Sexual Networks and Sexually Transmitted Infections: A Tale of Two Cities

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ABSTRACT Research on risk behaviors for sexually transmitted infections (STIs) has revealed that they seldom correspond with actual risk of infection. Core groups of people with high-risk behavior who form networks of people linked by sexual contact are essential for STI transmission, but have been overlooked in epidemiological studies. Social network analysis, a subdiscipline of sociology, provides both the methods and analytical techniques to describe and illustrate the effects of sexual networks on STI transmission. Sexual networks of people from Colorado Springs, Colorado, and from Winnipeg, Manitoba, Canada, infected with chlamydia during a 6-month period were compared. In Winnipeg, 442 networks were identified, comprising 571 cases and 663 contacts, ranging in size from 2 to 20 individuals; Colorado Springs data yielded 401 networks, comprising 468 cases and 700 contacts, ranging in size from 2 to 12 individuals. Taking differing partner notification methods and the slightly smaller population size in Colorado Springs into account, the networks from both places were similar in both size and structure. These smaller, sparsely linked networks, peripheral to the core, may form the mechanism by which chlamydia can remain endemic, in contrast with larger, more densely connected networks, closer to the core, which are associated with steep rises in incidence.

KEYWORDS Canada, Chlamydia, Colorado, Gonorrhea, Models/statistical, Review, Sexual partners, Sexually transmitted diseases/epidemiology, United States.

INTRODUCTION

Chlamydia trachomatis and *Neisseria gonorrhoeae* are bacterial sexually transmitted infections (STIs). Although understanding their infectious properties at the microscopic level has advanced rapidly with application of new molecular and biochemical techniques, our understanding of their transmission dynamics at the population level has proceeded more slowly.

Population-based studies of STIs have traditionally focused on individual risk behaviors such as number of sex partners and condom use.¹⁻⁸ However, STIs are not uniformly distributed in the population, demonstrated amply in geographic

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analyses of STI incidence, which have shown different incidence rates in different subpopulations, with the highest rates occurring in poor, inner-city, densely populated, contiguous census tracts.⁹⁻¹³ Therefore, cataloging risk behavior and demographic and socioeconomic characteristics has not provided adequate descriptions of STI risk.^{11,14-16} A more convincing explanation has been the hypothesis developed mathematically by disease ecologists that a small proportion of the population (core groups) who have high rates of STI and partner changes contribute disproportionately to STI transmission. Brunham¹⁶ has argued that population density reflects the increased likelihood that core group members form sexual partnerships with each other, and that these intra and extragroup pathways potentiate STI persistence.

Social network analysis, a subdiscipline of sociology, provides suitable tools for analyzing the influence of connections between people on disease transmission.^{17,18} The objective of this study was to review social network concepts and insights relevant to STI (excluding human immunodeficiency virus [HIV]) research and control. By way of illustration, we also present some empiric data from two North American cities.

REVIEW OF SEXUAL NETWORKS AND SEXUALLY TRANSMITTED INFECTIONS

Concepts and Methods

A network consists of a set of individuals or groups (nodes) connected by links that represent relationships (e.g., kinship, friendship) or interactions (e.g., sexual, monetary exchanges).¹⁹ Both social and sexual relationships can be illustrated and analyzed simultaneously, thus augmenting the context of STI transmission and indicating possible sex partners respondents may omit. However, groups of people directly and indirectly linked through sexual partnerships (sexual networks) are more commonly the focus of STI prevention and transmission research. Links can be weighted to indicate, for example, frequency of sexual exposure, acquaintanceship duration, or casual, commercial, or long-term sexual relationships.

