Partnership duration, concurrency, and HIV-prevention policy in sub-Saharan Africa

Abstract

A widely accepted explanation for the exceptionally high HIV prevalence in sub-Saharan Africa is the practice of long-term overlapping heterosexual partnering. This article shows that long-duration concurrent partnering can be protective against HIV transmission rather than promoting it. Monogamous partnering prevents sexual transmission to anyone outside the partnership and, in an initially concordant-seronegative partnership, prevents sexual acquisition of HIV by either partner. Those protections against transmission and acquisition last as long as the partnership persists without new outside partnerships. Correspondingly, these two protective effects characterize polygynous partnerships, whether or not the polygyny is formal or informal, until a partner initiates a new partnership. Stable and exclusive unions of any size protect against HIV transmission, and more durable unions provide a longer protective effect. Survey research provides little information on partnership duration in sub-Saharan Africa and sheds no light on the interaction of duration, concurrency, and HIV. This article shows how assumptions about partnership duration in individual-based sexual-network models affect the contours of simulated HIV epidemics. Longer mean partnership duration slows the pace at which simulated epidemics grow. With plausible assumptions about partnership duration and at levels of concurrency found in the region, simulated HIV epidemics grow slowly or not at all. Those results are consistent with the hypothesis that long-duration partnering is protective against HIV and inconsistent with the hypothesis that long-term concurrency drives the HIV epidemics in sub-Saharan Africa.

Keywords:

concurrency
sub-Saharan Africa
HIV
individual-based modelling

Introduction

The concurrency hypothesis asserts that overlapping heterosexual partnering is an important explanation for the extraordinarily high HIV prevalence in sub-Saharan Africa (SSA) and can account for the explosive growth in HIV in parts of the region in the late twentieth century. This hypothesis has helped to shape HIV-prevention policy in the region.

The concurrency hypothesis was first discussed in the early 1990s (Hudson, 1993; Watts and May, 1992). From the beginning, the hypothesis was about "stable, long-term partners" [page 300 in (Morris and Kretzschmar, 1995)]. Long-term partnering is key because "the longer the average duration of overlap, the greater the impact of concurrency on HIV transmission, which is why long-term concurrencies are the focus of most discussion in this field" [page 2 of (Epstein and Morris, 2011)]. Since the risk of sexual transmission within a partnership is a function of the number of exposures, short duration partnering entails a lower cumulative transmission risk than long duration partnering. Furthermore, if a recently infected individual has a succession of short partnerships interrupted by celibate interludes, much of the time of peak infectivity during the first few months of infection would occur during the intervals between partnerships [page 2 in (Epstein and Morris, 2011)]. Finally, it is the prevalence of long-term concurrent partnerships that distinguishes sub-Saharan Africa from other regions, not "one-off casual and commercial sexual encounters that occur everywhere" [page 4 in (Halperin and Epstein, 2004)]. This argument has been reiterated in numerous articles (Epstein, 2007; Epstein, 2008; Epstein, 2010; Epstein and Morris, 2011; Halperin and Epstein, 2007; Mah and Halperin, 2008; Mah and Shelton, 2011; Morris *et al.*, 2010). Despite extensive criticism (Lurie and Rosenthal, 2010a; Lurie and Rosenthal, 2010b; Sawers, 2013; Sawers *et al.*, 2011; Sawers and Stillwaggon, 2010; Tanser *et al.*, 2011), policy discourse and HIV prevention strategies still reflect a belief in the validity of the concurrency hypothesis.

The results presented below show that long-term concurrency is ineffective in spreading HIV. These results are generated by an individual-based stochastic model of dynamic sexual networks, a technique commonly used to explore the epidemic spread of HIV. Our simulations lend support to a substantial literature asserting that polygyny can be protective against HIV (Blower and Boe, 1993; Kretzschmar *et al.*, 2010; Lurie and Rosenthal, 2010b; Reniers and Tfaily, 2008; Reniers and Tfaily, 2012; Reniers and Watkins, 2010).

Partnership duration, concurrency, and HIV

In varying degrees, long-term concurrencies not sanctioned by formal marriage share characteristics with formal polygynous unions. One may generalize insights from the analysis of concurrent partnerships that are formally polygynous to those that are not. Halperin and Epstein argue that, in contrast to a "network of concurrent relationships . . . serial monogamy traps the virus within a single relationship for months or years" [page 5 in (Halperin and Epstein, 2004)]. Nevertheless, a stable polygynous marriage in which no partner has another partner outside the polygynous union would also "trap the virus" for the same reasons and subject to the same constraint (that is, until one or more partners establish a new partnership) as a two-person monogamous partnership. What traps the virus is not the number of people linked by sexual partnering—two or more than two—but its long-term stability and exclusivity. That is true for both monogamous and polygynous partnerships, whether they are formal or informal. Furthermore, both monogamous and polygynous partnering with no outside sexual encounters would protect against sexually acquired HIV if all partners in a sexual union are initially seronegative. Lastly, if any member of an otherwise stable, *n*-person sexual union has a single or very few sexual encounters with someone who is not a member of the union, the ability to "trap the virus" or to protect against HIV acquisition at the population level may not be importantly eroded, given the low per-act transmission efficiency of the virus.

The protective effect of both monogamy and polygyny lasts only until one or more members acquire another partner. When that happens, the number of people placed at risk of HIV depends on how many people in the formerly stable union acquire new partners. That could weaken the protective effect of polygynous unions at the population level.

