Social network dynamics and HIV transmission

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Objective: To prospectively study changes in the social networks of persons at presumably high risk for HIV in a community with low prevalence and little endogenous transmission.

Methods: From a cohort of 595 persons at high risk (prostitutes, injecting drug users, and sexual partners of these persons) and nearly 6000 identified contacts, we examined the social networks of a subset of 96 persons who were interviewed once per year for 3 years. We assessed their network configuration, network stability, and changes in risk configuration and risk behavior using epidemiologic and social network analysis, and visualization techniques.

Results: Some significant decrease in personal risk-taking was documented during the course of the study, particularly with regard to needle-sharing. The size and number of connected components (groups that are completely connected) declined. Microstructures (small subgroups of persons that interact intensely) were either not present, or declined appreciably during the period of observation.

Conclusions: In this area of low prevalence, the lack of endogenous transmission of HIV may be related in part to the lack of a network structure that fosters active propagation, despite the continued presence of risky behaviors. Although the relative contribution of network structure and personal behavior cannot be ascertained from these data, the study suggests an important role for network configuration in the transmission dynamics of HIV.

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Introduction

In studying HIV transmission dynamics, substantial attention has been devoted to observations about personal behavior [1–3]. Understanding of HIV transmission has been considerably advanced, however, by a series of modeling studies [4–7] that use a 'compartment' approach to consider the interactions of groups with varying characteristics and behaviors. More recently, mathematical modeling efforts have incorporated network structure into the evaluation of transmission dynamics. Watts and May [8] first proposed a model that took concurrent partnerships into account. Morris and Kretzschmar [9] also demonstrated the importance of concurrent, as opposed to sequential, sexual partnerships, in epidemic propagation. Kretzschmar and colleagues [10] used several aspects of network structure to evaluate gonorrhea control efforts. Ghani *et al.* [11] have examined the effect of sampling biases and missing data in network information.

Theoretical considerations of network structure have been paralleled by studies of actual networks of persons who, because of their sexual activity or drug use, are at risk for HIV/AIDS and other infectious conditions

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[12–15]. Little has been presented to date, however, on the changing character of such networks, a critical issue for understanding the transmission dynamics of HIV. In this report, we follow up earlier work on a cohort of 595 persons at risk for HIV transmission in Colorado Springs (Colorado, USA) [12,13,16–18]. We used the simple empirical approach reported by Morgan *et al.* [19], which we call the stability index, for determining the amount of change that respondents experience in their networks over a 3-year period and examined that change for the entire range of relationships as well as for uniplex connections (sexual, drug-using, and needle-sharing). We then assessed the changing size and shape of networks over the interval of observation, as well as changes in the risk-taking reported by respondents and in the risk configuration that they face, and considered how such changes may be used to evaluate the potential for disease transmission and, by extension, the potential for evaluation of intervention programs.

Methods

Study characteristics

The detailed methods used in this study have been described previously [12,13]. Between 1988 and 1992 in Colorado Springs (1990 population, 397 000), we recruited 595 persons at risk for HIV into a prospective study of social networks and disease transmission. Each respondent underwent an extensive interview that included demographic and medical history, drug use and sexual activity, knowledge about HIV, and the open-ended elicitation of social, sexual, drug-using (drugs, but not needles, used together), and needle-sharing contacts. Respondents were asked to provide specific information about their relationships with contacts (e.g., use of condoms, type of sexual contact, frequency of contact), and about the contacts' relationships with each other for the first 16 contacts named. The study design called for these interviews to be repeated at yearly intervals. In this highly mobile population, 178 persons were interviewed twice and 96 were interviewed three times. The general demographic characteristics of those interviewed one, two, or three times were not substantially different. Network data for those interviewed twice were not presented, since their dynamic change was similar to that observed for those interviewed three times.

Network configuration

For 96 persons who were interviewed three times approximately 1 year apart, we identified two cohorts: those interviewed first in year 1 of the study (cohort 1; 44 subjects), and those interviewed first in year 2 of the study (cohort 2; 52 subjects). For each cohort, we examined five sets of network connections (seeking contacts from the previous 6 months): sexual, social, drug-using, needle-sharing, and 'any' (implying that any of the four connections were present). These 30 groups of respondents (two cohorts × five connections × three interviews) together with the contacts they named were of varying size and were used to assess changes in network properties over time. For an additional 278 persons in the original cohort, we obtained two interviews and the remainder were interviewed once. Those with two interviews demonstrated change that was similar to the change observed for those interviewed three times.