Because network members are not randomly selected, standard biostatistical methods that extrapolate from a random sample of people to make inferences about a population mean are inappropriate. Comparisons between networks themselves may be justified, although because of incomplete responses from informants, it may be difficult to exclude the possibility that links between them exist unknown to the researcher. Matrix algebra is used to analyze network data, and new techniques for network analysis are currently under development.^{17,20}

Network concepts have been key (albeit unintended) in STI control through partner notification (contact-tracing) activities. This is the process by which sex partners of people with a notifiable STI are identified, located, informed of exposure, and encouraged to present for testing and/or treatment. Should a first-generation sex partner of an index case test positive, the cycle of partner notification is repeated for a second generation of sex partners, and so on, until no positive cases are found. As this is a standard control strategy in many public health offices, they are potentially a rich data source for network analysis, particularly if the data are centralized and computerized. Such data have rarely been used in research due to lack of communication between program personnel and researchers and idiosyncrasies of data management, by which sex partner data may not be coded consistently, structured in a useful manner, or computerized.

“Chain method” sampling can also be used to generate networks. A set of

participants who meet the researchers' criteria are enrolled and asked to name and/or recruit their friends or associates for participation in the study. A variant of this, known as *snowball sampling*, continues with all friends of newly enrolled participants in turn being asked to nominate and recruit their friends, and so on. Other chain methods include the selection of only some or one of the nominees by the participants or researchers, either randomly or according to other criteria.²¹ An intervention in a syphilis outbreak among a network of sex workers, pimps, drug pushers, clients of sex workers, and boyfriends in Vancouver, Canada,²² made use of an analogous sampling technique. A single dose of antibiotic was given to exposed clients, who were then offered similar doses to treat their sex partners or associates, thus using clients' "nominations" to access unidentified partners at risk of spreading the disease.

Ethnographic information is a useful addition to nominated data; it has been used in STI research to provide essential social context for network formation (such as drugs exchanged for sex or street gang interactions) and to develop a sense of network representativeness.^{17,23} It may also indicate which people would be valuable informants.²⁴ An important component of this methodology is the large proportion of time spent by staff with informants in communities affected by STIs,²⁵ fostering trust among possible informants and observing social interactions.

Methods for accurate network sampling are being evaluated. For example, Ghani et al.²⁶ created a known, simulated population containing networks. They then sampled the population using three methods: (1) self-reported data by respondents (ego) on numbers of sex partners and proxy estimates from ego for each of ego's sex partners, (2) snowball sampling, and (3) contact tracing. The last two methods produced more accurate estimates of network size than did the first, and more complete contact-tracing data produced accurate descriptions of network size and composition. Their results emphasize the need to improve the quality of contact tracing data.²⁷

Molecular Biology

Advances in molecular biology have provided an opportunity to validate the construction of networks from sexual partner data because biological specimens from network members can be typed. The assumption underlying these techniques is that the discovery of a different type within a network of people indicates introduction from outside the network. Typing methods for gonorrhea include auxotyping/serotyping, *opa* typing, and pulsed field gel electrophoresis (PFGE) of chromosomal DNA.²⁸⁻³¹ The discriminatory power of phenotyping may be insufficient to distinguish members of sexual networks, as the majority of gonococcal isolates belong to only three or four classes;²⁹ however, pulsed field gel electrophoresis may confirm network configuration. Two of us (A. J. and J. W.) are in the process of genotyping *Chlamydia trachomatis* from members of sexual networks. Preliminary data indicate that sexual networks constructed from partner notification data are concordant with the individual chlamydia genotypes.

Spatial Relationships

Potterat et al.³² initially recognized the importance of social context in STI transmission dynamics by grouping sexually connected people in "lots" (i.e., networks). A key feature of these networks was the members' habitual meeting places in 6 of the 93 drinking establishments in their community. This emphasizes the importance of

“place” in network formation and in targeting scarce resources for STI prevention.

On a larger geographic scale, sexual networks have also been constructed for the province of Manitoba, Canada.³³ Analysis of the 23 largest STI networks revealed that the majority spanned different communities, including some that were hundreds of miles apart. Analysis of networks within the capital (Winnipeg) revealed that, within the largest sexual network of 82 people, a single bridge relationship facilitated the flow of STI infections from the central urban core into a subnetwork in the peripheral areas of the city and back again. This last observation demonstrates the capability of network analysis to identify subtle geographical aspects of transmission dynamics.

