Evaluation of HIV Intervention Scenarios Targeted to Drug-Using Women from East Harlem: A Mathematical Modeling Approach

James M. McMahon, Ph.D.,[1] and Stephanie Tortu, Ph.D.[2]
[1]National Development and Research Institutes, Inc., New York, New York; [2]Tulane University School of Public Health and Tropical Medicine, New Orleans, Louisiana

Introduction

Low-income minority women make up one of the fastest-growing at-risk groups for HIV infection and have been targeted as a scientific and budgetary priority for both preventive and therapeutic research by the National Institutes of Health (NIH 1997; Nathanson 2000). Drug-using women from urban centers are at particularly high risk for HIV through both sex- and drug-related risk behaviors with male partners, especially injection drug users (IDUs) (Sterk 1988). Female crack-cocaine, cocaine, and heroin users from East Harlem provide a compelling example, having one of the highest HIV prevalence rates among women in the United States: 32 percent among IDUs, 20 percent among non-IDUs (Tortu et al. 2000). These women are further characterized by high unemployment, low education, frequent homelessness and exposure to violence, and high incarceration rates (Tortu et al. 2000). In addition, many female substance users turn to sex trading as a means of supplementing their income and supporting their illegal drug use (Tortu et al. 1999; Mallory and Stern 2000).

Our research in East Harlem has shown that drug-using women are at substantial risk for HIV infection through unprotected sex (Tortu et al. 1999, 2000) and receptive syringe sharing (Tortu et al. in press) with a variety of partners. We have also documented substantial heterogeneity in the patterns of HIV risk behaviors engaged in by these women. This finding has important implications for the development of HIV prevention programs. Prevention research over the past decade has demonstrated that the most effective interventions are those targeted at specific risk behaviors among specific risk groups (McCoy et al. 1998; Stevens et al. 1998). In the present study, an empirically based mathematical model was employed to assess the potential effectiveness of several HIV prevention scenarios targeted to drug-using women from East Harlem. Specifically, the model was used to estimate the number of HIV infections that would be averted in various risk groups under alternative intervention scenarios. The results of this study will help identify those risk subgroups, from among the study population, who are at greatest risk for HIV infection and who would therefore most benefit from prevention programs. A sensitivity analysis was conducted to quantify the effects of parameter uncertainty on the study outcomes.

Methods

Overview

Survey data from 390 HIV-negative drug-using women from East Harlem were applied to a mathematical model that predicted HIV incidence based on individual-level self-reported risk behaviors and other model parameters. Expected HIV incidence rates for this sample under various intervention scenarios were calculated and compared with the predicted baseline rate. This comparison provided an estimate of the number of HIV infections that would be averted under each intervention scenario. Univariate and multivariate sensitivity analyses were conducted to determine the effects of parameter uncertainty on the study results.

Subjects

Survey data from two studies on HIV risk behavior among female drug users were employed in the analysis. Data from the Women Drug-Users in Social Context (DUSC) study were used to model individual-level risk behaviors in the simulations. In the DUSC study, participants were recruited on the streets of East Harlem between September 1997 and June 1999 using targeted sampling (Watters and Biernacki 1989) and participant referrals. In order to participate, women had to be at least 18 years of age, heterosexually active a least once in the previous 6 months, and report the use of injected or noninjected heroin, cocaine, or crack in the previous 30 days. Study recruitment and survey procedures have been described in detail elsewhere (Tortu et al. 2000).

Data from a second ongoing study, Women Drug Users, Their Male Partners, and HIV Risk (Couples at Risk), were used to estimate some of the model parameters. In the Couples at Risk project, which began data collection in February 2001, female drug users who reported having a primary heterosexual partner (husband, common-law husband, or steady boyfriend of at least 1 year) were asked to enlist their partner in the study. Couples who participated were administered structured interviews in separate, private offices and were offered HIV counseling and testing.

Bernoulli mathematical model

The mathematical model used to estimate HIV incidence incorporates both sexual and injection risk exposures with primary, casual, and sex exchange partners. The model was applied to each subject on an individual basis. The probability (P) of acquiring HIV infection over a 12-month period was thus different for each of the 390 subjects in the data set, depending on their self-reported risk behaviors. The HIV incidence rate per 100 person-years was calculated as $100(\bar{P})$, where $\bar{P}$ is the mean infection probability for the sample.

The cumulative probability (P) of acquiring HIV infection over a 12-month period was computed for each subject in the data set using the following Bernoulli-process model:

$$P = 1-(1-A)(1-B)(1-C)(1-D) \quad (1)$$

where A is the probability of infection from a primary partner through condom-protected and unprotected vaginal and anal sex contacts, and receptive syringe sharing:

$$A = \pi_1 [1-(1-\alpha_a)^{mau} (1-\varepsilon\alpha_a)^{map} (1-\alpha_v)^{mvu} (1-\varepsilon\alpha_v)^{mvp} (1-\alpha_s)^{mrs}] \quad (1a)$$

B is the probability of infection from a casual sex partner through similar contacts, assuming an equal number of contacts for each casual sex partner:

$$B = 1 -[(1-\pi_2) + \pi_2 (1-\alpha_a)^{cau} (1-\varepsilon\alpha_a)^{cap} (1-\alpha_v)^{cvu} (1-\varepsilon\alpha_v)^{cvp} (1-\alpha_s)^{crs}]^{c} \quad (1b)$$

C is the probability of infection from a partner with whom sex was exchanged for drugs or money (assuming one contact per exchange partner), and D is the probability of infection through injection-related risk with a nonsexual partner:

$$C = 1-(1-\pi_3\alpha_a)^{xau} (1-\pi_3 (\varepsilon\alpha_a))^{xap} (1-\pi_3\alpha_v)^{xvu} (1-\pi_3 (\varepsilon\alpha_v))^{xvp} \quad (1c)$$

$$D = 1-(1-\pi_4\alpha_s)^{nrs} \quad (1d)$$

Equation 1 parameters are described in Table 1.

