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Network of Sexual Contacts and Sexually Transmitted HIV Infection in Burkina Faso

Vito Latora,[1] André Nyamba,[2] Jacques Simpore,[3] Bahiré Sylvette,[2] Sandwidi Diane,[2] Bukiki Sylvère,[2] and Salvatore Musumeci[3,4]*

[1]*Department of Physics and Astronomy, University of Catania and INFN-Catania, Catania, Italy*
[2]*Department of Sociology, University of Ouagadougou, Ouagadougou, Burkina Faso*
[3]*Department of Pharmacology, Gynecology and Obstetrics, Pediatrics, University of Sassari and Institute of Population Genetics, Alghero (SS), Italy*
[4]*Centre Medical Saint Camille, Ouagadougou, Burkina Faso*

Two thirds of the people who have been infected by human immunodeficiency virus (HIV) in the world live in Sub-Saharan African countries. The results of a study measuring the degree distribution of the network of sexual contacts in Burkina Faso are described. Such a network is responsible for the spread of sexually transmitted diseases, and in particular of HIV. It has been found that the number of different sexual partners reported by males is a power law distribution with an exponent $\gamma = 2.9$ (0.1). This is consistent with the degree distribution of scale-free networks. On the other hand, the females can be divided into two groups: the prostitutes with an average of 400 different partners per year, and females with a stable partner, having a rapidly decreasing degree distribution. Such a result may have important implications on the control of sexually transmitted diseases and in particular of HIV. Since scale-free networks have no epidemic threshold, a campaign based on prevention and anti-viral treatment of few highly connected nodes can be more successful than any policy based on enlarged but random distribution of the available anti-viral treatments. ***J. Med. Virol. 78:724–729, 2006.*** © 2006 Wiley-Liss, Inc.

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INTRODUCTION

A population, like many other complex systems, can be described as a network, in mathematical terms a graph, whose nodes are the single individuals and the links represent the interactions among them [Wasserman et al., 1994]. Since most infectious diseases spread by contact between infectious and susceptible individuals, the structure of the network plays an important role in the dynamics of the infectious disease propagation [Anderson and May, 1991; Potterat et al., 2000; Youm and Laumann, 2002]. In particular, the network density, the presence of sub-structures and the existence of long range connections typical of a class of networks named small worlds [Mollison, 1977; Watts and Strogatz, 1998; Latora and Marchiori, 2001; Boccaletti et al., 2006], increases the probability of secondary infections, enhancing critically the spread of infectious diseases. Moreover, the key role of central individuals [Wasserman et al., 1994; Freeman, 1979, 1980] has long been known, and epidemiologists have taken it into account in the modeling of disease spreading [Anderson and May, 1991].

In this article, the emphasis is on the simplest measure of node centrality, the degree, and on the consequences deriving from the heterogeneity of the degree distribution of the network. The degree k of a node is the number of its neighbors, that is, the number of links adjacent to the node: in the case under study, the number of sexual partners of an individual. Recently it has been found that many biological, social and communication networks are different from random graphs [Bollobas, 1985] and all share the same property of having a long-tailed *power-law degree distribution* $P(k) \simeq k^{-\gamma}$ with an exponent γ ranging between 2 and 3. Networks with such extremely heterogeneous degree distribution have been named *scale-free networks* [Strogatz, 2001; Albert and Barabasi, 2002; Dorogovtesev and Mendes, 2003; Boccaletti et al., 2006]. In such networks, due to the infinite variance of the degree distribution [Lloyd and May, 2001; May and Lloyd, 2001], viruses can spread and be maintained even when the infection

*Correspondence to: Prof. Salvatore Musumeci, Department of Pharmacology, Gynecology and Obstetrics, Pediatrics, University of Sassari, Italy, Viale San Pietro n. 43b-07100 Sassari, Italy. E-mail: smusumeci@tiscalinet.it