Temporal Aspects

Measuring temporal variables enhances the precision of describing transmission events; defining disease causation³⁴; and, in partner notification, in delineating source cases.³⁵ Time was an important consideration in an early social network analysis of the first 40 cases of AIDS that added substantially to the proof of a common infectious agent.³⁶ Overlapping exposures and multiple links between network members make it difficult to distinguish which individual transmitted the organism to whom. This situation occurred during investigations into an outbreak of syphilis in Georgia.²⁴ In this outbreak, a stable group of teenaged girls participated in communal sex parties with a group of white, older, affluent boys, alternating with a group of less-affluent, older black boys. The girls had sex with many male partners on each occasion, often simultaneously, as well as with each other. The use of network methods provided insights into the social and sexual conditions necessary to sustain syphilis transmission.

Ethnicity

In the US, African Americans experience higher rates of STI. In Canada and Britain, analogous situations occur within the aboriginal and black populations, respectively, despite controlling for sexual behavior and socioeconomic status and the absence of any known biological reasons.^{37–40} Recently, Laumann and Youm⁴¹ provided a network explanation for this phenomenon.⁴¹ African Americans with low numbers of sex partners were five times more likely to choose African American partners who had high numbers of partners. This factor, known as disassortative mixing, elevates the overall incidence rate in this population in comparison to whites, who exhibit more assortative sexual mixing, choosing partners who, like themselves, also have low numbers of partners. The limited sexual mixing between African Americans and other ethnic groups tended to confine STI within their networks. This depth of interpretation can be explored using social network concepts only.

Mathematical Models and Social Network Data

Social network analysis has also been used as a secondary source in improving mathematical models. Models are commonly used in forecasting the course of epidemics, but can also be used to explore possible outcomes of different interventions. These models stem from the study of disease ecology and summarize STI viability in the differential equation:

$$R_0 = \beta c x D$$

where R_0 (reproductive number) reflects the average number of secondary cases produced by an initial case (if greater than or equal to 1, the organism will continue to circulate; if less than 1, the organism will die out)⁴²; β is the probability of transmission from one infected individual to another; c denotes the mean number of sex partner changes, weighted by the population variance; x represents the proportion of those susceptible in the population; and D is the mean duration of infectiousness.

A major contribution made by network analysis has been the refinement of the parameter c . Potterat et al.⁴³ used network data to define transmitters who were documented to have spread the infection to two or more partners and calculated R_0 for STI index cases. The reproductive number was highest for men and women with concurrent sex partners, women with dual gonococcal and chlamydial infections, and men with no identifiable source of infection. Concurrency, a situation by which an individual has sex with two other people during the same period, compared with serial monogamy (one partner during a specified period) was one of the most important predictors of a high R_0 value. These results demonstrated the necessity of adding a qualitative component to c in the standard infectious disease formula described above.⁴⁴

Ghani et al.⁴⁵ incorporated network concepts into progressively more complex models to predict the viability of gonorrhea in a simulated population. The first model included the size of the population; the second, the mean number of partners weighted by the variance; the third, the sexual mixing patterns; and the last, the number of networks and network size. The last model, which incorporated network structure, was significantly better than the first three at predicting the successful establishment of the infection, factors affecting prevalence, and individual risk. In the future, inclusion of complex network measures within models has the potential to provide more accurate estimates of the effects of vaccines, enhance contact tracing, and enrich explanations of persistence of bacterial STI at very low prevalences.^{46–48}

A TALE OF TWO CITIES

To make the fullest use of the scarce network data available, sharing data and involving people from several disciplines in their analysis is crucial to the development of both social network analysis and STI prevention and control. Therefore, the remainder of this article focuses on a comparison of sexual networks from Colorado Springs, Colorado, and Winnipeg, Manitoba, Canada, in an attempt to assess the generalizability of network data. Our hypothesis that networks of people infected with *C. trachomatis* would be of similar sizes and structures in the two cities was based on the following: Incidence rates in 1996 were comparable for both Winnipeg⁴⁹ (199.6/100,000) and El Paso County (260/100,000) (H. Rogers, oral communication, April 2001); both areas had implemented chlamydia screening programs that targeted women under age 25 with multiple sex partners; both had public health staff actively involved in partner notification for chlamydia (a rare occurrence),⁵⁰ and both are midwestern North American cities of similar size, with people employed largely in farming, manufacturing, and service industries.