Table 1. Bernoulli equation parameters

Symbol	Description	Model parameter estimates	Derivation/source of estimate
Estimated parameters			
π_1	probability that a primary sex partner is infected	1 to .13	Tortu unpublished data from Couples study
π_2	probability that a casual sex partner is infected	.23	Deren et al. 1997; Tortu unpublished
π_3	probability that an exchange sex partner is infected	.15	Tortu unpublished
π_4	probability that a non-sexual injection partner is infected	.33	Des Jarlais et al. 1998; Tortu unpublished
α_a	per contact probability of HIV transmission (infectivity) for anal sex	.02	Mastro et al. 1996
α_v	per contact infectivity for male-to-female vaginal sex	.001	Mastro and Kitayaporn 1998; Gray et al. 2001
α_s	per contact infectivity for receptive syringe sharing	.0067	Kaplan and Heimer 1992
ε	condom failure rate	.10	Pinkerton et al. 1997; Poppen and Reisen 1997
Measured parameters			
mau	number of acts of unprotected anal intercourse with primary partner		
map	number of acts of protected anal intercourse with primary partner		
mvu	number of acts of unprotected vaginal intercourse with primary partner		
mvp	number of acts of protected vaginal intercourse with primary partner		
mrs	number of acts of receptive syringe sharing with primary partner		
cau	number of acts of unprotected anal intercourse with casual sex partners		
cap	number of acts of protected anal intercourse with casual sex partners		All measured parameter values were derived from individual-level self-reported risk behavior survey data from the DUSC study.
cvu	number of acts of unprotected vaginal sex with casual sex partners		
cvp	number of acts of protected vaginal intercourse with casual sex partners		
crs	number of acts of receptive syringe sharing with casual sex partners		
c	number of casual sex partners		
xau	number of unprotected anal sex acts with exchange sex partners		
xap	number of protected anal intercourse acts with exchange sex partners		
xvu	number of unprotected vaginal sex acts with exchange partners		
xvp	number of protected vaginal sex acts with exchange sex partners		
nrs	number of acts of receptive syringe sharing with non-sex partner		

Intervention scenarios

The effects of several alternative interventions on HIV incidence rates were modeled by modifying specific risk behavior parameters corresponding to the different intervention scenarios under evaluation. For example, to assess an intervention achieving a 50 percent reduction in the number of clients among female sex exchangers, a simulation with no modification of reported risk (baseline) was compared against a simulation in which the number of sex exchange partners was reduced by 50 percent among women who reported such behavior. Expected HIV incidence rates were computed for baseline and exchange intervention scenarios using the Bernoulli-process model described above. The number of HIV infections averted due to the intervention was then calculated as the difference in HIV incidence between the unmodified (baseline) and modified (intervention) runs. It is this value—the number of primary HIV infections averted—that was the outcome measure used to evaluate alternative prevention strategies (Pinkerton et al. 1998).

Six alternative intervention scenarios were compared and evaluated using the methods described. The six interventions were aimed at reducing (1) both the proportion of unprotected sex acts and syringe-sharing events between drug-using women and their primary heterosexual partners; (2) the proportion of unprotected sex acts with primary partners; (3) the number of sex exchange partners; (4) the proportion of unprotected sex acts with exchange partners; (5) the number of casual sex partners; and (6) the proportion of unprotected sex acts with casual partners. Target group sizes are presented in Table 2.

Table 2. Number of women from DUSC sample (N=390) in various risk subgroups

	Risk partnerships in previous 12 months			
Risk behaviors	**Primary**	**Casual**	**Exchange**	**Nonsexual**
Unprotected sex	246	63	89	—
Receptive syringe sharing	13	1	0	4

Model parameter estimates

The parameters used in the Bernoulli model can be classified into two basic types: measured and estimated. Measured parameters were obtained from individual self-reported risk behaviors (e.g., frequency of unprotected vaginal sex with a primary partner), whereas estimated parameters were approximated from population data (e.g., per-contact infectivity rate for HIV during unprotected vaginal sex).

Measured parameters. Sixteen risk behavior parameters were included in the simulation models (see Table 1). The values for these parameters were obtained from self-reports provided by the 390 uninfected women in the DUSC sample. Women reported on the frequency of their sex and injection practices over the previous 30 days (frequency of risk behavior with current partners), 6 months (frequency of risk behavior with past partners), and 1 year (number of casual and sex exchange partners). Extrapolations of these risk behaviors to a 12-month time period were performed where applicable.

