncertainty about serostatus (Kaplan and Shayne, ; Gold and Skinner, 1996; O'Leary, ; Wiktor et al., 1990; Dawson et al., 1994). Consistent with the notation for the SIS model, a player may be one of two types chosen from the type space $\Theta = \{S, I\}$. Each player chooses between using protection (P) or no protection (U) for a given sexual encounter. If both players select the same action, the outcome of the game is the same as the chosen action. We assume that if both players select different actions the encounter does not proceed and the effective contact rate for the pair of players is 0. In order to characterize the strategy space for this game, it is convenient to use the type-contingent notation $\sigma_j(\theta_i) = a_i \in \{P, U\}$[1] to denote the action player i would choose if she was of type θ_i under the jth strategy. A complete strategy for a player then specifies a pair of actions $\sigma_j := \sigma_j(\theta_i = S)\sigma_j(\theta_i = I) \in \{PP, PU, UP, UU\}$. Without loss of generality, the type-dependent payoff (utility) to player 1 for a given pair of actions and types is written $u_1(\sigma_j(\theta_1), \sigma_k(\theta_2), \theta_1, \theta_2)$ (where the first argument specifies player 1's action assuming type θ_1 under strategy j and the second entry player 2's action assuming type θ_2 under strategy k) . Then player 1's overall expected payoff for a particular strategy profile (i.e. for a pair of type-contingent strategies σ_j and σ_k for each player) is the double expectation of $u_1(\sigma_j(\theta_1), \sigma_k(\theta_2), \theta_1, \theta_2)$ over both players potential types (Fudenberg and Tirole, 1991), that is,

$$E\left[u_1(\sigma_j(\theta_1), \sigma_k(\theta_2), \theta_1, \theta_2)\right] = \sum_{\theta_1} Pr(\theta_1)\left[\sum_{\theta_2} p_1(\theta_2 | \theta_1) \, u_1(\sigma_j(\theta_1), \sigma_k(\theta_2), \theta_1, \theta_2)\right] \tag{4}$$

where $E[u_1(\sigma_j(\theta_1), \sigma_k(\theta_2), \theta_1, \theta_2)]$ is sometimes written more simply as $E[u_1(\sigma_j, \sigma_k)]$. The probabilities for each player being of either type, $Pr(\theta \in \{S, I\})$, are given by the distribution of susceptible and infected individuals in the population. This distribution acts as the common

[1] Players in this game are interchangeable so we do not specify distinct strategy sets for each player.