City Demographics

In 1995, Colorado Springs, 65 miles south of Denver, had a population of 465,000. Of the population, 82% was white, 8% Hispanic, 7% African American, and 3%

other.⁴³ Several large military installations host approximately 30,000 in the service. Winnipeg, Manitoba, located 850 miles northeast of Colorado Springs on the Canadian prairies in the geographic center of North America, had a population of 611,630 in 1996, comprised of 88.1% whites, 0.06% Hispanic, 1.6% black, 8.9% Asian, and 7.1% aboriginal, of whom 3.2% were North American Indians.

Data Sources and Analysis

Data gathered through partner notification activities in the two jurisdictions as part of their respective STI control programs were used as previously described.^{33,43,51} For our current purpose, we used data from both jurisdictions on all reported chlamydia cases during a 6-month period. Data from November 1997 to May 1998 were available from Manitoba databases, whereas in Colorado Springs, data were collected from January to June 1996 as this was the last 6-month period during which Chlamydiazyme (Abbott Laboratories) was still in use. In Winnipeg, partner notification of sex partners potentially exposed by the index case within the last 90 days was accomplished in one of three ways: (1) self-referral, by which the client notified his or her own partners; (2) contracting, by which the client gave the partners' locating information to a public health nurse, but agreed to refer his or her partners within a specified period of time, after which the nurse would intervene; and (3) traditional contact tracing, by which the nurse would complete all aspects of partner notification. Practices differed slightly in Colorado Springs, with the last two options being routinely used by disease intervention specialists; partners were elicited for the past 180 days instead of 90; and, if only one partner was reported, disease intervention specialists inquired about the penultimate sex partner. All of these practices would have increased the number of partners identified, although not necessarily located.

The freeware program Pajek was used to plot the links between cases and contacts for delineation of sexual networks.⁵² All individuals from Winnipeg and Colorado Springs with laboratory-confirmed cases of chlamydia and their named contacts, with or without laboratory-confirmed infection, were selected. Contacts or cases who may have resided in areas outside the two cities, but were directly linked to Winnipeg or Colorado Springs cases were extracted from the larger databases. This strategy resulted in networks containing individuals from other areas as second-generation contacts, at which point the network would be truncated unless the exogenous case or contact was linked to yet another individual located in the two cities.

Results

In Winnipeg, 442 networks were identified, comprising 571 cases and 663 contacts. Data were not available for 51 individuals with cases diagnosed previous to the study period who named contacts within the study period, for a total of 1,278 individuals (Table 1). Colorado Springs data yielded 401 networks, comprised of 468 cases and 700 contacts. Male cases and contacts were older than their female counterparts in both cities. In Colorado Springs, 34% of cases and 35% of contacts were African Americans, despite the fact that they constitute only 7% of the population. Ethnic origin was not routinely gathered in Winnipeg, but 18.5% of chlamydia cases occurred in registered North American Indians, although they comprise only 3.2% of the population.

Of chlamydia cases within the Winnipeg networks, 95% resided within the city, compared with 98% in Colorado Springs. The remaining exogenous cases are

TABLE 1. Interviewed persons with chlamydia from Winnipeg, Manitoba, Canada, November 1997 through April 1998 and Colorado Springs, Colorado, from January 1996 through June 1996 and their sexual contacts