Estimated parameters. Parameters for which no self-reported or individual-level data were available were estimated from population-level data. Three types of estimated parameters were used in the analysis: (1) per-contact probability of HIV transmission from an infected to an uninfected individual (infectivity rate), (2) the probability that a particular risk partner was HIV infected during risk activity, and (3) condom failure rate.

1. HIV infectivity rates (α).The parameter estimates for HIV infectivity rates used in the Bernoulli model were taken from published estimates as follows: .001 for male-to-female penile-vaginal intercourse (Mastro and Kitayaporn 1998; Gray et al. 2001); .02 for heterosexual penile-anal intercourse (Mastro et al. 1996); .0067 for receptive syringe sharing of a contaminated needle (Kaplan and Heimer 1992).
2. Probability that a given partner was HIV infected (π). Parameter estimates for π_1, the probability that a primary male partner is HIV infected, were derived from the Couples at Risk study. In this study, HIV testing was conducted on the primary sex partners of drug-using women in East Harlem (Tortu et al. 2002). These data were used to estimate π_1 for each subject in the simulation, based on the characteristics of their primary sex partner. For women who reported that their primary partner was HIV infected, π_1 was set to 1.0; for women who were uncertain of their partner's status, π_1 was determined on the basis of two important risk factors: IDU status and men who had sex with men (MSM); for primary partners who were IDU and MSM, $\pi_1 = .32$; IDU but not MSM, $\pi_1 = .23$; and neither IDU nor MSM, $\pi_1 = .13$.

   The parameter estimate for π_2, the probability that a casual sex partner is HIV infected, was set at .23—the population prevalence for male drug users in East Harlem (Deren et al. 1997; Tortu unpublished data; S-Y Kang personal communication).

Few studies have documented HIV prevalence among male clients of female commercial sex workers (FCSW); and none generalize well to current East Harlem populations (e.g., Elifson et al. 1999; Wallace et al. 1988; Chiasson et al. 1988). Based on HIV test results for males who exchanged drugs or money for sex in the Couples at Risk survey, we used an estimate of .15 for π_3, the probability that a female sex exchanger will encounter an HIV-positive client.

The mean estimate for π_4, the probability that a nonsexual injection partner is HIV infected, was set at .33—the combined population prevalence for male and female IDUs in East Harlem (Des Jarlais et al. 1998; Tortu unpublished data).

3. Condom failure rate (ε). The population estimate for the rate of condom failure was set at .10 (Pinkerton and Abramson 1997; Poppen and Reisen 1997).

Sensitivity analysis methods

Analyses were conducted to assess the degree to which study findings are sensitive to modifications of model parameters. Sensitivity analyses were employed to establish the conditions necessary for the study results to change. For example, what particular combination of model parameters would be required for an intervention scenario focused on sex exchange partners (rather than on primary partners) to yield the greatest number of HIV infections averted? Sensitivity analysis was conducted in two stages. First, a univariate technique was employed to identify model parameters with the greatest influence on the outcome measure. Second, a multivariate technique was used to determine specific combinations of model parameters that produced results different from those obtained in the initial simulation analysis.

In the univariate analysis, the intervention simulations were run multiple times, each time modifying a single parameter in the model. In this way, the effects of altering a single parameter at a time were assessed on model outcomes. High and low values (one-half and double the initial parameter estimates listed in Table 1) were used in place of initial estimates for six parameters (α_a, α_v, α_s, ε, π_2, π_3), and the corresponding outcomes were compared with initial results.