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probability (the transmissibility) is extremely small. This result has been proven initially for the spread of computer viruses over the Internet [Pastor-Satorras and Vespignani, 2001a,b], although it can be relevant to understand the spread of pathogens in other types of networks, as networks of sexual contacts, that are important for the transmission of sexually transmitted diseases: herpes genitalis, gonorrhea, syphilis, Chlamydia, and HIV [Liljeros et al., 2003; Wylie et al., 2005]. It has been pointed out in the literature that in such networks some individuals can have a large numbers of partners [Hethcote and Yorke, 1984; May and Anderson, 1987; Anderson and May, 1991]. A recent survey in Sweden has shown that the network of sexual contacts is a scale-free networks and the numbers of different sexual partners over individual lifetime is a power law distribution with an exponent $\gamma = 3.1$ (0.2) for females, and $\gamma = 2.6$ (0.3) for males [Liljeros et al., 2001]. Motivated by the results of Liljeros et al. [2001], the same protocol was applied to study the network of sexual contacts in Sub-Saharan African countries, where two thirds of the people who have been infected by human immunodeficiency virus (HIV) in the world live. Sexual contacts in these areas are responsible for the spread not only of sexually transmitted diseases, as in the case of Sweden, but also of HIV [Piot et al., 2001].

METHODS

General Characteristics of Population

The main aim of this study was to collect a representative sample of the degree distribution of the network of sexual contacts in Ouagadougou, the capital of Burkina Faso. In Burkina Faso 7.17% of the African population infected by HIV live and the estimated percentage of people with HIV infection in Ouagadougou is the 7.14% [Ilboudo et al., 2003]. The most common social HIV-positive groups includes prostitutes (58% are infected) [Lankoande et al., 1998a]; truck drivers (19%) [Lankoande et al., 1998b] and pregnant women (8%) [Simpore et al., 2005]. The estimated population of Ouagadougou is of 1,200,000 inhabitants, with a proportion of 48% males and 52% females. More than 50% of its inhabitants are under 15 years of age, while only 0.5% are over 70. Although the role of heterosexual transmission of HIV in Africa is still a topic of intense debate [Brody, 1997; Brody and Potterat, 2003; Gisselquist and Potterat, 2003], there is good empirical evidence that in Burkina Faso heterosexual transmission accounts for the majority of the cases with some transmission in injecting drug users [Ouedraogo, 1994]. A study conducted by the Ministry for Social Affairs and Family reveals that there were about 8,000 prostitutes between 15 and 45 years of age only in the city of Ouagadougou [Meda et al., 1998].

Survey Instrument

The survey instrument used is a pre-coded two-page questionnaire that takes approximately 10 min to be completed. It has been filled either directly by the respondent or with the help of an assistant. The questionnaire is in French and the survey questions were designed to cover a broad array of issues with the aim of collecting general information such as age, occupation, number of children, sectors of Ouagadougou where subjects live, economical and cultural level, and confidential information on sexual attitudes. In particular, the respondent interviewed has been asked an estimate of the number of different sexual partners in the last 12 months and during his/her lifetime.

Sampling Design

The survey covered different sectors of Ouagadougou. One thousand questionnaires have been collected, interviewing a sample of 500 females and 500 males, who declared not to be sex workers. The interviewed were chosen at random, stratified by seven different sectors of the city, with a number of interviewed in each sector proportional to the number of the inhabitants of the sector. Only individuals in the range of age 18–60 were interviewed. The interviewed were found and contacted in the streets by a staff of the Department of Sociology of the University of Ouagadougou, and they were interviewed in person. The information on sexual practices was extremely difficult to obtain for obvious reasons. The answer to the question on the number of different sexual partners in the last 12 months was obtained in 466 out of 1,000 interviewed, with only 80% also answering the question on the number of different sexual partners in the respondents' entire life. Among the 466 respondents, 287 are males and 179 are females (none of them declared to be prostitutes). The age distribution of the respondents is reported in Figure 1 (notice that the age distribution of the inhabitants of Ouagadougou is the following: 13% of inhabitants are between 20 and 30, 12% are between 30 and 40, 8% are between 40 and 50, 8% are between 50 and 60).

