Epidemics 8 (2014) 9–17

Contents lists available at ScienceDirect

Epidemics

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

Could there have been substantial declines in sexual risk behavior across sub-Saharan Africa in the mid-1990s?

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ARTICLE INFO

Article history:
Received 9 October 2013
Received in revised form 2 May 2014
Accepted 23 June 2014
Available online 1 July 2014

Keywords:
HIV transmission
Mathematical model
Sexual risk behavior
Sub-Saharan Africa
Sexual network

ABSTRACT

Background: HIV prevalence is decreasing in much of sub-Saharan Africa (SSA), but the drivers of the decline are subject to much dispute. Using mathematical modeling as a tool for hypothesis generation, we demonstrate how the hypothesis that the drop in prevalence reflects declines in sexual risk behavior is self-consistent. We characterize these potential declines in terms of their scale, duration, and timing, and theorize on how small changes in sexual behavior at the individual-level could have driven large declines in HIV prevalence.
Materials and methods: A population-level deterministic compartmental model was constructed to describe the HIV epidemics in 24 countries in SSA with sufficient trend data. The model was parameterized by national HIV prevalence and HIV natural history and transmission data. The temporal evolution of sexual risk behavior was characterized using established tools and uncertainty and sensitivity analyses on the results were conducted.
Results: Declines in the scale of sexual risk behavior between 31.8% (Botswana) and 89.3% (Liberia) can explain the declining HIV prevalence across countries. The average decline across countries was 68.9%. The transition in sexual risk behavior lasted between 2.7 (Botswana) and 16.6 (Gabon) years with an average of 8.2 years. The turning point year of the transition occurred between 1993 (Burundi) and 2001 (Namibia), but clustered around 1995 for most countries. The uncertainty and sensitivity analyses affirmed our model predictions.
Conclusion: The hypothesis that HIV prevalence declines in SSA have been driven by declines in sexual risk behavior is self-consistent and provides a convincing narrative for an evolving HIV epidemiology in this region. The hypothesized declines must have been remarkable in their intensity, rapidity, and synchronicity to explain the temporal trends in HIV prevalence. These findings provide contextual support for the hypothesis that changes in sexual behavior that materialized in the 1990s are a dominant driver of the recent decreases in HIV prevalence.

Introduction

Sub-Saharan Africa (SSA) remains the region most affected by HIV, with 70% of the global HIV disease burden and 1.6 million new infections in 2012 (UNAIDS, 2013a, 2013b). However, recent evidence suggests that HIV prevalence and incidence have declined in parts of East and Southern Africa (The World Bank, 2014; UNAIDS, 2010, 2013a, 2013b; UNAIDS/WHO, 2010a, 2011). HIV incidence appears to have declined by more than 50% between 2001 and 2011 in 25 low- and middle-income countries, mostly from SSA (UNAIDS, 2012). Nevertheless, the drivers of the decline in prevalence and incidence are not well understood and subject to much dispute. Several mechanisms can contribute to such declines such as reduction in sexual risk behavior (Hallett et al., 2006, 2009; Kilian et al., 1999; UNAIDS, 1999), natural epidemic dynamics (Garnett et al., 2006), increased HIV-associated mortality (UNAIDS, 1999; Walker et al., 2008), impact of interventions (UNAIDS, 1999), and/or heterogeneity in host susceptibility to HIV infection (Nagelkerke et al., 2009, 2014).

Different studies have suggested that substantial reductions in different aspects of sexual behavior may have occurred in SSA including fewer sexual partners, increased condom use, or delay in

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http://dx.doi.org/10.1016/j.epidem.2014.06.001
1755-4365/

sexual debut (UNAIDS/WHO, 2011). Uganda provides an example where rapid reductions in sexual risk behavior appear to have led to a dramatic drop in HIV prevalence (Kamali et al., 2000; Kilian et al., 1999; Low-Beer and Stoneburner, 2003; Stoneburner and Low-Beer, 2004). Other studies in other countries have also suggested that reductions in sexual risk behavior have led to declines in HIV prevalence such as in Zimbabwe, Kenya, and Malawi (Bello et al., 2011; Boily et al., 2005; Gregson et al., 2010; Hallett et al., 2006, 2009; Kilian et al., 1999; Low-Beer and Stoneburner, 2003; Walker et al., 2008). It is not clear, however, whether such changes have occurred widely across SSA. The scale and timing of these changes in sexual behavior, and duration over which they have occurred, are also poorly understood.

Self-reported sexual behavior provides one methodology for assessing the temporal changes in sexual risk behavior. Nevertheless, such data are fraught with potential flaws such as social desirability and recall biases, among other non-random biases, and informational limitations of egocentric sexual behavior data (Abu-Raddad et al., 2010; Cleland et al., 2004; Helleringer et al., 2011; Morris, 2004; Obasi et al., 1999). It is also challenging to quantify simultaneously the multitude of aspects that represent sexual risk behavior such as age at sexual debut, rate of partnership formation, contact with sex workers, concurrent partners, and risk group cohort mixing (Abu-Raddad et al., 2006; Watts and May, 1992). Last but not least, it is still not well understood how specific aspects of sexual behavior can drive HIV infection acquisition and transmission more so than others (Abu-Raddad et al., 2010).