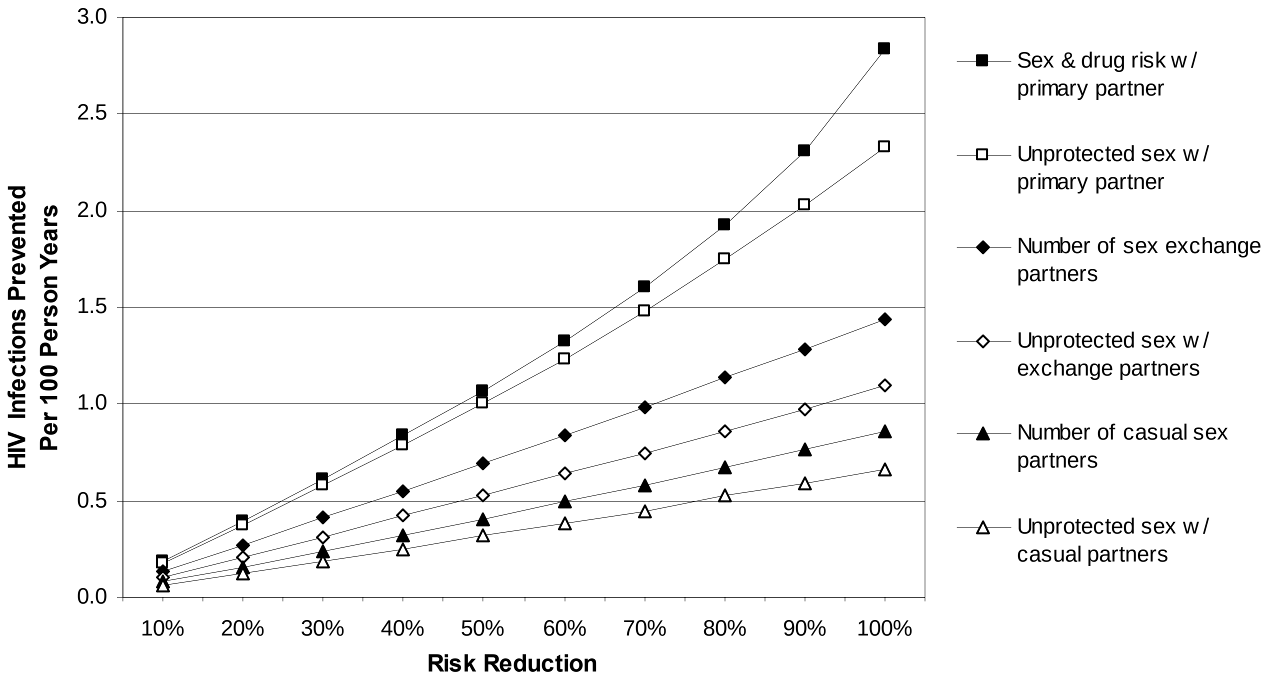
After identifying potentially influential parameters, the next phase of the sensitivity analysis was aimed at determining the conditions necessary for the initial study results to change. A Monte Carlo method was used to model random variation in selected parameters over 1,000 simulation runs. For instance, in simulation 1 of 1,000, a population estimate for parameter π_3 was selected (say, .21) from a triangular distribution about the initial estimate of .15. Accordingly, for this first run the population estimate for parameter π_3 was set to .21 for all 390 subjects for the baseline and the six intervention simulations. Estimates for other model parameters were likewise selected. This process was repeated for runs 2 through 1,000, each run selecting a new set of parameter estimates applied to the baseline and intervention simulations. Since the parameter estimates for π_1 (the probability of a primary partner being HIV infected) were based on empirical data of HIV tests of primary partners of drug-using women in East Harlem, initial parameter estimates for π_1 were retained in the sensitivity analysis. The HIV incidence rates, number of HIV infections averted due to each intervention (at various levels of efficacy), and the set of parameter estimates used in each of the 1,000 simulation runs were recorded.

Using the resulting data set, multiple regression techniques were applied to identify models (i.e., linear combinations of parameter estimates) under which different intervention scenarios would be most effective at preventing HIV infections. To simplify the analysis, one HIV intervention scenario (i.e., the scenario aimed at increasing condom use with primary partners) was used as a reference against which the other intervention scenarios were evaluated. Separate regression models were applied to each HIV intervention scenario at 20 percent and 50 percent risk-reduction levels. In the regression models, the outcome variable was the difference between the number of HIV infections averted by a given scenario and the reference scenario. The predictor variables were the model parameters that were varied in the Monte Carlo simulations: π_2, α_v, and ε for models involving scenarios focused on risk reduction with casual partners, and π_3, α_v, and ε for models involving interventions focused on risk reduction with exchange partners. The evaluated regression models were then used to determine sets of parameters values (thresholds) under which each HIV intervention scenario would prevent a greater number of infections than the reference scenario.

Results

The Bernoulli-process model predicted a baseline HIV incidence of 2.77 per 100 person-years over the sample of 390 women drug users (3.85 for IDUs, n=100; 2.40 for non-IDUs, n=290). The number of HIV infections prevented due to each of the six intervention scenarios is presented graphically in Figure 1.

Figure 1. Simulation model results



Each line on the graph represents one of six HIV prevention scenarios targeting a specific risk group. Points on the graph correspond to the number of HIV infections averted per 100 person-years due to the intervention (vertical axis) at various levels of risk reduction (horizontal axis). Percent risk reduction achieved due to the intervention (efficacy level) is given in 10 percent intervals.

Given the assumptions of the model, an HIV intervention that successfully reduces syringe sharing and the proportion of unprotected sex with primary partners would result in the greatest number of HIV infections prevented among female drug users from East Harlem. However, an intervention aimed at reducing only unprotected sex with primary partners would yield nearly the same number of HIV infections averted, especially at lower levels of intervention efficacy. For example, an HIV intervention achieving a 50 percent reduction in both receptive syringe sharing and unprotected sex with primary partners would be expected to prevent 1.07 HIV infections per 100 person-years, whereas an intervention achieving a 50 percent reduction in unprotected sex only would result in 1.00 HIV infection prevented per 100 person-years.

HIV interventions that reduce women's sexual risk behavior with sex exchange partners (either by reducing the number of exchange partners or by increasing condom use with such partners) yielded substantially fewer HIV infections averted. For example, as noted, an intervention achieving a 50 percent reduction of unprotected sex with primary partners will result in 1.00 HIV infection averted per 100 person-years, whereas a comparable intervention reducing unprotected sex with exchange partners would produce .53 HIV infections averted; reducing the number of exchange partners by 50 percent would result in .70 HIV infections averted.

The fewest number of HIV infections prevented, according to the model, would be achieved by prevention measures targeted at sexual risk behavior with casual partners. An intervention achieving a 50 percent reduction in the number of casual sex partners over a 1-year period would be expected to yield .41 HIV infections averted; a 50 percent decrease in the proportion of unprotected sex with casual partners would avert .32 HIV infections.