Evidence about partnership duration in sub-Saharan Africa

In the last two decades, there have been scores of surveys of sexual behaviour in sub-Saharan Africa that measure concurrency, but few of them report partnership duration. The most important exception for the purposes of this article is a survey in Rakai, Uganda by Morris [Table 1, page 112 in (Morris and Kretzschmar, 2000)], see also (Morris *et al.,* 2010), which is the only survey in SSA that measures average duration of primary and secondary partnerships for a large sample of adults (N = 1994). Other exceptions are found in the literature on formal polygyny (Reniers and Tfaily, 2008; Reniers and Tfaily, 2012; Reniers and Watkins, 2010). In

addition, recent Demographic and Health Surveys provide evidence on the duration of primary partnerships. In 16 countries in sub-Saharan Africa, women reported mean duration in married or cohabiting partnerships of 12.1 years and men reported mean duration of 13.1 years, virtually the same as in 16 low-income countries outside Africa for which there are data (based on datasets obtained from The DHS Program, ICF International).[1] These data are for principal, not secondary, partnerships, but they reinforce the finding that partnerships in the region often last for many years.

Other studies of partnership duration are not useful for the present article. One study interviewed patients in an STI clinic, who are not representative of the general population (Powers *et al.*, 2011). Other studies have examined only youth (Goodreau *et al.*, 2012; Harrison *et al.*, 2008; Harrison and O'Sullivan, 2010). Studies of youth shed little light on partnership duration for all adults since young people have not yet lived long enough to have had lengthy partnerships. Additionally, youth are likely to have different partnering patterns than those who are older.

Methods

Individual-based stochastic simulation modelling can help to untangle the interactions among duration, concurrency, and HIV (Chen *et al.*, 2008; Kim *et al.*, 2010). Morris and Kretzschmar's seminal model (hereafter, the MK-1997 model) is widely cited in support of the concurrency hypothesis (Morris and Kretzschmar, 1997). Simulations generated by the MK-1997 model are characterized by explosive growth in HIV prevalence, even at low concurrency prevalence.

Although mathematical models of disease propagation have been used by biologists for over a century, the use of individual-based simulation models is more recent. Morris and Kretzschmar were the first to use individual-based stochastic simulation modelling to examine the epidemic spread of HIV through networks of sexual partnerships. Individual-based modelling is now recognized as particularly suited to that task. These models simulate the partnership formation and sexual interactions of a population of individuals. The simulated individuals typically follow behavioural rules based at least partially on empirical studies. Since the

[1] The countries in SSA were Burundi, Burkina Faso, Cameroon, Congo Brazzaville, Côte d'Ivoire, Ethiopia, Gabon, Lesotho, Madagascar, Malawi, Mozambique, Rwanda, Senegal, Tanzania, Uganda, and Zimbabwe. The other countries were Albania, Armenia, Bangladesh, Bolivia, Cambodia, East Timor, Egypt, Guyana, Haiti, Honduras, Indonesia, Jordan, Nepal, Peru, the Philippines, and Tajikistan.

behaviour of real individuals has an unpredictable component, the behaviour of the simulated individuals also has a stochastic character. The MK-1997 model includes male and female heterosexual individuals, a small, random subset of whom are initially infected (seeded) with HIV. Individuals in the model randomly form sexual partnerships, which have a parameterized daily probability of dissolving. Seropositive individuals have a fixed daily probability of infecting their sexual partners This model, by showing how rapidly HIV can spread through sexual networks, proved extremely influential in promoting the concurrency hypothesis. Morris and Kretzschmar's three papers describing their original modelling of concurrency have been cited in over 1600 scholarly works on the subject (Kretzschmar and Morris, 1996; Morris and Kretzschmar, 1995; Morris and Kretzschmar, 1997).

In 2000, Morris and Kretzschmar published a modified version of their model (Morris and Kretzschmar, 2000), hereafter the MK-2000 model. Instead of assuming mean duration of both primary and secondary partnerships to be 200 days, as in their 1997 paper, they set the mean duration at about 20 years for primary partnerships and at just over 2 years for secondary partnerships. (Primary partnerships are the partnership individuals form when they have no partner and secondary partnerships are all subsequent partnerships.) The partnership durations were keyed to the survey in Rakai, Uganda mentioned above (Morris and Kretzschmar, 2000). Simulations produced by the original MK-1997 model showed a 250-fold increase in HIV prevalence in five years at the level of concurrency found in the Rakai survey. In contrast, simulated epidemics generated by the MK-2000 model incorporating much longer mean partnership durations led to much slower growth in HIV prevalence, which only tripled in 5 years (from 1.0% to 2.92%).

Others have also modified the MK-1997 model. Jeffrey Eaton, Timothy Hallett, and Geoffrey Garnett Geoffrey (hereafter, the EHG-2011 model) added a realistic daily HIV transmission rate that incorporates the consensus agreement among experts about how transmission risk varies over the course of the disease (Eaton *et al.*, 2010). Larry Sawers, Alan Isaac, and Eileen Stillwaggon (hereafter the SIS-2011 model) incorporated varying degrees of coital dilution (lower coital frequency in secondary partnerships) into the EHG-2011 model (Sawers *et al*., 2011). With those two modifications, simulated epidemics grow slowly or are unsustainable (that is, they move to extinction; alternately, the basic reproduction number R_0 is less than zero) at even unrealistically high levels of concurrency.