	Winnipeg, % (SD)				Colorado Springs, % (SD)			
	Cases (N = 571)		Contacts (N = 663)		Cases (N = 468)		Contacts (N = 700)	
	Male (N = 128)	Female (N = 443)	Male (N = 542)	Female (N = 121)	Male (N = 138)	Female (N = 330)	Male (N = 494)	Female (N = 206)
Age, years	25.5 (8.1)	23.3 (6.6)	23.5 (7.4)	20.7 (5.1)	23.9 (5.2)	21.1 (4.7)	23.7 (6.2)	22.2 (5.1)
Ethnicity								
White					54 (39)	161 (49)	167 (40)	85 (47)
Black					60 (44)	77 (24)	170 (41)	52 (29)
Hispanic					18 (13)	65 (20)	68 (16)	32 (18)
Indian	24 (19)	81 (18)	21 (4)	3 (2)	2 (1)	5 (2)	6 (1)	2 (1)
Other					3 (2)	18 (6)	4 (1)	8 (4)
Unknown					1 (1)	4 (1)	79 (16)	27 (13)
Residence in city	118 (92)	430 (97)	417 (84)	101 (94)	137 (99)	321 (97)	352 (79)	155 (78)
Residence outside city	10 (8)	13 (3)	80 (16)	6 (6)	1 (1)	9 (3)	92 (21)	44 (22)
Residence unknown	0 (0)	0 (0)	45 (8)	14 (12)	0 (0)	0 (0)	50 (10)	7 (3)
Repeaters	10 (8)	35 (8)	N/A	N/A	0 (0)	5 (2)	N/A	N/A
Coinfected	9 (7)	28 (6)	N/A	N/A	17 (12)	16 (5)	N/A	N/A

the sex partners named by cases in the two cities who subsequently became laboratory-confirmed cases. In Winnipeg, 16% of male contacts and 6% of female contacts were from outside the city, whereas in Colorado Springs, exogenous contacts were more evenly distributed between the genders, 21% and 22%, respectively. A higher proportion (8%) of people testing positive more than once in the 6-month study period was observed in both genders in Winnipeg and less frequently in Colorado Springs (1%). Last, about 7% of men and women with chlamydia in Winnipeg had gonorrhea as well, as did 8.5% in Colorado Springs, with males having a higher rate of coinfection (12%) than females (5%).

Both cities yielded comparable variation in network sizes. In Colorado Springs and Winnipeg, respectively, 57% of 401 networks and 54% of 442 networks were dyads (two people linked by a sexual partnership), and 30% and 29%, respectively, were triads (three people linked by sexual partnerships). However, there were 4 networks in Colorado Springs containing 7 or more members (Table 2; Fig. 1), and in Winnipeg, there were 8 networks of 7 or more people, the largest of which contained 20 people (Table 2; Fig. 2). In both cities, there were several people who named no partners or were not interviewed to elicit such information and were not included as network members (data not shown). In the Colorado Springs cases, there were 71 females and 30 males who were more likely to have presented at private medical clinics for care than were individuals who named sex partners. In Winnipeg, 52 women and 13 men named no partners.

TABLE 2. Frequency distribution of network components, Winnipeg, Manitoba, and Colorado Springs, Colorado

Size of component	Winnipeg		Colorado Springs	
	No. of components	Cumulative persons (%)	No. of components	Cumulative persons (%)
20	1	20 (2)	0	0 (0)
19	0	20 (2)	0	0 (0)
18	0	20 (2)	0	0 (0)
17	1	37 (3)	0	0 (0)
16	0	37 (3)	0	0 (0)
15	0	37 (3)	0	0 (0)
14	0	37 (3)	0	0 (0)
13	1	50 (4)	0	0 (0)
12	0	50 (4)	1	12 (1)
11	1	61 (5)	0	12 (1)
10	3	91 (7)	0	12 (1)
9	0	91 (7)	0	12 (1)
8	1	99 (8)	1	20 (2)
7	7	148 (12)	2	34 (3)
6	6	184 (14)	9	88 (8)
5	16	264 (21)	8	128 (12)
4	38	416 (33)	28	240 (23)
3	128	800 (63)	122	606 (57)
2	239	1,278 (100)	230	1,066 (100)
Total	442	1,278 (100)	401	1,066 (100)

Discussion

In this preliminary comparison of networks from two areas, to maximize comparability, all reported chlamydia cases were selected from both areas with similar control programs, for identical periods of time, and diagnosed by the same method.