To assess the accuracy of our model, we compared the model-predicted HIV incidence rate against published HIV surveillance data. The model-predicted HIV incidence rate for female drug users (mixed IDU and non-IDU) in East Harlem was 2.77 per 100 person-years (3.85 among IDUs). Very few studies have documented HIV seroincidence among non-IDUs or mixed IDU/non-IDU groups. Among IDUs, the model-predicted rate of 3.85 seroconversions per

100 person-years falls within the range of published results for large U.S. cities. In a review of HIV prevalence and incidence estimates in 96 U.S. metropolitan areas, Holmberg (1996) found that "estimated incidence was from two to five infections per 100 person-years in . . . eastern cities." Des Jarlais et al. (2000) reported HIV incidence rates ranging from 0.00 to 2.96 for 10 separate studies on IDUs in New York City. The model-predicted HIV incidence of 3.85 for IDUs in this study falls within the 95 percent confidence intervals of 5 of the 10 studies.

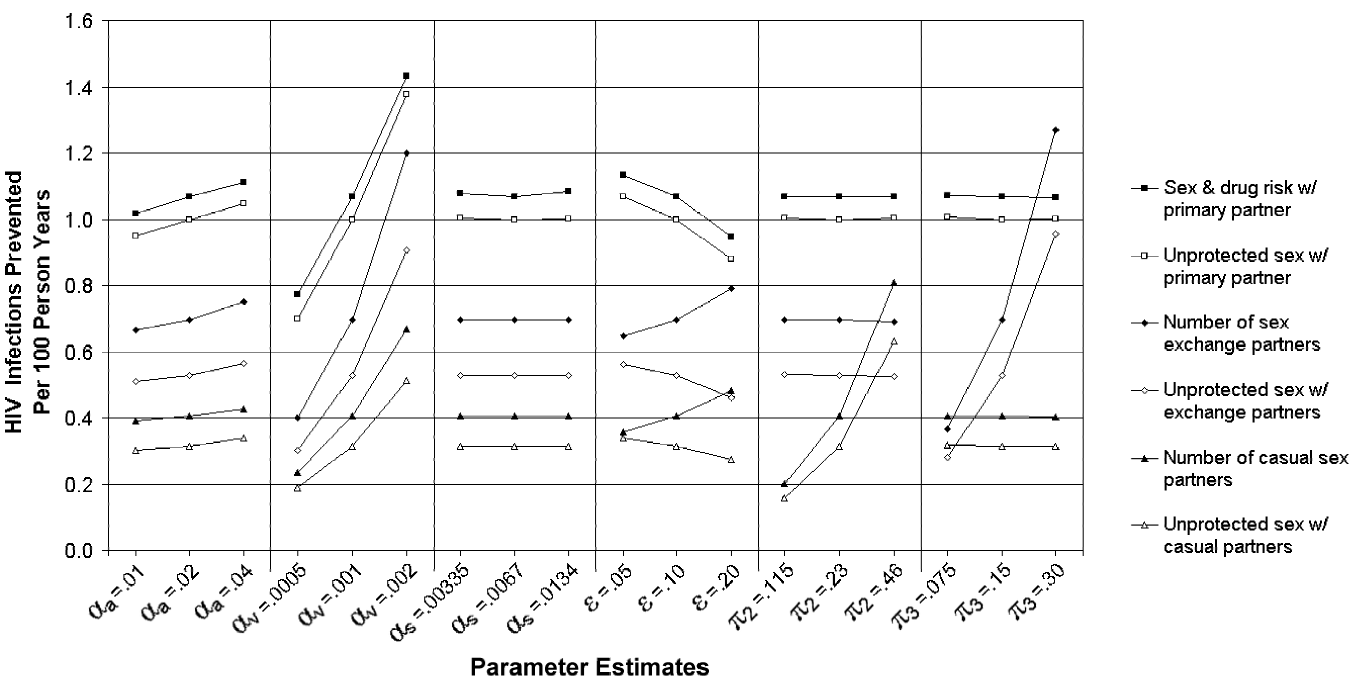
Sensitivity analysis results

Figure 2 graphically presents the results of the univariate sensitivity analysis. It can be seen that modifications to the HIV infectivity rates for anal (α_a) and vaginal intercourse (α_v), and receptive syringe sharing (α_s) produced no changes to the order of intervention effectiveness in terms of preventing the greatest number of HIV infections. However, increasing the male-to-female HIV infectivity rate for vaginal intercourse narrowed the gap between interventions focused on reducing risk with primary partners and those focused on risk reduction with nonprimary partners.

Modifications to the condom failure rate (ε) also produced a differential impact on outcomes. Specifically, increasing the condom failure rate in the model enhanced the preventive power of interventions focused on reducing the number of sex partners but diminished the preventive power of interventions focused on increasing condom use. Even with a condom failure rate of 20 percent, however, interventions focused on risk reduction with primary partners remained the most effective strategies for the prevention of HIV within this sample.