In this paper, we have modified the EHG-2011 model to incorporate Morris and Kretzschmar's assumptions about partnership duration based on the Rakai, Uganda survey that they used to parameterize the MK-2000 model. With that modification, the model, as we shall see, generates only epidemics that move to extinction. In sum, modifying the original MK-1997 model by using more realistic parameter values and model structures shows how (and by how much) the original model exaggerated the effect of concurrent partnering on the spread of HIV.

Others have built individual-based stochastic simulation models using more elaborate model structures and different parameter values than the various incarnations of the MK-1997 model. Their simulations also generated HIV epidemics that grew, if at all, very slowly (Goodreau *et al.*, 2012; Leclerc *et al.*, 2009). Since those models deviated in many ways from the MK-1997 model, it is difficult to use them to determine why the MK-1997 model generates such rapid growth in HIV prevalence. Morris and Kretzschmar's twenty-year-old model continues to be by far the most frequently cited model in support of the concurrency hypothesis (about 60 citations in 2016 and early 2017), and it is therefore important to determine why the model's results so exaggerate the importance of concurrency in explaining HIV epidemic dynamics.

The simulations reported here combine in a novel way previous modifications of the MK-1997 model but still allow direct comparisons to the original model and to its close relatives. Our contribution seeks to determine the effect of introducing more realistic assumptions about partnership durations than the 200-day mean duration in the MK-1997 model. As described below, we vary mean primary partnership duration from 100 days to 20 years, which encompasses the 200-day assumption of the original MK-1997 model and the 239.1-month duration assumed in the MK-2000 model.

Additionally, the original MK-1997, the EHG-2011, and the SIS-2011 models all assume that both primary and secondary partnerships have the same mean duration. In contrast, our model allows different mean durations for primary (the partnership an individual forms when he or she has no partner) and secondary partnerships (all other partnerships). Data on the relative partnership duration in concurrent relationships is scarce. Morris's survey in Rakai found that the average duration of secondary partnerships was about 12% of average duration of primary partnerships (28.4 months vs. 239.1 months). Our exploration of concurrency and partnership

duration incorporates Morris's estimate of average duration dilution, that is, the shorter mean duration of secondary partnerships compared with primary partnerships.

In contrast to the MK-1997 and MK-2000 simulations, which run only 5 years, the EHG-2010 and SIS-2011 simulations consider both near-term and long-run outcomes by simulating daily outcomes over 250 years. The EHG-2010 model also modifies the MK-1997 model with two key improvements: realistic staged transmission rates, which vary over the course of the disease, and vital dynamics, which is the addition of uninfected individuals to the population, implicitly through birth or migration, and the removal of infected individuals due to death. That is the innovation that allows modelling to continue beyond 5 years. The SIS-2011 model includes the EHG-2010 modifications and adds two key improvements: distinguishing between primary and secondary partnerships, and allowing for coital dilution among multiple partners. As in the MK-1997 and subsequent models, partnership formation occurs by means of chance daily encounters in which individuals may form partnerships, and duration reflects the small probability of dissolution each day after formation.

In order to maintain comparability, the simulations reported below involve the minimal possible modifications of the EHG-2010 and SIS-2011 models. Other ways in which these models are the same include the following. The partnership network and HIV prevalence evolve on a daily schedule over 250 years in a population of 20,000 individuals. There are equal numbers of males and females, with no gender asymmetry in concurrency propensity or transmission rates.[2] Only heterosexual partnerships are considered. The number of partners is not capped but is constrained by the propensity for concurrency and the probability of dissolution. When there is no propensity for concurrency, partnerships are monogamous. An initial HIV infection is produced by randomly seeding 1% of the population with HIV. Each of our many scenarios is replicated 100 times for the entire period and population, which is more than 90,000 iterations across the entire population for each replicate. Reported results for each scenario are the mean outcomes across the replicates for that scenario. Scenarios include variations in the propensity to form concurrent partnerships, where we follow the EHG-2010 and SIS-2011 models exactly.[3]

[2] In ongoing work, we have found that allowing for gender asymmetry has only small effect on outcomes.

[3] We implemented our model in Python. The source code is available upon request.

Our work extends the SIS model to explore the implications of partnership duration. Sawers, *et al.* argued that coital dilution is likely to be substantial and has an important effect on HIV transmission. Data on coital frequency in sub-Saharan Africa and elsewhere are thin, but evidence suggests substantial coital dilution with multiple partners, so that assuming otherwise is unrealistic. For example, respondents in the Rakai survey (Morris *et al*., 2010) reported coital dilution of more than 75%. [See also (Gaydosh *et al.*, 2013; Reniers and Tfaily, 2010; Reniers and Tfaily, 2012; Reniers and Watkins, 2010; Sawers *et al.*, 2011) for additional evidence of coital dilution.] Since the inclusion of coital dilution dampens HIV transmission, we adopt a conservative 25% coital dilution rate for secondary partnerships in our focal simulations. Some authors report surveys that did not find empirical evidence of coital dilution (Delva *et al.*, 2013; Jenness *et al.*, 2015), so we present additional simulations in Table 2 that assume no coital dilution.