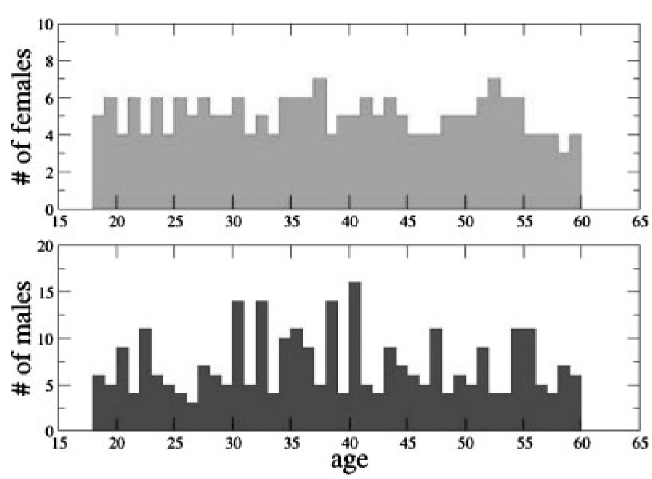

Fig. 1. Age distribution of the 466 respondents (179 females and 287 males) answering the question on the number of different sexual partners in the last year.

A sample of 30 prostitutes was also interviewed. The prostitutes contacted each other on participating in the study. The percentage of HIV among the prostitutes interviewed was 60%, and only 10% used condoms during intercourse.

RESULTS

The number of different sexual partners in the last 12 months were used to construct the degree k of each individual in the network of sexual contacts, and consequently the degree distribution $P(k)$. Unlike Liljeros et al. [2001], the number of different sexual partners in the respondents' entire life has not been used, since the analysis and interpretation are strongly based on the assumption that the links are concurrent [Moody, 2002]. The 179 female respondents reported an average of $\langle k \rangle = 1.14 \pm 0.01$ (median 1, range 1–5) different partners in the last 12 months, while the 287 male respondents have reported an average of $\langle k \rangle = 1.94 \pm 0.03$ (median 2, range 1–18) different partners. Seven percent of interviewed was serological positive for HIV, when controlled by the method Genius II Rapid Test. (BioRad Laboratories, France), confirmed by enzyme immunoassay (EIA), using the IMX System (Abbott Laboratories, France). Considering that more than 7% of population is HIV positive, the power of diffusion is enormous [Simpore et al., 2005].

Degree Distribution

The degree distribution $P(k)$ is the probability that a node of the network (an individual) has k links to the other nodes (k different partners), and is defined as $P(k) = N(k)/N_{\text{tot}}$, where $N(k)$ is the number of individuals with k links while N_{tot} is the total number of considered individuals. In Figure 2 the cumulative degree distributions $P_{\text{cum}}(k)$, obtained from the data set, is reported. Empty circles and full circles represent, respectively, females and males. Both a linear-linear scale (a) and a log-log scale (b) are used. The cumulative probability is defined in terms of the probability distribution $P(k)$ as [Dorogovtesev and Mendes, 2003]:

$$P_{\text{cum}}(k) = \sum_{k' \geq k} P(k')$$

The distribution for males is asymmetric and extremely wide, with the presence of men with more than 15 different partners, a value much larger than the average number of 1.94 ± 0.03. Women must be divided into two different groups: non-prostitutes and prostitutes.