Modifications to model parameters associated with the probability that a given risk partner is HIV infected (π_2, π_3) also resulted in differential outcomes. Increasing or decreasing the probability that a casual sex partner is HIV infected (π_2) resulted in a corresponding increase or decrease of the relative preventive power of interventions focused on risk with casual sex partners but had little or no effect on other intervention types. Likewise, increasing or decreasing the probability that a sex exchange partner is HIV infected (π_3) influenced the relative preventive power of interventions focused on exchange partners but again had no impact on other intervention types.

Figure 2. Univariate sensitivity results



Each line on the graph represents one of six HIV prevention scenarios (see key at right). Points on the graph correspond to the number of HIV infections averted per 100 person-years due to the intervention (vertical axis) under low, middle, and high estimates for six selected model parameters (horizontal axis). All data shown assume 50 percent risk reduction.

Multivariate sensitivity analyses revealed a three-parameter model that established threshold conditions under which different intervention scenarios would prevent the greatest number of HIV infections. These parameters are (1) the condom failure rate, (2) the probability that a given risk partner is HIV infected, and (3) level of intervention efficacy. Figures 3 and 4 graphically depict these parameter combinations (thresholds).

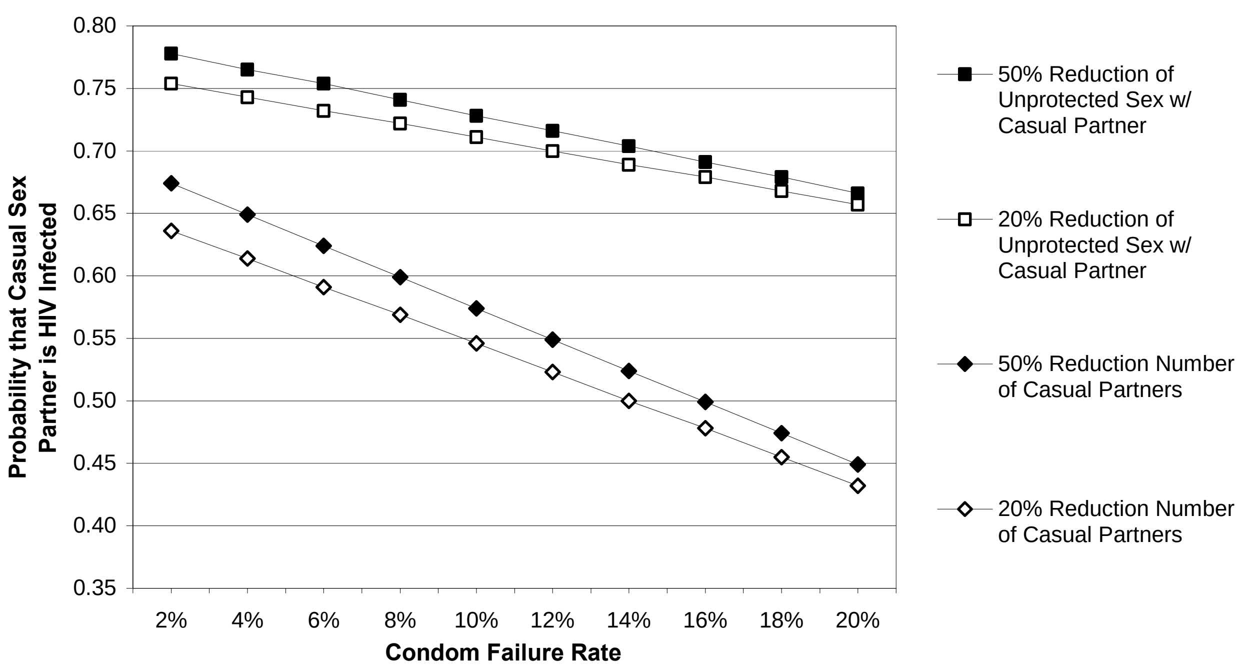
Figure 3 shows that an intervention reducing sexual risk with casual partners will prevent more HIV infections than an intervention reducing the proportion of unprotected sex with primary partners (i.e., the reference intervention) under various parameter combinations. For example, an intervention achieving a 20 percent reduction in the *number of casual sex partners* will avert more HIV infections than the reference intervention only if the probability of a casual sex partner being HIV infected (π_2) is greater than .46 to .64 (depending on the condom failure rate). For an intervention achieving a 20 percent reduction in the proportion of *unprotected sex with casual partners* to prevent more HIV infections than the reference intervention, π_2 would need to be greater than .71 to .76.

Multivariate results for interventions reducing HIV risk with sex exchange partners are presented in Figure 4. The results indicate that an intervention achieving a 20 percent reduction in the number of sex exchange partners will prevent more HIV infections than the reference intervention only if the probability of an exchange partner being HIV infected (π_3) is greater than .16 to .26 (depending on the condom failure rate). For an intervention achieving a 20 percent reduction in the proportion of unprotected sex with exchange partners to avert more HIV infections than the reference intervention, π_3 would need to be greater than .27 to .30.