Assessing network stability

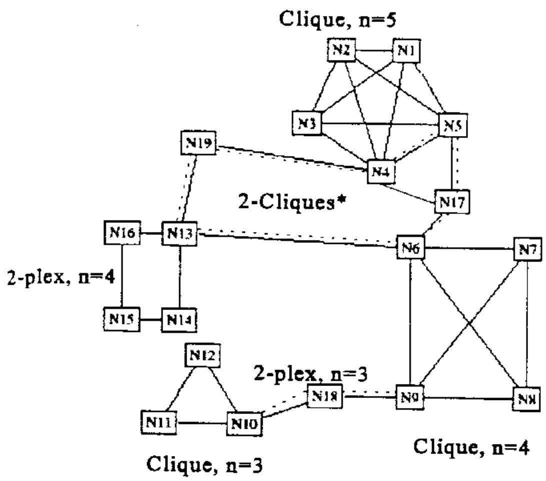
We used a measure of network stability described by Morgan *et al.* [19]: the proportion of all the named contacts who appear in a network at two timepoints, B/(A + C − B), where A represents the persons at time 1, C represents the persons at time 2, and B is the intersection of A and C . We chose this measure (referred to here as the stability index) in preference to others that use more complicated transformations [20,21] because it contains information on the proportion of contacts who were members of a person's network at both timepoints, and on the relative size of the networks named at the two timepoints.

Assessing behavioral change

In keeping with hypotheses about the influence of network structure on transmission [14,22,23], we distinguished between risk behavior (what a person does) and risk configuration (the context in which such behavior occurs). Since we had information on multiplex relationships, we assigned each person a risk configuration based on the sum of sexual partners plus needle-sharing partners divided by the total number of possible relationships (i.e., four times the number of contacts named, since a respondent could name up to four types of relationships with a contact). We estimated risk behavior as the sum of needle-sharing partners plus sexual partners (adjusted for condom use) plus drug-using partners (multiplied by 0.5 to adjust for unreported risk) plus social partners (multiplied by 0.1 to adjust for unreported risk) divided by the number of actual connections. These adjustment factors were based on an arbitrary impression of the extent to which risky behavior may not have been reported. Thus, risk configuration provided an estimate of risky structure within a personal network, and risk behavior provided an estimate of the proportion of available risk in which the respondent might partake.

Assessing structural change

For each of the 30 subgroups we used UCINET IV [24] and KRACKPLOT [25] to assess the number and size of connected components (a subgroup of the network within which there is a path of some length from each person to every other person), degree centrality (the number of persons or contacts to which an individual is directly connected), information centrality (an



***There are two 2-Cliques in this group of six: N5-N4-N17-N19-N6 and N13-N19-N6-N4-N17.**

Fig. Definitions for structural measures showing an example of a network for these analyses. A 'clique' is a group of at least size *n* within which each person is connected to every other person in the group (in this analysis we use *n* = 3). An '*N*-clique' is a group of at least size *n* within which each person is *N* or fewer steps from every other person; connections outside the *N*-cliques are used to count steps (in this analysis we use *n* = 3 and *N* = 2). A '*k*-plex' is a group of size *n* within which each person is directly connected to at least *n* − *k* members of the group (in this analysis we use *n* = 3 or *n* = 4 and *k* = 2).

estimate of the mean distance of a person from every other person in the network), the number of cliques of size 3 (where a clique is a group of size *n* within which each person is connected to every other person in the group), the number of 2-cliques of minimum size 3 (where an *N*-clique is a group of at least size *n* within which each person is *N* or fewer steps from every other person; connections outside the *N*-cliques are used to count steps), and the number of *k*-plexes of sizes 3 and 4, with *k* = 2 (where a *k*-plex is a group of size *n* within which each person is directly connected to at least *n* − *k* members of the group). All these measures are standard tools of network analysis [24,26], which, despite complicated definitions, are straightforward measurements of network structure (Fig. 1). Most of the lower order structures on which we focus have simple visual analogs. A clique of size 3 is a triangle, and a clique of size 4 is a square with the diagonals present. A 2-plex (*n* = 3) is simply a line passing through three people. A 2-plex (*n* = 4) is a square without the diagonals. Only the 2-clique is more complex, since it involves contacts outside the small group itself. These measures of connectivity, whose higher order manifestations require this formal notation, are frequently used by researchers to examine the microstructure of networks. In our analysis, we use them as summary measures of the extent to which a particular network is interconnected, and the way in which such connectivity changes over time.

Statistical methods

Although a considerable statistical literature relates network analysis to graph theory [26] and provides tools for inference and hypothesis testing, many of these methods are not applicable to targeted samples [27,28]. In the latter case, the use of standard statistical methods is impeded by potential violation of assumptions about random samples drawn from normally distributed populations. Nonetheless, in the data presented here, a network assessment involving a substantial number of subnetworks that have been similarly constructed, statistical testing may be useful as a mechanism for comparison. We used a critical ratio for the difference of proportions to compare changes in risk configuration and risk behavior, a χ^2 for goodness of fit to assess changes over time, and the Pearson's rank correlation to compare the stability index with network size.

