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A risk-based model for predicting the impact of using condoms on the spread of sexually transmitted infections

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ABSTRACT

We create and analyze a mathematical model to understand the impact of condom-use and sexual behavior on the prevalence and spread of Sexually Transmitted Infections (STIs). STIs remain significant public health challenges globally with a high burden of some Sexually Transmitted Diseases (STDs) in both developed and undeveloped countries. Although condom-use is known to reduce the transmission of STIs, there are a few quantitative population-based studies on the protective role of condom-use in reducing the incidence of STIs. The number of concurrent partners is correlated with their risk of being infectious by an STI such as chlamydia, gonorrhea, or syphilis. We develop a Susceptible-Infectious-Susceptible (SIS) model that stratifies the population based on the number of concurrent partners. The model captures the multi-level heterogeneous mixing through a combination of biased (preferential) and random (proportional) mixing processes between individuals with distinct risk levels, and accounts for differences in condom-use in the low- and high-risk populations. We use sensitivity analysis to assess the relative impact of high-risk people using condom as a prophylactic intervention to reduce their chance of being infectious, or infecting others. The model predicts the STI prevalence as a function of the number of partners of an individual, and quantifies how this distribution of effective partners changes as a function of condom-use. Our results show that when the mixing is random, then increasing the condom-use in the high-risk population is more effective in reducing the prevalence than when many of the partners of high-risk people have high risk. The model quantifies how the risk of being infected increases for people who have more partners, and the need for high-risk people to consistently use condoms to reduce their risk of infection.

1. Introduction

There are approximately 19.7 million new Sexually Transmitted Infections (STIs) every year in the United States of America (Satterwhite et al., 2008). More than half of the people in the U.S. will have an STI at some point in their lifetime (Koutsky, 1997). Mathematical models can provide frameworks to understand the underling epidemiology of STI and how they are

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correlated to the social structure of the infectious population (Del Valle, Hethcote, Hyman, & Castillo-Chavez, 2005; Del Valle, Hyman, Hethcote, & Eubank, 2007; Hyman & Li, 1997a, 1997b). Transmission-based models can help the medical community to understand and to anticipate the spread of diseases in different populations, and help them to evaluate the potential effectiveness of different approaches for bringing an epidemic under control.

We develop and analyze a continuous risk-based transmission model that can be used to understand the spread of STIs in the adolescents and young adult population. The model predicts the impact of people having different number of concurrent partners or using prophylactics, such as condoms, on the rate the infection spreads. These new equations extend our previous two-risk group STI model for the spread of Chlamydia in heterosexual populations (Azizi, Xue, & Hyman, 2016).

The sexually active population is divided into the susceptible population (S), and the infectious population (I). Once a person has recovered from infection, they are again susceptible to infection. That is, the model has an $S \rightarrow I \rightarrow S$ (SIS) structure. Using this model, **we study the impact of variations in number of partners, mixing patterns in selecting partners, and condom-use to determine optimal STI prevention policies. We study how the number of partners of an individual, and how often they use condoms, affect the spread of STIs.**

Chlamydia, gonorrhea, syphilis, and chancroid are highly infectious STIs where the number of partners an infectious person has is one of the most important risk factors in spreading the infection. **In our risk-based integro-differential model, the risk is defined based on the number of partners a person has per year.** The distribution of risk behavior for a population, such as the fraction of the population having multiple partners, affects the spread of STIs. Also, the number of partners that their partners have (their partner's risk) affects the spread of an STI and must be accounted for in the model. Our model accounts for a broad range of risk behavior, defined as the number of partners per year, that is captured as a continuous variable.

We use the terms low-risk and high-risk to differentiate between people with only a few partners per year (<3) and those with high number of partners per year (>3). This model could also be used to include separate core high-risk groups, such as sex workers. However, in the young adult population being modeled, sex-workers are not believed to be a major factor in the spread of highly infectious STIs, like chlamydia.

The risk of contracting STI is primarily a function of a person's risk, the probability that a partner is infectious, and the use of prophylactics (e.g. condoms). We use the selective mixing model developed by Busenberg & Castillo-Chavez, (1991) to capture the heterogenous mixing among people with different number of partners. Our model is closely related to the STI models for the spread of the HIV/AIDS in heterosexual networks (Hyman & Stanley, 1988, 1989) that distribute the population based on their risk, such as the number of partners (Hyman, Li, & Stanley, 2001, 2003; Hyman & Stanley, 1988, 1989).

Chlamydia and gonorrhea are transmitted when infected semen or vaginal fluids contact mucosal surfaces. Male latex condoms can, if used correctly, block the discharge of semen or protect the male urethra against exposure to vaginal secretions (Centers for Disease Control Prevention & et al., 2002, p. 2007). Condoms can greatly reduce (but not eliminate) the risk of STI, and are the primary strategy for STI prevention in sexually active individuals worldwide (Centers for Disease Control Prevention & et al., 2002, p. 2007; Mann, Stine, & Vessey, 2002). The condom-use parameter is an aggregated measure that accounts the effectiveness of condoms to prevent spread of infection when used appropriately or inappropriately.

The parameters in the model, such as the distribution of risk, are estimated based on recent surveys (Beadnell et al., 2005; Lescano et al., 2006) and from a pilot study of the number of partners for young sexually active people living in New Orleans. We use local sensitivity analysis to identify the relative importance of condom-use and illustrate how this analysis can be used to prioritize individual-level behavioral strategies based on their predicted effectiveness.

2. Mathematical model

We assume a closed steady-state population $N(r) = S(t,r) + I(t,r)$ of people with risk $r \in [r_0, r_\infty]$ is divided into $S(t,r)$, and $I(t,r)$, where $S(t,r)$ $(I(t,r))$ is the number of susceptible (infectious) people with risk r at time t. The susceptible population becomes infectious at the rate λ per year, and infectious population recovers with constant rate γ to again become susceptible. We assume both susceptible and infectious people leave the population at the migration rate μ per year and **that people maintain the same risk *r* while in the modeled population**.

Our integro-differential equation model for the spread of STIs is

$$\begin{aligned}
\frac{\partial S(t,r)}{\partial t} &= \mu(N(r) - S(t,r)) - \lambda(t,r)S(t,r) + \gamma I(t,r),\\
\frac{\partial I(t,r)}{\partial t} &= \lambda(t,r)S(t,r) - \gamma I(t,r) - \mu I(t,r),\\
S(0,r) &= S_0(r), \;\; I(0,r) = N(r) - S_0(r),
\end{aligned} \tag{2.1}$$

where initial distributions of the susceptible and infectious population are given at time $t = 0$.

Note that this model does not distinguish between men and women and is appropriate for homosexual STIs or infections when the distribution of risk and infection incidence in men and women is approximately the same. This also requires that the probability of transmitting the infection from an infectious man to a susceptible woman is approximately the same as the