Discussion

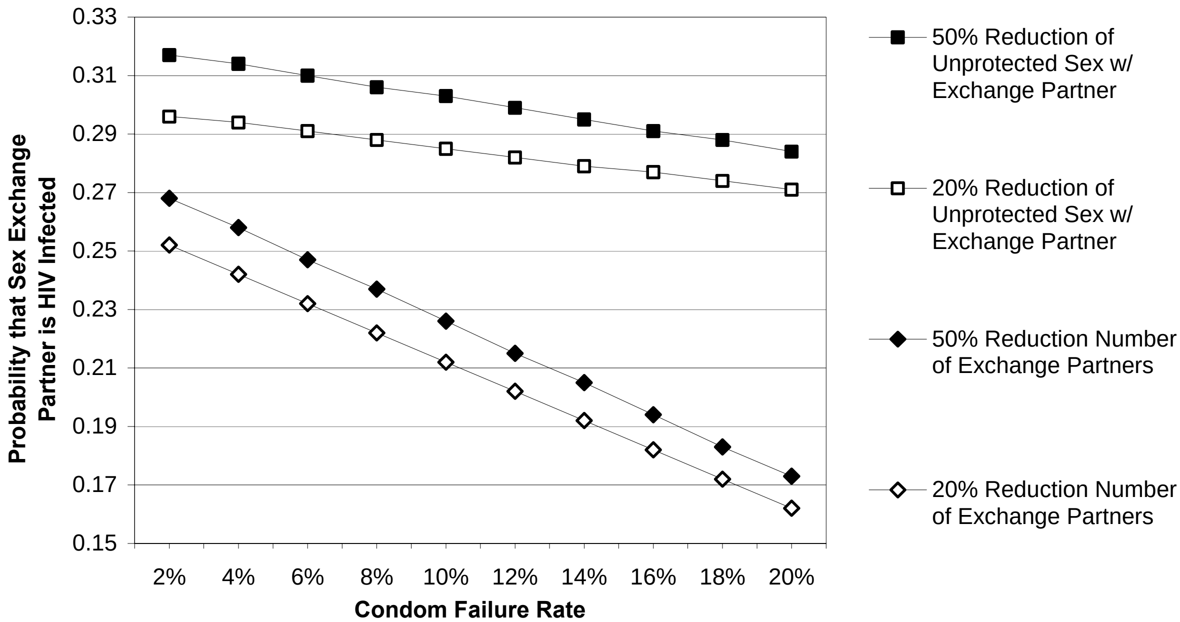
The results of this study suggest that unprotected sex with primary male partners may carry the greatest risk for HIV infection among female drug users in East Harlem, and that prevention measures tailored to drug-involved low-income women in primary heterosexual relationships may hold the most promise for reducing the spread of HIV/AIDS within this high-risk group.

Figure 3. Multivariate sensitivity results for risk reduction with casual sex partners



Each line on the graph represents an HIV prevention scenario focused on risk with casual sex partners, at a specific level of risk reduction (see key at right). Points on the graph correspond to parameter combinations under which the specified intervention scenarios would prevent the greatest number of HIV infections (compared with a reference scenario).

Figure 4. Multivariate sensitivity results for risk reduction with sex exchange partners



Each line on the graph represents an HIV prevention scenario focused on risk with sex exchange partners, at a specific level of risk reduction (see key at right). Points on the graph correspond to parameter combinations under which the specified intervention scenarios would prevent the greatest number of HIV infections (compared to a reference scenario).

Sensitivity analyses indicated that the study outcome measure (i.e., number of HIV infections averted per 100 person-years) was highly sensitive to several model parameters, including vaginal infectivity rate, condom failure rate, and the probability that a given risk partner is HIV infected. However, analyses further demonstrated that the parameter values required to change the study results were unrealistic in most cases.

The finding that sexual risk behavior within primary relationships may carry the greatest risk of HIV infection is in contrast to the widespread view that sex with multiple non-monogamous partners poses the greatest risk of infection. There is a growing body of evidence, however, to suggest that some groups of women are at greatest risk of acquiring HIV from their primary intimate partners (DeZoysa et al. 1996; O'Leary 2000; CDC 2000). The view that sex with multiple partners poses the greatest risk of HIV infection for both men and women stems from two main areas of research: (1) mathematical modeling of disease transmission, and (2) empirical studies of sexually transmitted disease (STD) risk factors.

Mathematical models of disease transmission have demonstrated that the probability of infection from $n + k$ sex contacts with a single partner is less than from n contacts with one partner and k contacts with another (Pinkerton and Abramson 1993). However, these models assume equal infectivity among all partners. In contrast, recent studies have reported that condom use (and by extension, infectivity) varies by partner type (Tortu et al. 2000; Macaluso et al. 2000). Unprotected sex occurs much more frequently within close primary relationships than within new or casual relationships, a finding demonstrated for heterosexual drug users (Watkins et al. 1993; Friedman et al. 1994; Booth 1995; Siegal et al. 1996; Falck et al. 1997), minority women (Catania et al. 1995; Wagstaff et al. 1995; Lansky et al. 1998; Dixon 1998; McKay 1999; Crosby et al. 1999; Tortu et al. 2000), and other populations (see reviews in Misovich et al. 1997 and Macaluso 2000).

In light of these observations, Pinkerton and Abramson (1993) developed a more complex model of HIV transmission to evaluate the risks of infection based on number of sex partners, frequency of condom use, and population prevalence. They found that, in general, increasing condom use was a more effective HIV prevention strategy than reducing the number of sex partners. For example, assuming an infectivity rate of 0.001 for vaginal intercourse, the risk of infection from 1,000 one-night stands with 50 percent condom use is less than that for 1,000 unprotected monogamous sex acts (under random mating with a population prevalence of 0.01).