Results

The subgroups within this large network of persons at risk for HIV (cohort 1, begun in the first year of the study, and cohort 2, begun in the second year) both changed with regard to participants, behavioral configuration, and network structure. Although not designed as an intervention project, this study was able to use these techniques to record dynamic differences over a 3-year period that suggest diminution in risk on the part of respondents who remained with the project for the entire interval.

Network stability

At 1-year intervals, the stability of networks varied with the type of relationship. For example, the stability index was 6.3% for drug-using partners in cohort 2 and 39.5% for sexual partners in cohort 1 (Table 1). In general, for both cohorts, sexual and social networks became more stable in the second interval comparison (time 2 − time 3 versus time 1 − time 2), drug-using partnerships did not change in their low stability, and needle-sharing partnerships remained unstable in cohort 1 but became somewhat more stable in cohort 2. As expected, there was a negative correlation between the total network size and the stability index. This correlation was small and non-significant for drug-using (r = −0.13, $P > 0.10$) and needle-sharing (r = −0.16, $P > 0.10$) networks, but was larger and significant for sexual (r = −0.28, $P < 0.01$) and social (r = −0.26, $P < 0.01$) networks (data from both cohorts combined).

Table 1. Change in stability index from time 1 to time 2 (T1 – T2) and time 2 to time 3 (T2 – T3) for sexual, needle-sharing, drug-using, social, and all contacts.

	Change in stability index (%)	
	T1 – T2	T2 – T3
Cohort 1		
All	12.7	22.6
Sexual	13.6	39.5
Needle-sharing	9.5	9.2
Drug-using	8.6	7.9
Social	17.3	26.3
Cohort 2		
All	14.1	20.6
Sexual	22.2	36.9
Needle-sharing	15.3	24.5
Drug-using	6.3	8.9
Social	17.2	26.8

Risk behavior and risk configuration

Both behavior and configuration changed in the direction of decreasing risk from the first to the third time interval (Table 2). The two cohorts differed with respect to the amount and statistical significance of change. The smaller cohort (cohort 1) changed little in its overall configuration throughout the period of observation. Although there was a 6% decline in risk behavior, the decline was not significant. Cohort 2, on the other hand, demonstrated a significant decline in both configuration (4%) and behavior (9%). This overall measure of network change was probably the result of a substantial change in the extent to which needle-sharing occurred. Those who remained in the study and who continued to share needles reported fewer sharing partners, and many reported that they no longer shared needles. The diminution in needle-sharing was accompanied by significant network structural changes (Fig. 2), such as an increase in the number and decrease in the size of connected components (see below). The change in needle-sharing accounted for 22% of the risk behavior reduction observed for cohort 2 between time 1 and time 3.

Structural change

Connected components (networks of persons in which there is a path of some length between all members) reflect the degree of interconnectedness, and hence of potential transmission, in a group. Over the 3 years of observation, the number of components increased for multiplex relationships, suggesting increasing segmentation (diminished intergroup contact) of the overall group (Table 3). However, such segmentation was not demonstrable for any of the specific uniplex relationships (sexual, drug-using, needle-sharing, social) in

Table 2. Change in risk configuration and risk behavior over the 3-year interval (T1 to T3) of observation.

	Configuration change			Risk change		
	T1 – T2	T2 – T3	T1 – T3	T1 – T2	T2 – T3	T1 – T3
Cohort 1						
Difference*	0.01	–0.02	–0.01	–0.02	–0.04	–0.06
P value	NS	NS	NS	NS	NS	NS
Cohort 2						
Difference*	–0.03	–0.01	–0.04	–0.07	–0.02	–0.09
P value	NS	NS	< 0.01	< 0.05	NS	< 0.01

Difference in the proportion between the two time periods is indicated. A critical ratio (z-value) was used to test for significance.

Table 3. Changes in connected components and measures of centrality in the subgroups at three time periods (T1, T2, T3) spaced 1 year apart.

