Sexual network structure, partnership mixing patterns and HIV epidemic outcomes

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Short abstract

By means of a simulated epidemic in a population that resembles a southeastern African country, we demonstrate the effects of sexual network structure and mixing patterns on epidemic outcomes in terms of HIV prevalence, the fraction of incidence that is due to primary infection and the sex ratio of infections. The sexual mixing patterns and sexual network attributes that we explore are loosely based on empirical patterns and relate to partnership concurrency, partnership turnover rates, coital dilution, serosorting, elevated dissolution rates in HIV discordant couples, and the disproportionate recruitment of HIV positive women into polygynous unions. We find that high partnership turnover rates and partnership concurrency advance the spread of HIV, but these effects are mitigated (or reversed) by coital dilution, serosorting, and elevated dissolution rates in HIV discordant couples. Partnership concurrency also increases the fraction of incident cases that are due to primary infection as well as the gender imbalance in new infections.
Extended abstract

1. Introduction

Empirical studies in sub-Saharan Africa and elsewhere have documented a range of very specific sexual mixing patterns, but their implications for epidemic outcomes are not always well understood or easy to anticipate. We provide answers via a simulated epidemic in a population that resembles that of a southeastern African country. We are interested in three attributes of the HIV/AIDS epidemic: (1) the severity or HIV prevalence level, (2) the fraction of the incident cases that are due to primary infection and (3) the sex ratio of infections. Our focus on HIV prevalence hardly requires justification as it is the single most important indicator for monitoring the burden of HIV/AIDS in a population. The fraction of incident cases that occur during primary or acute infection is important because these infections are more difficult to prevent since the index case is usually unaware of the infection him or herself. The sex ratio of infections, in turn, is a marker of gender inequity.

The skewed sex ratio in generalized epidemics has in part been attributed to the greater biological susceptibility of women. Because of the protective effect of circumcision for men, the gender imbalance tends to be larger in populations where the rates of male circumcision are higher (Hertog 2008), and substantial age differences between sexual partners have also been proposed as a reason for the relatively high prevalence rates in young women in particular (Gregson et al. 2002). Reniers and Eaton (2009) further argue that the presumed gender differences in HIV infection may be inflated by larger bias in male compared to female HIV prevalence estimates. In this study we propose a couple of complementary explanations.

As causative agents behind the outcomes discussed above, we consider a handful of salient sexual mixing patterns and sexual network attributes. One that has featured prominently in the literature is partnership concurrency (Morris and Kretzschmar 1997), and we will evaluate its effects in populations with different partnership turnover rates (we will label these static and dynamic networks). We also evaluate the effect of a number of network attributes and sexual mixing patterns that stem from analyses on the relationship between polygyny and HIV infection (Reniers and Tfaify 2012; Reniers and Watkins 2010). We thus compare gender symmetric (assumed in the early modeling by Morris and Kretzschmar), and gender asymmetric concurrency (i.e., the network structure of polygyny) and contrast those with a monogamous sexual network. Similarly, we assess the effects of coital dilution on epidemic outcomes as well as the impact of the HIV Status based selection into polygynous unions. These analyses partly replicate those presented elsewhere (Santhakumaran et al. 2010; Sawers, Isaac and Stillwaggon 2011), but extend them in the sense that we also assess interactions with partnership turnover rates and evaluate a broader set of epidemic outcome measures.

A final set of sexual mixing patterns that we evaluate relate to HIV status-based partnership formation and dissolution, namely (1) elevated dissolution rates in serodiscordant couples, (2) lower partnership formation rates of HIV positives, and (3) serosorting. HIV status-based partnership choices will become an increasingly important factor in the epidemiology of HIV as the uptake of HIV testing and counseling (HTC) increases, but from previous research we also know that individuals often act on imperfect information about one’s own or someone else’s HIV infection (Watkins 2004). There are at least three studies that have suggested that partnership dissolution rates (through widowhood and divorce or separation) are significantly higher in serodiscordant couples, and particularly so in female positive serodiscordant couples (Carpenter et al. 1999; Grinstead et al. 2001; Porter et al. 2004). We will retain this gender imbalance in our simulations. Similarly, we will develop scenarios with lower partnership formation rates among HIV positives. Such a pattern may arise from HIV related morbidity, but also because those who are known or suspected to be HIV positive are less desirable partners or withdraw from the partnerships market on their own initiative. Empirical work previously referred to these partner recruitment dynamics as ‘positive selection’ (Reniers 2008), or, the drifting of HIV positives from the core to the periphery of sexual networks (Helleringer and Kohler 2007). Serosorting or assortative mating on HIV serostatus, in turn, has been well described among men who have sex with men in concentrated
epidemics (Parsons et al. 2005; Suarez and Miller 2001), but has—in our view—received insufficient attention as a mediating factor in populations with generalized epidemics (Reniers and Helleringer 2010). Again, we anticipate that the potential for serosorting will increase as more individuals become aware of their HIV status via the expansion of HTC and AIDS care programs.