Network members from the two cities are remarkably similar. African Americans bear a disproportionate burden of STIs in Colorado Springs, as do North American Indians in Winnipeg. In neither city is this phenomenon likely to be artifactual. In both places, women comprised the majority of cases, and men were the contacts due to ascertainment bias generated by selective screening of women under age 25 and those with multiple sex partners; presumptive or syndromic treatment of men; and underdiagnosis in men. The gender differences partly explain differences in age as males tend to select female partners younger than themselves.¹⁵ A higher proportion of contacts named by people in Colorado Springs were from outside the area, probably due to travel associated with the large military bases. In comparison, sex partnerships outside the city of Winnipeg may be restricted by the long distances to any other major center. Winnipeg appears to have a higher number of people who tested positive more than once in the 6-month period. This is probably the result of complete electronic reporting from one public health laboratory and a centralized notifiable disease database, in which Winnipeg cases may have been recorded despite presenting at locations around the province. The ratio of contacts named for each case was higher in Colorado Springs (1.5) than in Winnipeg (1.2), largely due to differences in contact-tracing methods, above.

FIGURE 1. The four largest components from Colorado Springs, from upper left clockwise, of 12, 8, 7, and 7 members. Each symbol represents an individual (node or actor in network terminology) and solid lines represent sexual contact (edges, links, or ties in network terminology). The symbol and code for an individual indicates positive results for chlamydia (CT), gonorrhea (GC), or both (CT/GC); negative test result (NEG); or unknown test result (UNK). Gender of the individuals is also indicated. Asterisks indicate people with more than one infection in the 6-month study period (repeaters).

Larger networks were identified in Winnipeg than in Colorado Springs, despite the higher numbers of contacts elicited in the latter city. This is due to two factors, neither of which can be ascribed to inherent differences in network members, network size, or network structure. First, a higher proportion of contacts named by Winnipeg case individuals were located within the city (allowing for more complete testing and treatment), whereas those from Colorado Springs were more likely to be outside the city. Second, locating information in the database of patients eligible for publicly funded health care in Manitoba is updated continuously when a patient presents anywhere for hospital or medical services, thus facilitating partner follow-up. The distributions of network size and the structures of networks from the two places look remarkably similar. None contain dense loops of four or more people for which sexual links form an enclosed circle (n clique) and all feature linear links or contain at least one person with a large radial network. These networks may form the routes through which chlamydia is spread at a level adequate to maintain endemicity, but not allow for any increase in disease. Networks associated with increase in disease incidence tend to be connected more densely, showing more links between members.^{23,24} Having said this, it is important to recognize that network data are partial and likely to underestimate the number of members. It is

FIGURE 2. The four largest components from Winnipeg, from upper left clockwise, of 17, 13, 11, and 20 members. Symbols and codes are as in Fig. 1.

therefore also likely—and core group theorists would argue essential—that the smaller networks shown here are connected to a core center of transmission, which facilitates a constant flow of chlamydia infection into peripheral areas of the larger network and occasionally back again, thus maintaining endemicity.

Two major questions (among others) that affect generalizability would bear further investigation. The first is whether the networks containing African Americans resemble those in Winnipeg that contain North American Indians. This elucidation would accomplish two objectives: (1) It would illustrate the network structures by which chlamydia is maintained at a higher level in these groups than in the remainder of the population⁴¹ and (2) if in fact those structures are similar, a more general hypothesis concerning networks of disadvantaged subpopulations bearing a disproportionate burden of STI in other areas may be possible. Second, future work is essential to establish whether these splintered networks are connected to a densely connected core group at some point, or whether these kinds of analyses will always produce seemingly disconnected splinter networks due to incomplete reporting of partners, partners who are not tested, significant numbers of males who spontaneously cure, and possible long-term, latent infections.

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