The distribution of women who were not prostitutes shown in Figure 2 is more homogeneous than the distribution for males: 148 women (not prostitutes), out of 179, had only one sexual partner in the last 12 months. The woman with the largest number of different sexual partners had five partners. On the other hand, the information obtained on the sexual behavior of prostitutes in Ouagadougou from the sample of 30 prostitutes interviewed is that they have an average of $\langle k \rangle = 400 \pm 50$ different partners per year (with a median equal to 420, and an interquartile range equal to 70). Although the small size of the sample does not allow to draw a definitive conclusion on the shape of the degree distribution $P(k)$, we observed a symmetric around the average. The next step was to check whether the network under study was a scale-free network, that is, if it has a power law degree distribution with $2 < \gamma \leq 3$. If $P(k) \simeq k^{-\gamma}$, then the cumulative distribution is a power law $P_{\text{cum}}(k) \simeq k^{-\alpha}$ with the two exponents being related as $\gamma = \alpha + 1$. Commonly, the exponent α is extracted from the empirical data, and then γ is derived from α [Liljeros et al., 2001]. The results of the fitting are shown as dotted line for females, and dashed line for males (Fig. 2).

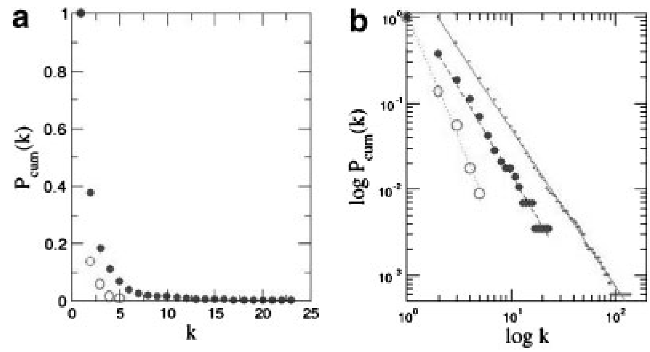

Fig. 2. The cumulative distribution of the number of sexual partners in the previous 12 months is reported both for the 179 females (not prostitutes) (open circles) and for the 287 males (filled circles) in a linear scale (**a**) and in a log-log scale (**b**).

The small dots and the relative fit (full line) represent the cumulative distribution of an artificial scale-free graph with 5,000 nodes and $\langle k \rangle = 5$, constructed by using the method proposed by Albert and Barabasi [2002] (the BA model). The fit is a power law with an exponent $\alpha = 1.9 \pm 0.1$. The distribution for females (not prostitutes) is fitted by a power-law $P_{\text{cum}}(k) \simeq k^{-\alpha}$, with an exponent$\alpha = 2.9 \pm 0.2$ (dotted line), corresponding to $\gamma = 3.9 \pm 0.2$, while that of males is fitted by a power-law with an exponent $\alpha = 1.93 \pm 0.10$ (dashed line) corresponding to $\gamma = 2.93 \pm 0.1$. The results indicate that the distribution of males is extremely heterogeneous and compatible with a scale-free distribution ($2 < \gamma \leq 3$), while the distribution for females (not prostitutes) has rapidly decaying tails $\gamma > 3$. The distribution of females in general is also extremely heterogeneous (it has a bimodal distribution), because of the presence of prostitutes with a large number of partners. For comparison, the cumulative distribution of an artificial scale-free graph much larger than the database is also described. The graph has 5,000 nodes and $\langle k \rangle = 5$, and has been obtained by using the model proposed by Albert and Barabasi [2002]. The corresponding fit is a power law with an exponent $\alpha = 1.9 \pm 0.1$ (dashed line) corresponding to $\gamma = 2.9 \pm 0.1$.