Results

Our primary interest is the effect of partnership duration on the spread of HIV, which we measure as the change in disease prevalence. We distinguish three types of outcomes: (1) HIV prevalence rising slowly from the seeding prevalence of 1% to at least 3% in 25 years, (2) HIV prevalence rising very slowly from the seeding level of 1% to at least 2% in 25 years, and (3) HIV prevalence not rising from the seeding level but instead falling to extinction. We do not introduce categories for more rapid spread, since most of our simulations do not reach 3% HIV prevalence in 25 years. None of our simulations produce HIV prevalence rising as much as 5.25 percentage points over the first quarter century of an epidemic, and that increase requires assuming equal duration and coital frequencies in primary and second partnerships and unrealistically brief partnership durations. By way of contrast, in the most rapidly growing simulated epidemic generated by the original MK-1997 model, HIV prevalence rose from 0.05% to nearly 70% in 5 years. In our modelling, the maximum increase in HIV prevalence over the first 5 years of an epidemic is from 1% to 1.51%.

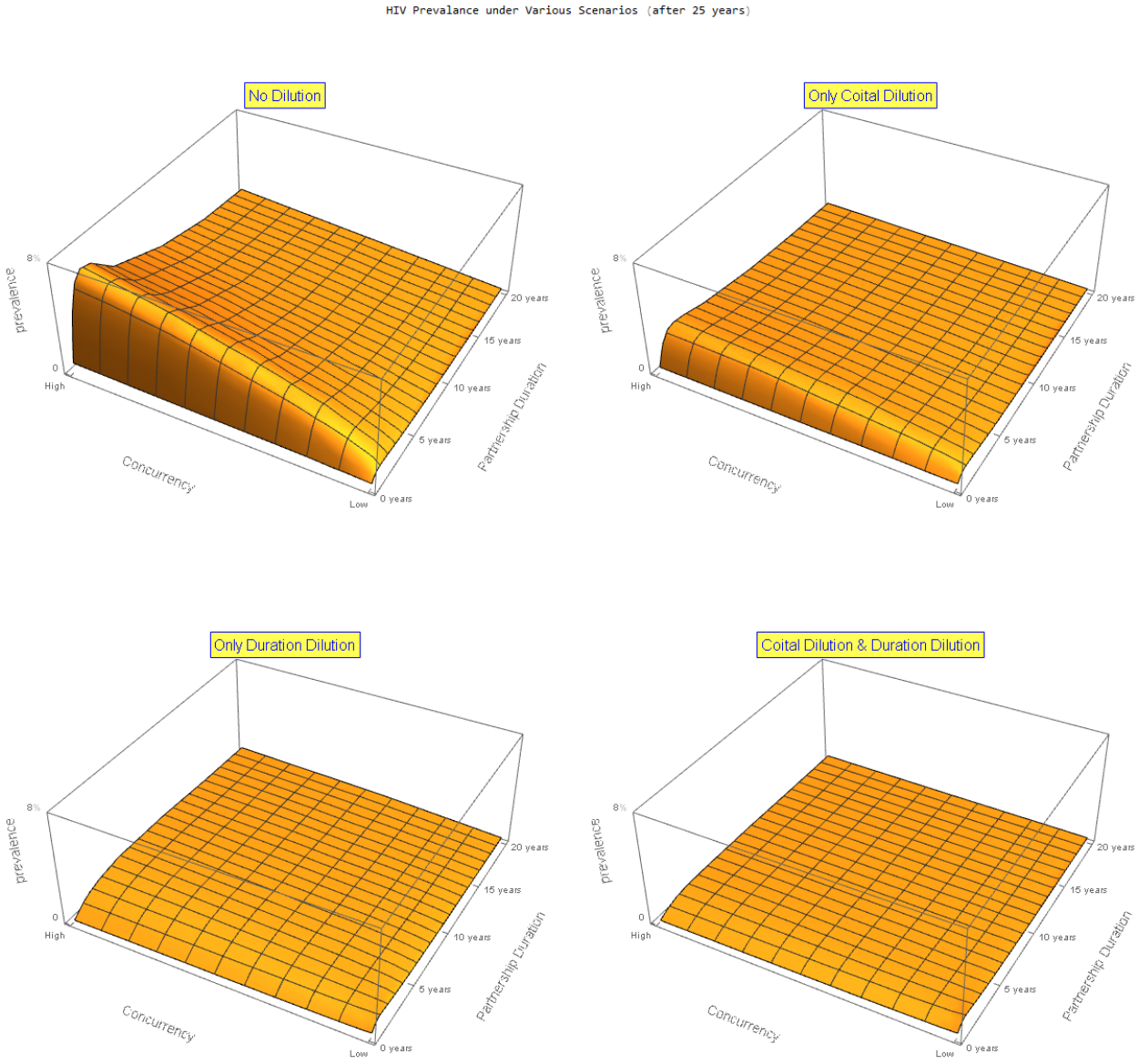
Our focal simulations are shown in the first 3 columns of Table 1. Assuming duration dilution (when secondary partnerships have shorter duration than primary partnerships) and coital dilution (when secondary partnerships have lower coital frequencies than primary partnerships), our simulation model does not produce any epidemics in which HIV prevalence

grows over time. A mean primary-partnership duration anywhere between 100 days and 20 years produces the same result: after the initial seeding of HIV infections, the epidemic is unsustainable, that is, only moves to extinction.

Morris and Kretzschmar showed in the 2000 version of their model that assuming duration dilution sharply dampens the ability of HIV epidemics to grow, and our simulations confirm their findings. The first 2 columns of Tables 1 and 2 show that, whether or not coital dilution is included, simulated epidemics with duration dilution cannot grow even as little as 1 percentage point above the seeding prevalence of 1% in 25 years. As shown in Table 2 column 3, even assuming no coital dilution, mean primary partnership duration must be at least 3 years for simulated HIV epidemics to be sustainable as long as duration dilution is included. In order to produce stimulated epidemics in which HIV prevalence rises above 3% (from seeding level of 1%) in 25 years, one must assume that primary and secondary partnerships have the same mean duration and coital frequency (Table 2 column 4), partnerships must last at least 300 days, and concurrency prevalence must be 16% or higher.