2. Methods

To elucidate the effect of the sexual mixing patterns described above, we have developed a discrete-time agent-based model with one-month time steps built in NetLogo (Wilensky 1999). A screen shot of the user interface that displays some of the input and outputs is presented in Figure 1. The simulation tracks the characteristics of adult men and women and models their relationships. We only account for heterosexual relationships and do not distinguish between formal and informal sexual partnerships. Each relationship has a constant hazard rate of dissolving, and each individual may have up to three relationships simultaneously. The rate at which an individual forms a new (or additional) relationship depends on their sex and their current number of relationships. These rates for forming new partnerships are automatically selected so that the desired steady-state distribution of men and women with the number of partnerships in a user-defined scenario is attained. Before the start of the simulation, the relationship part is run for 10 years to ensure that the initial partnerships distribution is in a steady-state. Entry and exit rates from partnerships can be made dependent on HIV status as is also the case for the choice of future partners.

Figure 1: User interface of the simulation model

HIV transmission is a key part of the model. The simulation tracks the HIV status of each individual as well as the stage of infection: acute, chronic, or AIDS. The acute stage, and the final AIDS
stage are 8 times and 4 times as infectious as the chronic stage, respectively. A woman in the chronic stage will infect any HIV-partner with a probability of 0.019 each month and twice that for untreated men. The latter acknowledges the greater biological susceptibility of women. For infected women with polygynous partners, this probability may be multiplied by a factor which represents a coital-dilution effect.

The model is initialized by randomly selecting 5% of the individuals who are determined to be infected by HIV. We have chosen 5%, because we are primarily interested in the dynamics of generalized epidemics and not so much in the conditions that explain the early expansion of the epidemic. The time of infection for these seed cases is set to match the historical estimates of incidence in Williams et al. (2006). An infected individual is in the acute stage for the first three months after seroconversion. The length of their remaining life is chosen from a Weibull distribution with mean 9.7 years and shape factor of 2.25 and these simulations assume that treatment is not available. The first 90% of the remaining lifespan is considered to be in the chronic stage and the last 10% in the final AIDS stage.

Our model focuses on adults aged 15-50. We assume that the number of males and females are equal, and that the age distribution for each sex follows the age pyramid of Zambia. At this point we do not model specific patterns of age-mixing. Individuals may die from AIDS or from causes unrelated to AIDS at a rate of 0.006/12 per month. One further constraint is that the simulated population is held constant: each person who dies or turns 50 re-enters the population as an uninfected 15-year old individual of the same sex without existing relationships.

3. Model inputs

The simulation model settings and key characteristics of the baseline scenarios are summarized in Table 1. Aside from the overall model parameters it specifies the partnership distributions under different levels of concurrency, k, as defined by Morris and Kretzschmar (1997), and different specifications for the network structure, namely gender symmetric concurrency or gender asymmetric concurrency (i.e., polygyny). In the gender asymmetric scenario with k=40, for example, we assume that the mean number of partnerships per person is about 0.9 and that 24% of the men have more than one partner at any point in time. In Togo, one of the countries with the highest polygyny rates sub-Saharan Africa, 25% of the men aged 15-59 have more than one spouse (Anipah et al. 1999). In the symmetric case, k=40 implies a sexual network where about 12% of both men and women have multiple partnerships. Note that the scenarios with low and high levels of concurrency also differ in terms of the mean number of partnerships per person.