While numerous studies have reported an association between number of sex partners and STDs (Anderson and Dahlberg 1992), few studies have examined the relative risks of infection with different partner types. In one instructive study, Evans et al. (1995) compared the STD rates of women who reported having sex with multiple casual partners with those reporting sex with primary partners only, over a 12-month period. They found no difference in the incidence of STDs between the two groups. However, in a previous study in 1982 the same team of investigators had found that having multiple partners carried the greatest risk for STDs (Evans et al. 1993). These authors attributed this change to a differential increase in condom use with casual sex partners compared with primary partners following the HIV-related condom promotion campaigns of the late 1980s and early 1990s.

The effects of this shift in protective behavior may be amplified for HIV, which has a lower infectivity rate than many other STDs. Pinkerton and Abramson (1993) have demonstrated that under conditions of low infectivity and high prevalence the importance of multiple sex partners in the transmission of HIV is greatly diminished. This finding is consistent with several recent HIV surveillance studies in high prevalence areas, which indicate that women are more likely to become infected by their primary partner than by any other partner type (DeZoysa et al. 1996; O'Leary 2000; CDC 2000).

A factor compounding sexual risk within intimate relationships is that women often underestimate the potential risk of HIV infection through heterosexual contact with their primary partners (Kost and Forrest 1992; Campbell 1995; Wingood and DiClemente 2000). Our research with high-risk couples in East Harlem offers a revealing example. In the Couples at Risk study, both male and female partners (N=193 couples) were offered HIV testing and were privately asked to report on their own and their partner's HIV serostatus prior to testing. Of the 162 women who reported that their partner was HIV negative or who were not aware of their partner's serostatus, 21 (13 percent) had partners who tested HIV positive; of 128 couples who reported that they were both HIV negative, 12 (9 percent) were actually HIV serodiscordant; and while 112 (58 percent) of the couples tested HIV seroconcordant negative, 80 (71 percent) of these had at least one member who reported engaging in sex- or drug-related HIV risk behavior with individuals outside their primary relationships.

Study limitations

The Bernoulli-process model employed in this study relies on a number of key assumptions: (1) individual risk contacts are probabilistically independent; (2) infectivity rates are homogeneous within and across individuals; (3) intervention-induced risk-reduction behavior is sustained at a given level for the duration of the intervention effect but immediately returns to pre-intervention levels once the effect subsides; and (4) for sexual contacts with casual and exchange partners, there is complete random mixing (i.e., partners chosen at random).

In addition to these model limitations, secondary infections (i.e., infections spread to partners of intervention participants) were omitted from the model, and this may have resulted in an underestimation of the outcome measure in the analysis. Although the model incorporates women's egocentric networks (i.e., personal risk connections), it does not take into account sociometric network effects of larger interconnected populations.

A further assumption deals with the interpretation of the simulation results. Comparisons of the number of HIV infections averted across alternative intervention scenarios were made at equivalent levels of efficacy. For example, the prevention benefits of an intervention aimed at reducing risk with primary partners with that of an intervention focused on risk reduction with casual partners were made at 20 percent, 50 percent, or some other level of risk reduction. Several authors have suggested, however, that the level of risk reduction achieved by HIV prevention measures may vary according to partner type and risk behavior. Specifically, sexual risk behavior (as opposed to injection risk behavior) and risk behavior with close intimate partners may be the most difficult to modify (Cohen 1991; Ickovics and Yoshikawa 1998). Therefore, interventions of equivalent content and dosage might achieve different levels of risk reduction effectiveness depending on the risk behavior and the risk group targeted.

Another assumption of the model is that HIV interventions will effect change in the target behavior only, without modifying any other risk behavior. It is reasonable to assume, however, that interventions targeted at one set of risk behaviors (e.g., unprotected sex with primary partners) may have some residual effect on other risk behaviors (e.g., unprotected sex with casual partners).

Summary of findings and future research

Evaluation of several simulated HIV intervention scenarios targeted to drug-using women from East Harlem indicate that prevention strategies aimed at reducing sexual risk behavior with primary intimate partners may be the most effective at preventing HIV infections. This finding is based on a mathematical model of HIV transmission that employed self-reported HIV risk behavior data from the study population and other model parameters. This study differs from previous research in that additional data were available from an ongoing couples study, from which empirically based estimates were derived for a key model parameter—the probability that a given *primary* partner was HIV infected during risk activity. Sensitivity analyses demonstrated that the study results were invariant to reasonable modifications of model parameters.

The application of mathematical modeling of HIV transmission to several areas of HIV prevention research deserves further study. Specifically, assessments of the potential effectiveness of alternative intervention strategies prior to an efficacy study may provide useful information pertaining to future intervention design and content. In addition, the use of mathematical models to assess the relative efficacy of experimental and control interventions in terms of the number of HIV infections averted may provide insights not afforded by standard statistical methods. The utility of this approach will be enhanced by further development of the models to incorporate more realistic conditions, more reliable empirically based parameter estimates, and the inclusion of population-based sociometric network structures.

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