As the SIS-2011 model shows, coital dilution also has a powerful dampening effect on simulated HIV epidemics. That can be seen by comparing each column in Table 1 (which assumes coital dilution) with the corresponding column in Table 2 (which assumes no coital dilution). Each comparison shows that, assuming a small degree of coital dilution, sustainable HIV epidemics are more difficult to generate and higher levels of concurrency are needed to produce even slow growth in HIV prevalence.

Next, consider the effects of partnership duration on disease spread. Our results show that long primary partnership duration (in excess of 500 days) retards rather than promotes the spread of HIV. One can see the effect of duration in Tables 1 and 2 in columns with concurrency rates instead of asterisks. Those columns do not assume both coital or duration dilution. The concurrency prevalence needed to allow slow, very slow, or no growth in HIV prevalence steadily rises as duration increases from 500 days to 20 years. Note that the evidence shows that primary partnerships in sub-Saharan Africa typically last far longer than 500 days. That is far shorter than the 20-year primary partnerships found in the Rakai, Uganda study reported earlier and the 12–13-year primary partnerships found by the DHS in 16 sub-Saharan African countries



Not only is it important to consider both duration dilution as well as coital dilution when modelling HIV, the two interact. Figure 1 illustrates this by representing the prevalence outcomes 25 years after the initial infection. Each subchart shows the HIV prevalence outcomes for a particular scenario. The upper left chart incorporates neither coital dilution nor duration dilution, and we find serious HIV epidemics (with HIV prevalence approaching 7% in 25 years after seeding) are possible (if concurrency prevalence is high and mean partnership duration is low). In the upper right figure, we allow for modest coital dilution, and we find epidemic extinction at most durations regardless of the level of concurrency. The lower left chart shows

that we get even greater suppression of HIV prevalence if we only allow duration dilution (but not coital dilution). The lower right chart shows that when we allow both coital dilution and duration dilution in secondary partnerships, sustainable HIV epidemics are impossible.

Our results raise serious questions for researchers who rely on simulation models that ignore duration dilution, particularly those who also use unrealistically short values for mean partnership duration. This would include the original MK-1997 model but not the MK-2000 version. We also find that it is crucial to consider coital dilution as well.

Is concurrency sufficiently prevalent to drive HIV epidemics in sub-Saharan Africa?

Are the concurrency prevalences that allowed HIV epidemics to grow as shown in Tables 1 and 2 found among adults in sub-Saharan Africa? Table 3 shows the reported point prevalence of concurrency in 31 countries in SSA. Those data are from all of the DHS in the region that report concurrency measured using the UNAIDS protocol (UNAIDS Reference Group on Estimates, Modelling, and Projections, 2009). An advantage of the DHS is that they are the only source of data on concurrency prevalence measured in the same way for adult populations in a large number of countries. Furthermore, those 31 DHS report concurrency measured the same way that modellers typically report concurrency (including all the models discussed in this article), as the average of men's and women's point prevalence (at a point in time rather than over the previous year). That allows a direct comparison of modelled concurrency with measured concurrency. (Concurrency is most often measured over the previous year, producing a measure that is about double the point prevalence in sub-Saharan Africa.) In the 31 countries, average reported point prevalence of concurrency for adult men and women age 15–49 ranges from 0.8% to 10.2%, the unweighted mean of which is 4.7%. At levels of concurrency reported in these 31 surveys (that is, with concurrency prevalence no higher than 10.2%), there are no simulated epidemics (making plausible assumptions about dilution) that are sustainable (see Table 1, column 6). Even if one makes the improbable assumptions that there is no coital dilution or duration dilution, our simulations indicate that in none of the 31 countries is concurrency prevalence high enough to produce epidemics that, even if they do not move to extinction, grow only as little as 1 percentage point in their first 25 years (see Table 2, column 5).

Due to social desirability bias, it is almost certain that female concurrency and possibly male concurrency are underreported in the DHS and other sexual behaviour surveys (Sawers,

2013). The last column of Table 3 shows mean reported point prevalence of concurrency adjusted for underreporting in the 31 sub-Saharan African countries. The adjustment assumes that women's actual concurrency prevalence was 8 times their reported level. (Women's concurrency is capped at 20% in Sierra Leone, Equatorial, Guinea, Gabon, and Liberia, where simply multiplying by 8 produces concurrency prevalences between 24% and 40%. Even 20% appears to be implausibly high.) Social desirability bias is unlikely to cause men in polygamous unions to underreport concurrency, but for other men, we adjust their concurrency to double their reported level. These adjustments for social desirability bias are necessarily arbitrary, but we deliberately tried to exaggerate rather than understate the degree of underreporting in order to bias the result against the argument presented in this article (Sawers, 2013). Some have argued that men and even some women might over-report rather than under-report concurrency (Nnko *et al.*, 2004). See also (Morris *et al.*, 2014), whose data suggest our adjustments overstate women's under-reporting of concurrency (though perhaps understating men's). Furthermore, it is plausible that higher reported concurrency rates may reflect in whole or in part less stigma rather than different behaviours. If that is so, these adjustments for under-reporting due to social desirability bias exaggerate concurrency in countries with high levels of reported concurrency, and our adjusted concurrency measures for Sierra Leone, Equatorial, Guinea, Congo Brazzaville, and perhaps other countries should be viewed with some scepticism.