Modeling Epidemic Spread in Scale-Free Networks

The presence of a continuous hierarchy of high-degree nodes is the main characteristic which makes scale-free graphs different from random graphs. In particular, a power-law distribution with $2 < \gamma \leq 3$ implies that scale-free networks have a finite first moment $\langle k \rangle$, while $\langle k^2 \rangle$ and larger order moments are infinite. Pastor-Satorras and Vespignani [2001a,b] studied the propagation of a computer virus on the Internet represented as a scale-free graph with $2 < \gamma \leq 3$. They considered the susceptible-infected-susceptible (SIS) model, in which susceptible nodes acquire infections at a rate ν, the so called *transmissibility*, if connected to infected nodes, and infected nodes recover to the susceptible state at a rate δ, that is, the *average duration* of the infection is $D = 1/\delta$ [May and Lloyd, 2001]. The most important result in this study is the absence of epidemic threshold in scale-free networks [Lloyd and May, 2001; May and Lloyd, 2001]: in scale-free networks a virus can spread no matter how small is the factor $\lambda \equiv \nu/\delta = \nu D$. Conversely, the SIS model on regular lattices or on random graphs [Bollobas, 1985] predicts a critical value λ_c, such that for $\lambda \geq \lambda_c$, the infection spreads and becomes persistent, while for $\lambda < \lambda_c$ the infection dies. A similar result has been confirmed for the susceptible-infected-recovered (SIR) model [May and Lloyd, 2001; Newman, 2002], a model that takes into account the permanent immunization after the recovery. In mathematical epidemiology, the role of contacts distribution in the disease spreading is usually taken into account in the formula for the *basic reproductive number* R_0 [Anderson and May, 1991]. R_0 is defined as the expected number of secondary cases produced by a single case, and is equal to the product of the transmissibility ν, the duration of the infection $D = 1/\delta$ and of a measure of the network connectivity properties, namely:

$$R_0 = r_0(1 + C_k^2)$$

where $r_0 = \nu D\langle k \rangle = \lambda \langle k \rangle$ is the basic reproductive number in the hypothesis of an entirely homogeneous population, that is, if every individual had exactly $\langle k \rangle$ neighbors, and

$$C_k^2 = \frac{\sigma_k^2}{\langle k \rangle^2} = \frac{\langle k^2 \rangle}{\langle k \rangle^2} - 1$$

is the coefficient of variation of the connectivity distribution [Anderson and May, 1991]. The epidemic behavior shows a sudden change from a regime without epidemic ($R_0 < 1$) to a regime with epidemic that appears when $R_0 > 1$. May and Lloyd [2001] showed that the results of Pastor-Satorras and Vespignani [2001a,b] are in agreement with the formula for the basic reproductive number. In fact, for a scale-free network with $P(k) \simeq k^{-\gamma}$ and $2 < \gamma \leq 3$, R_0 is infinite for any non-zero transmission rate ν. The absence of epidemic thresholds in scale-free graphs has important consequences for the immunization strategies in the Internet. A strategy that is commonly implemented is based on the idea that the reduction of the transmissibility ν and/or of the duration of the infection D has the potential of bringing the system below the epidemic threshold. For instance, it was expected that the adoption of an ad-hoc anti-virus in a computers network would completely rule out the possibility of the diffusion of a virus as soon as the percentage of the "immunized" computers is such that λ is smaller than the epidemic threshold (or in other terms that the basic reproductive number R_0 is smaller than 1). This was revealed to be untrue in real experiments on computer networks, and now there is a theoretical explanation valid for ideal[1] scale-free networks where, as mentioned before, R_0 is infinite for any non-zero transmission rate ν and any non-zero D. Pastor-Satorras and Vespignani [2002b] and Dezso and Barabasi [2002] have studied the best immunization strategies on scale-free networks. In synthesis such results indicate that for a scale-free network:

1) the reduction of the trasmissibility without any information based on the connectivity of the network is not a good strategy.
2) the more oriented a strategy is towards the nodes with large k, the more chance it has to bring the epidemic threshold below the virus' spreading rate.

Developing Strategies Against Sexually Transmitted Diseases

In the case under study, unlike that of Liljeros et al. [2001], the degree distribution for males is a power law with an exponent $2 < \gamma \leq 3$, while the degree distribution for females is not a power law. This is due to the promiscuous behavior of many married and unmarried men. In particular it was found that the 65% of the males with more than 10 different partners per year are truck drivers having intercourses mainly with prostitutes in different regions of Burkina Faso where they travel for work. Conversely, the females are divided into two very different groups, women with one stable partner (and a rapidly decreasing degree distribution), and the prostitutes with an extremely high number of different partners. Consequently, public health strategies for control and eradication of sexually transmitted diseases based on reducing the transmissibility, shortening the duration of the infection, and reducing the contact rate between susceptible and infected individuals [Nguyen et al., 2003] in Burkina Faso should target the individuals with a high number of partners.