Static networks are defined as networks where the monthly partnership dissolution rate through separation or divorce is d=0.01667. In dynamic networks, the monthly dissolution rate is d= 0.0556. This translates into average partnership durations (in the absence of widowhood) of 5 [note: to be changed to 7 years in future versions] and 1.5 years, respectively. These levels are not necessarily chosen to represent empirically observed patterns for entire populations, but could represent the partnership turnover rates in sub-populations.
Table 1: model settings in the baseline scenarios

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<thead>
<tr>
<th>Global settings</th>
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<tr>
<td>Population size</td>
<td>3000</td>
<td></td>
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<tr>
<td>% HIV positive at t₀</td>
<td>5%</td>
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<tr>
<td>% on ART</td>
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<tr>
<td>Monthly HIV transmission rate (chronic stage)</td>
<td>0.019</td>
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<tr>
<td>Acute infectivity ratio</td>
<td>8</td>
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<td></td>
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<tr>
<td>AIDS stage infectivity ratio</td>
<td>4</td>
<td></td>
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<tr>
<td>Simulation length</td>
<td>25 years</td>
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<tr>
<th>Scenario specific settings</th>
<th>Mean # of partners(m) and level of concurrency (k)</th>
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<tbody>
<tr>
<td>Partnership distribution</td>
<td>Monogamy m=0.8, k=0</td>
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<tr>
<td>Male</td>
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<tr>
<td># partners</td>
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<tr>
<td>0</td>
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<tr>
<td>1</td>
<td>0.8</td>
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<tr>
<td>2</td>
<td>-</td>
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<tr>
<td>3</td>
<td>-</td>
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<tr>
<td>Female</td>
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<tr>
<td># partners</td>
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Partnership dissolution (divorce/separation) rates (per month)
- Dynamic: 0.01665
- Static: 0.05560

4. (Very) preliminary and selected results

Figure 2 highlights the contribution of concurrency as well as elevated partnership turnover rates to the HIV epidemic size. A comparison of monogamy with the two concurrency scenarios in each panel shows that partnership concurrency increases the epidemic potential in a population, but its effect is rather small at low levels of concurrency, and particularly so in what we have labeled a static network. In a static network with low partnership concurrency, the epidemic even decreases in size. In sexual networks with k=40, the epidemic size after 25 years is almost twice that of a monogamous population with the same average number of partners per individual.

The differences between symmetric and asymmetric concurrency are also negligible even though it seems that asymmetric partnership concurrency leads to slightly smaller epidemics in static networks. Small differences between gender symmetry and gender asymmetric concurrency have also been reported by Santhakumaran et al (2010). The differences between static and dynamic networks are much more striking, however. Irrespective of the sexual network structure (monogamous, symmetric or asymmetric concurrently) and concurrency level, dynamic sexual networks produces epidemics that are about four times as large as is the case in their static variant.

Aside from its effect on the epidemic size, partnership concurrency also increases the fraction of new HIV cases that are acquired from index cases who are themselves in the acute stage of infection (and therefore probably unaware of their HIV status). This is illustrated in Figure 3. In populations that practice monogamy, the fraction of new infections that are due to acute infection never surpasses a couple
of percentage points. With partnerships concurrency, up to $1/5$ of the new infections fall in this category [note: we need to explore the reasons for the apparent decline in dynamic networks with $k=40$].

Another less desirable aspect of partnership concurrency, gender asymmetric partnership concurrency to be precise, is that it inflates the female to male sex ratio of infections. This is illustrated in Figure 4. Whether a sexual network is static or dynamic does not seem to matter much in this regard.

[note: in the paper we will (1) elaborate on these results and relate them to empirical findings and HIV prevention policies, and (2) analyze the mediating effects of coital dilution, the disproportionate recruitment of HIV positive women into polygynous unions, the elevated dissolution rates in serodiscordant couples, the lower partnership formation rates among HIV positives, and serosorting on each of the outcomes described above]

**Figure 2.** Epidemic growth (HIV%) in static and dynamic sexual networks under monogamy and partnership concurrency

Legend: green= monogamy, orange= gender asymmetric concurrency, blue= gender symmetric concurrency (area represents 95% confidence intervals)
Figure 3. The percentage of HIV incident cases that are due to primary infection

Legend: green= monogamy, orange= gender asymmetric concurrency, blue=gender symmetric concurrency (point estimates plus 95% confidence intervals)
Figure 4. The female to male sex ratio of infections

Legend: green = monogamy, orange = gender asymmetric concurrency, blue = gender symmetric concurrency (95% confidence intervals)
References