The next step is to compare the measures of concurrency prevalence adjusted for social desirability bias in the last column of Table 3 with the modelled HIV epidemics described in Tables 1 and 2. Can one find countries in SSA with concurrency prevalence high enough to generate even slowly growing HIV epidemics? The answer is no if one assumes that secondary partnerships have lower coital frequencies and shorter durations than primary partnerships. Indeed, our model cannot generate growing epidemics with those assumptions (see Table 1, column 3). To generate epidemic growth in our model at plausible levels of concurrency, one must assume away coital dilution or duration dilution. That is, one must assume that primary and secondary partnerships have the same duration or the same coital frequencies.

Let us assume provisionally no duration dilution but allow for modest coital dilution. If partnerships last only 400 or 500 days, then 19% prevalence of concurrency can produce very slow growth in HIV prevalence in simulated epidemics. (See Table 1, column 5, rows 4 and 5.) The last column in Table 3 shows that in only 3 of 31 countries in sub-Saharan Africa (Sierra

Leone, Equatorial Guinea, and Congo Brazzaville) is reported concurrency (adjusted for social desirability bias) as high as 19%. If mean partnership duration is higher than 500 days, our simulations show that, if coital dilution is assumed, even fewer countries would have levels of concurrency sufficient to generate even very slow growth in HIV.

Next, let us consider a related experiment: allow for duration dilution, but not coital dilution. With those assumptions, there are no simulated epidemics that can grow by as much as 1 percentage point in their first 25 years at any level of concurrency. (See Table 2, column 2.)

Lastly, assume neither duration dilution nor coital dilution. If partnerships last only 200 days, as in the original MK-1997 model, then 13% prevalence of concurrency can produce very slow growth in HIV prevalence (Table 2, column 5 and row 2). The last column in Table 3 shows that 8 of 31 countries in sub-Saharan Africa have concurrency prevalence (adjusted for social desirability bias) of 13% or higher. Nevertheless, mean partnership duration is surely higher than 200 days. If mean partnership duration is as little as 3 years—note that primary partnerships in the Rakai survey lasted on average about 20 years—then our simulations show that 19% concurrency prevalence is required to produce even very slow growth in HIV prevalence (Table 2, column 5 and row 7). Again, only 3 of 31 countries in SSA have adjusted concurrency prevalence that high. Still assuming neither kind of dilution and 3 year partnerships, only a single country in Table 3 has adjusted concurrency prevalence high enough to produce even a 2 percentage point increase in HIV prevalence in the first 25 years of its epidemic.

In sum, with plausible assumptions about differences in mean partnership duration and coital frequency between primary and secondary partnerships, simulated HIV epidemics are unsustainable. Even if we relax both of those assumptions (but assume that the mean duration of primary partnerships is 3 years), there are only 3 countries in SSA that have concurrency prevalence (adjusted for social desirability bias) sufficiently high to generate even very slow HIV growth (1 percentage point increase in prevalence in the first 25 years). There are no plausible assumptions with which we can generate rapidly growing HIV epidemics.

Discussion

As noted earlier, proponents of the concurrency hypothesis argue that long duration overlapping partnerships promote the spread of HIV. That is obviously true for any serodiscordant partnership in which the partners have regular sexual contact—the longer the partnership lasts,

the greater the likelihood of transmission. The simulations reported in this article are the first to test whether the assertion is correct at the population level. We find that, contrary to the arguments of concurrency hypothesis proponents, there is a population-level protective effect of formal and informal polygyny that grows stronger with longer partnerships. The available evidence on the prevalence of partnership concurrency and duration combined with the results of the simulations presented in this article indicate that neither short-term nor long-term concurrency are primary drivers of HIV epidemics in sub-Saharan Africa.

Morris and Kretzschmar's 1997 model is the single most influential publication on the subject of concurrency and HIV. The iconic stature of their model and its continuing impact on the discourse regarding HIV in sub-Saharan Africa make it appropriate to explore how its results were shaped by the parameter values and model structure chosen by its authors. The model was a pioneering effort to establish a proof of concept that showed it was possible to use individual-based stochastic modelling of dynamic sexual networks to shed light on HIV epidemic dynamics. They were the first to do so at a time when individual-based modelling was still in its infancy. The trouble is that the authors themselves and numerous others have taken their results not as proof of concept that concurrency could be modelled, but proof that concurrency drives the HIV epidemics in SSA. It took a decade before the model's parameterization was subjected to any critical appraisal (Deuchert and Brody, 2007; Lurie and Rosenthal, 2010b). By then, the concurrency hypothesis had become established as the conventional explanation for SSA's burgeoning HIV epidemics.

There are now other individual-based stochastic models incorporating different partnership types, such as transient partnerships with commercial sex workers (Johnson *et al.*, 2009; Leclerc *et al.*, 2009) or long-term and short-term partnerships (Goodreau *et al*., 2012). Models that go beyond Morris and Kretzschmar's framework appear to offer interesting insights. [But see Appendix II to (Sawers, 2013), which argues that most do not.] Nevertheless, as models proliferate it becomes increasingly difficult to determine which differences in assumptions and approaches critically affect the differences in results. The path chosen in this article is to build on the work of others who have made important but readily isolated modifications to the MK-1997 model (choosing a realistic daily transmission risk and adding coital dilution) by exploring the effect of varying mean partnership duration. This approach constitutes a kind of controlled

experiment—changing one thing while holding constant every other assumption—that provides interesting insights.