The difference between expected versus observed HIV and HCV coinfected individuals in Burkina Faso (Simpore et al., 2005) suggests the importance of the transmission route: sexual and through blood transfusions, reusable needles, traditional healers or medical and surgical interventions. In fact, when the parenteral

[1]Of course many real networks present a bounded scale-free behavior, that is, a power law degree distribution with a natural cut-off for large k, due either to the finite size of the network or to physical constraints. Although in these networks the presence of the cut-off induces the existence of an epidemic threshold, such a threshold is vanishing small, that is, it goes to zero with the system size [Pastor-Satorras and Vespignani, 2002b].

way prevails (as e.g., in Morocco, Egypt, and Gabon) the probability of contracting HCV is higher, but although HIV is transmitted parenterally by the same route, it is spread to a lesser extent than sexually. In contrast, when the transmission route is commonly related to sex, the probability of acquiring HCV is lower than the probability of acquiring HIV. Moreover, an individual may first acquire HIV sexually and then be infected with HCV through unsafe medical practices, traditional healers, when treated for an HIV-related illness.

Studies [Pastor-Satorras and Vespignani, 2001a,b] on the propagation of infectious diseases in scale-free networks on one hand could explain the failure of campaigns aiming at a generic social group, like the diffusions of condoms among students at schools. On the other hand, they suggest that the correct measure to adopt is to target the highly connected nodes of the graph of sexual contact, that is, the individuals with a large number of partners which should be the prostitutes and the men with a high number of partners. Along this direction some educational programs on women in young age have already been started by Camillians in Burkina Faso [www.camilliani.org/stmissioni/] with the purpose of reducing the risk of prostitution. At the same time, wide programs of sex education and the use of anti-retroviral drugs for prostitutes and promiscuous men such as the truck drivers, would help in breaking the connection of the network in countries where the HIV infection shows an uncontrolled spread. In fact, the adoption of anti-retroviral drugs modifies the infectivity of the highly connected nodes [Cu-Uvin et al., 2000; Fiore et al., 2003], with the consequences of restoring the epidemic threshold in a scale-free network, as demonstrated by Pastor-Satorras and Vespignani [2002a] and by Dezso and Barabasi [2002]. Such a strategy is often associated with the adoption of the protocol of HIV prophylaxis for the newborns [Simpore et al., 2006]. It is clear that even a full participation in preventive anti-retroviral therapy of all mothers who test positive, does not control completely mother to child transmission of HIV, without other specific interventions [Sobieszczyk et al., 2005]. However, if anti-retroviral therapy could become a reality in developing countries with low economical and social resources, the artificial feeding of newborns should not be necessary since it is more expensive than tri-therapy during pregnancy and in the first 4–6 months of breast feeding [Simpore et al., 2006].

Of course, the use of anti-retroviral therapy must be preceded by accurate health education programs for the rational use of condoms and other contraceptive methods [Sondo et al., 2001], directed at all at risk categories.

CONCLUSIONS

Knowledge of the structure of the sexual network provides important hints on the public health strategies for control and eradication of sexually transmitted diseases and in particular of HIV. It has been found that the sexual network in Burkina Faso exhibits scale-free properties. As a consequence, public health interventions based at reducing the transmissibility by means of a random implementation of anti-retroviral therapies and/or condom use could fail to eradicate the disease. The best strategy to adopt in Burkina Faso should consist of control and treatment of promiscuous individuals, with extensive use of anti-retroviral drugs, mainly female prostitutes and males with a high number of partners, who can be easily identified and therefore targeted. In scale-free networks, as that found in Burkina Faso and in Zimbabwe by Schneeberger et al. [2004], more than in random networks, a campaign strongly based on focused control, prevention and treatment of few highly connected nodes can be more successful than any policy based on large-scale but random distribution of the available treatments.

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