Against this background, we attempt to answer the following question: Are the trends in HIV prevalence in SSA consistent with the hypothesis that the declines in prevalence (and incidence) occurred as a consequence of large and recent reductions in sexual risk behavior? To address this question, we used mathematical modeling as a tool for hypothesis generation, by constructing a mathematical model to conduct a "*Gedanken experiment*" (thought experiment) to assess the "internal validity" of this hypothesis. While our approach is an indirect one and does not prove *per se* the validity of this hypothesis, it demonstrates the self-consistency and plausibility of this hypothesis across 18 countries in SSA. It also quantifies the scale of the hypothesized reductions, their duration, and when they occurred. Among the strengths of this approach is that it is independent of the limitations of using self-reported sexual behavior data to generate inferences about the trends in sexual risk behavior, and that it disentangles the declines in HIV prevalence due to natural epidemic dynamics (such as high risk group depletion), from those due to the hypothesized changes in sexual risk behavior. Our approach in essence provides a comparative analysis of the reductions in the risk of HIV exposure, irrespective of the specific drivers of this reduction, across multiple countries in SSA using a unified and systematic methodology.

Methods

Mathematical model

A deterministic compartmental mathematical model was constructed, based on extension of earlier models (Abu-Raddad and Longini, 2008; Abu-Raddad et al., 2006), to describe the heterosexual transmission of HIV in a given population (Supplementary Material (SM)). The model consists of a system of coupled nonlinear differential equations, and stratifies the population according to HIV status, stage of infection and sexual risk group. HIV progression in the model is divided into the three stages of acute, chronic, and advanced. The mixing between the sexual risk groups is described by a mixing matrix that incorporates both an assortative component (choosing partners only from within their risk group), and a proportionate component (choosing partners with no preferential bias based on the kind of risk group).

Our model incorporates 10 sexual risk groups in the population, starting from lower to higher levels of sexual risk behavior. Replacement of individuals into the different risk groups occurs by assuming that individuals enter the sexually active population at a fixed rate and a fixed distribution across these risk groups. It is also assumed that people stay in the same risk group throughout their sexual lifespan. The distribution of the population across the risk groups follows a gamma distribution (Eq. S8 of SM) based on empirical data from SSA of the degree distribution in a sexually active population (distribution of the number of sexual partners per year) (Bansal et al., 2007; Cuadros et al., 2011; Hamilton et al., 2008; Handcock and Jones, 2004). Accordingly, a vast majority of the population will enter the lower risk groups whereas a small proportion of the population will enter the higher risk groups.

The level of sexual risk behavior was parameterized by the effective partnership change rate in each risk group, and in essence it is a measure of the overall risk of exposure to the HIV infection (that is the force of infection) reflecting both behavioral as well as possibly biological co-factors. The effective partnership change rate, in units of number of partners per year, captures the number of new sexual partners an individual in a specified risk group acquires, but also effectively other factors that enhance the risk of exposure to the infection such as concurrency and clustering within sexual networks (Abu-Raddad and Longini, 2008; Kretzschmar and Morris, 1996; Morris, 1997; Morris and Kretzschmar, 1997; Watts and May, 1992), and variability in sexual risk behavior in the population (May and Anderson, 1988). Since the exact nature of sexual behavior and sexual networks in SSA is not well-understood and varies within and across communities (Ferry et al., 2001; Lagarde et al., 2001), the partnership change rate is effectively a summary measure of the population-specific level of sexual risk behavior, and captures the distribution and strength of the risk of exposure to HIV infection.

We assumed that the distribution of the level of sexual risk behavior across the different risk groups follows a power law function. This form is motivated by the results of simulations exploring the diversity in the level of sexual risk behavior in human populations (Awad et al., 2012), and also by analyses of the properties of complex weighted networks (Barabási, 2003; Barrat et al., 2004; Boccaletti et al., 2006; Watts and Strogatz, 1998). We parameterized the time dependence of the level of sexual risk behavior in each risk group through a Wood-Saxon function (Velicia, 1987; Woods and Saxon, 1954), to characterize the temporal evolution of sexual risk behavior during the HIV epidemic (Eq. S10 of SM). This logistic function is specifically designed to parameterize transitions in terms of their scale and strength, duration, and the turning point (Velicia, 1987; Woods and Saxon, 1954).

We assumed that the change in the level of sexual risk behavior for all risk groups follows the same time trajectory, that is all risk groups have the same scale of reduction in the level of sexual risk behavior. Table S1 of SM, using Kenya as an example, displays the proportion of individuals in each risk group, the risk-group-specific effective partnership change rate prior and after the transition in sexual risk behavior, and the risk-group-specific basic reproduction number (the average number of secondary infections in a fully susceptible population, R_0) prior and after the transition in sexual risk behavior. Further details about the model structure can be found in the SM.

Data source and model fitting

The model was parameterized using recent empirical epidemiological and natural history data from SSA. The model's parameter values along with their references are listed in Table S2 of SM. The