Our experiment shows why Morris and Kretzschmar's model greatly exaggerated the importance of concurrency in spreading HIV. They assumed a daily transmission risk that is orders of magnitude larger than can be justified by careful research (Boily *et al.*, 2009; Hollingsworth *et al.*, 2008; Wawer *et al.*, 2005), assumed no coital dilution despite the evidence, assumed implausibly rapid partnership turnover (mean partnership duration of 200 days), and assumed that primary and secondary partnerships are of equal duration. It was those unrealistic assumptions that produced the explosive growth in simulated HIV epidemics. As we have shown here, assuming reasonable values for these parameters generates simulated HIV epidemics that do not grow at all, but instead move to extinction.

It is clear that sexual behaviour varies widely in SSA (see Table 3) both between and within countries. Surely there are groups of individuals within national populations with high levels of concurrency, high unprotected coital frequencies, and rapid partner turnover—behaviour that could produce high HIV incidence. When considering the implications of this observation for MK type simulations, including ours, it is important to keep in mind the stochastic nature of partnership dynamics in these models. Partnerships form randomly in the face of individual encounters, and a partnership faces a daily risk of dissolution. Individuals have heterogeneous experiences in terms of the length of partnerships, the number partnerships, and the amount of overlap between partnerships. Network dynamics in which subsectors of the larger population engage in high-risk behaviour thus to some extent are captured by our simulations.

The perspective of this article is that most individuals in most parts of the world—including sub-Saharan Africa—establish stable, long-term partnerships that isolate them from high-risk behaviours and high levels of HIV. Our simulations demonstrate that in such a social environment, empirically relevant levels of concurrency cannot account for the spread of HIV across broad sectors of the population, given the usual assumptions about HIV transmissibility.

These conclusions are drawn from an analysis based on an unfortunately thin empirical foundation. Despite a quarter century of surveys asking the people of sub-Saharan Africa about the intimate details of their sexual lives, we still have only fragmentary evidence about issues central to the arguments of this article. In particular, our estimates of the extent of both coital

dilution and duration dilution are importantly influenced by a single survey carried out in the mid 1990s in a single province of one country in the region (Morris *et al.*, 2010; Morris and Kretzschmar, 2000). That survey also provides important information about the average length of heterosexual partnerships in SSA. The MK-2000 model calibrates spousal and non-spousal durations to these data. Similarly, we separately calibrate the mean duration of primary and secondary partnerships, but we then explore the consequences of proportionally changing the mean partnership durations.[4]

Fortunately, we have a broad empirical foundation (16 DHS) for our assertion that partnerships for adults in the region typically last far longer—indeed, many years longer—than the 200 days assumed by the MK-1997 model (and both the EHG-2011 and SIS-2011 models). Those data inspire considerable confidence in our finding of a population-level protective effect of longer duration partnerships. That confidence is not undermined by the thin empirical foundation for our assertions about coital and duration dilution because we still find that protective effect even if we assume that both primary and secondary partnerships are assigned the same coital frequencies and the same duration.

The core issue addressed by this article is how to explain persistently high HIV prevalence in sub-Saharan Africa and its extremely rapid growth in certain countries in the region during the last decade or two of the 20th century. We show that individual-based simulations of HIV transmission and concurrent partnering—under all empirically plausible parameterizations—cannot generate sustainable HIV epidemics at levels of concurrency found in sub-Saharan Africa. Even when we consider empirically implausible, epidemic enhancing assumptions about partnership duration and coital frequency, only a few countries in the region have sufficiently prevalent concurrency to produce even very slow growth in HIV. And as an empirical matter, none of those countries with high levels of concurrency have HIV prevalence much above the sub-Saharan African average. We find that concurrency at levels prevailing in

[4] For any mean duration, we adopt the same distributional assumptions as the MK-1997 model (and the related literature). Specifically, partnership duration is effectively drawn from a geometric distribution, where mean partnership duration determines the daily risk of partnership dissolution. This daily risk fully determines all moments of the duration distribution, including the mean and variance. This approach to partnership duration is standard in the literature, and replacing it would reduce comparability of our results to previous work. Fortunately, in additional to the conceptual plausibility of a partnership facing repeated risk of dissolution, actual partnership durations appear crudely geometric (Burington *et al.*, 2010). Nevertheless, future work might fruitfully explore different approaches to modelling partnership duration.

sub-Saharan Africa does not produce simulated epidemics that track the rapid growth of HIV epidemics in sub-Saharan Africa or keep HIV epidemics in most countries in the region from moving to extinction if they become established. Our findings indicate that the two-decade effort to explain HIV prevalence in sub-Saharan Africa by focusing on the role of concurrency has been a mistake.

Table 1. **Assuming 25% coital dilution, level of concurrency at which HIV prevalence can rise at least 1 or 2 percentage points above seeding prevalence of 1% in 25 years or level of concurrency at which HIV epidemic is sustainable.**

Row	Mean duration of primary partnership	Duration dilution: Secondary partnerships are 12% as long as primary partnerships			No duration dilution: Secondary partnerships are as long as primary partnerships		
		1. HIV prevalence rises at least 2 percentage points above seeding prevalence in 25 years	2. HIV prevalence rises at least 1 percentage point above seeding prevalence in 25 years	3. HIV epidemic is unsustainable	4. HIV prevalence rises at least 2 percentage points above seeding prevalence in 25 years	5. HIV prevalence rises at least 1 percentage point above seeding prevalence in 25 years	6. HIV epidemic is unsustainable
1	100 days	*	*	*	*	*	*
2	200 days	*	*	*	*	*	14.%
3	300 days	*	*	*	*	*	13%
4	400 days	*	*	*	*	19%	13%
5	500 days	*	*	*	*	19%	14%
6	2 years	*	*	*	*	21%	16%
7	3 years	*	*	*	*	23%	19%
8	5 years	*	*	*	*	25%	23%
9	10 years	*	*	*	*	*	25%
10	15 years	*	*	*	*	*	*
11	20 years	*	*	*	*	*	*

*No concurrency prevalence using the range of values for the propensity to form concurrent partnerships used in the MK and derivative models can generate growth in HIV prevalence that meets the criterion.

Table 2. **Assuming no coital dilution, level of concurrency at which HIV prevalence can rise 1 or 2 percentage points above seeding prevalence of 1% in 25 years or level of concurrency at which HIV epidemic is unsustainable.**

Row	Mean duration of primary partnership	Duration dilution: Secondary partnerships are 12% as long as primary partnerships			No duration dilution: Secondary partnerships are as long as primary partnerships		
		1. HIV prevalence rises at least 2 percentage points above seeding prevalence in 25 years	2. HIV prevalence rises at least 1 percentage point above seeding prevalence in 25 years	3. HIV epidemic is unsustainable	4. HIV prevalence rises at least 2 percentage points above seeding prevalence in 25 years	5. HIV prevalence rises at least 1 percentage point above seeding prevalence in 25 years	6. HIV epidemic is unsustainable
1	100 days	*	*	*	*	*	*
2	200 days	*	*	*	*	13%	10%
3	300 days	*	*	*	16%	14%	7%
4	400 days	*	*	*	17%	15%	7%
5	500 days	*	*	*	17%	14%	8%
6	2 years	*	*	*	19%	16%	10%
7	3 years	*	*	12%	22%	19%	14%
8	5 years	*	*	15%	24%	22%	19%
9	10 years	*	*	19%	25%	25%	23%
10	15 years	*	*	21%	*	26%	25%
11	20 years	*	*	*	*	26%	25%

*No concurrency prevalence using the range of values for the propensity to form concurrent partnerships used in the MK and derivative models can generate growth in HIV prevalence that meets the criterion.

Table 3**. Point prevalence of concurrency in 31 countries in sub-Saharan Africa measured using the UNAIDS protocol from the Demographic and Health Surveys (DHS) 2010–2014 in percent ranked by average of men's and women's concurrency ages 15–49**

		Percentage Point Prevalence of Concurrency			
Rank	*Country*	*men ages 15–49*	*women ages 15–49*	*mean of men and women ages 15–49*	*mean of men and women adjusted for under-reporting**
1	Sierra Leone	16.6	3.7	10.15	24.0
2	Equatorial Guinea	15.2	5.0	10.10	23.6
3	Congo Brazzaville	14.1	1.3	7.70	19.0
4	Cameroon	13.3	1.9	7.60	18.2
5	Côte d'Ivoire	12.9	1.1	7.00	15.1
6	Benin	12.0	0.3	6.15	10.0
7	Chad	12.2	0.1	6.15	7.2
8	Gabon	9.2	3.0	6.10	18.6
9	Mozambique	10.9	0.9	5.90	12.3
10	Liberia	8.0	3.4	5.70	17.1
11	Niger	11.0	0.2	5.60	6.4
12	Republic of Congo	9.8	0.7	5.25	9.7
13	Burkina Faso	10.4	0.1	5.25	7.0
14	Guinea	9.3	1.1	5.20	11.1
15	Togo	10.0	0.2	5.10	10.8
16	Uganda	9.7	0.4	5.05	8.1
17	Lesotho	8.0	2.1	5.05	16.4
18	Tanzania	8.1	1.2	4.65	12.7
19	Mali	8.0	0.3	4.15	6.2
20	Zambia	7.1	0.4	3.75	7.1
21	Nigeria	6.8	0.4	3.60	6.3

22	Ghana	6.3	0.3	3.30	6.7
23	Gambia	5.5	0.1	2.80	3.7
24	Senegal	5.1	0.2	2.65	3.9
25	Kenya	4.8	0.2	2.50	4.8
26	Zimbabwe	3.8	0.3	2.05	4.3
27	Malawi	3.8	0.1	1.95	3.0
28	Namibia	2.2	0.4	1.30	3.2
29	Ethiopia	2.3	0.0	1.15	1.2
30	Rwanda	1.6	0.1	0.85	1.6
31	Burundi	1.5	0.0	0.75	1.0
	Unweighted Mean	8.3	1.0	4.67	9.7

Source: The DHS can be found at http://dhsprogram.com/publications/publication-search.cfm?type=5. The DHS from Burkina Faso, Burundi, and Senegal do not report point prevalence of concurrency or report it only for men. The missing concurrency prevalences were calculated using datasets from Measure DHS-IFC Macro (www.measuredhs.com).

* The adjustment assumes that the men's actual concurrency was double their reported concurrency if they were not in a formally polygynous union (and that men in polygynous unions correctly reported concurrency). Furthermore, the adjustment assumes that women's actual concurrency prevalence was 8 times their reported concurrency but was capped at 20%.

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