	Any contact			Sex			Needle			Drug			Social		
	T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3
Cohort 1															
Connected components															
Number	17	27	28	34	39	36	9	9	10	16	20	14	34	35	39
Largest	328	199	219	71	35	88	22	24	30	107	39	62	20	20	30
Degree															
Mean	13	10	12	6	5	5	5	5	4	2	2	2	2	2	2
Largest	55	33	50	54	33	48	15	13	14	20	24	17	19	15	20
Information centrality															
Mean	0.50	0.41	0.50	0.81	1.02	0.71	0.69	0.86	0.79	0.49	0.63	0.44	0.55	0.63	0.61
Largest	0.65	0.53	0.62	0.98	1.28	0.88	0.86	1.01	0.92	0.86	1.12	0.78	0.99	1.11	1.11
Cohort 2															
Connected components															
Number	35	47	46	42	47	48	12	9	7	28	27	26	44	50	50
Largest	174	68	74	34	12	14	16	8	5	32	24	54	37	15	22
Degree															
Mean	10	8	8	5	3	3	4	3	2	2	2	2	2	2	2
Largest	36	25	24	14	11	13	15	7	4	31	13	18	36	14	21
Information centrality															
Mean	0.56	0.86	0.86	0.85	1.25	1.31	1.16	1.27	1.51	0.60	0.70	0.54	0.62	0.73	0.73
Largest	0.70	0.96	0.99	1.03	1.49	1.61	1.35	1.46	1.67	1.09	1.19	0.95	1.14	1.28	1.29

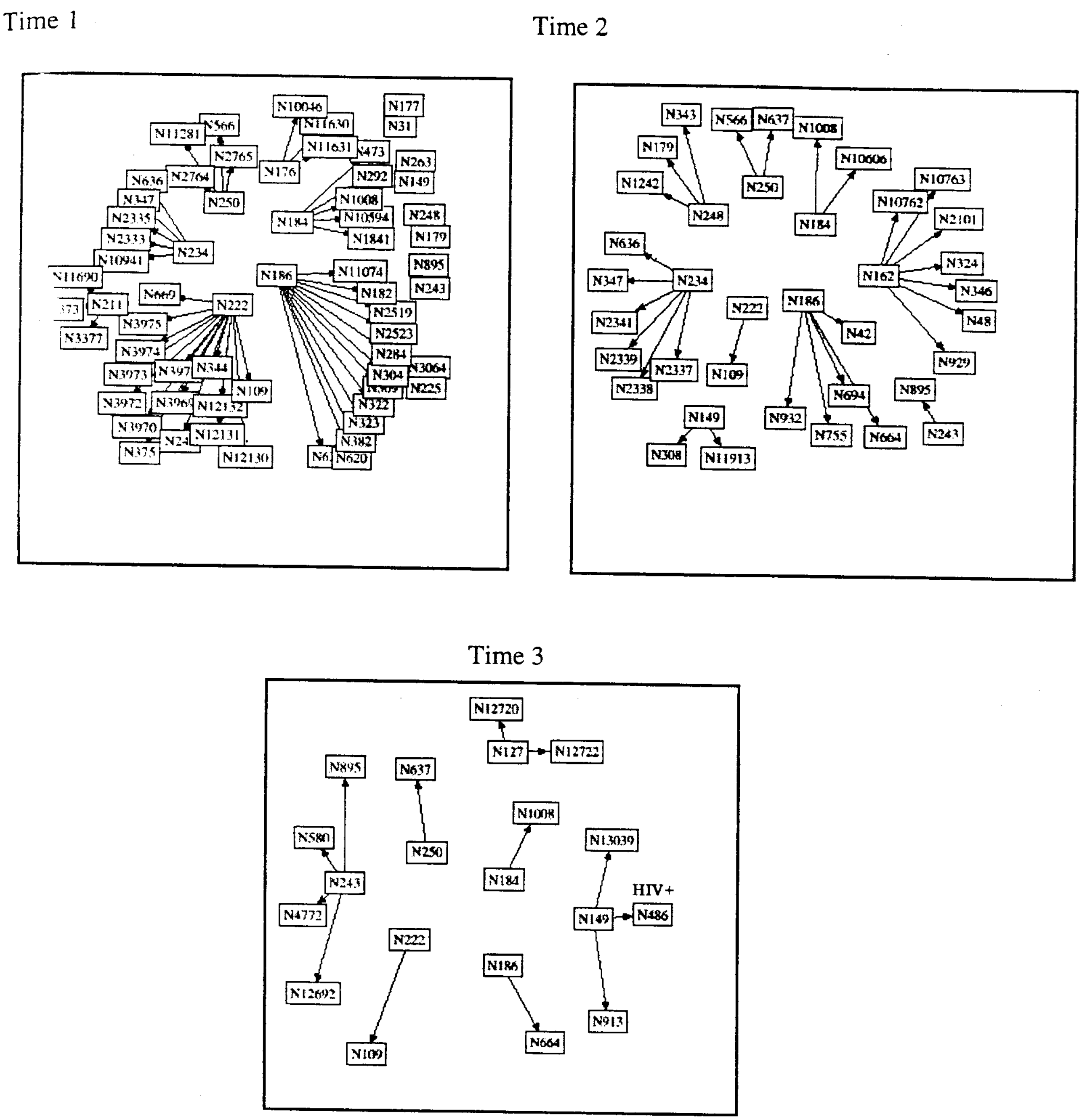


Fig. 2. Change in needle-sharing network of the 52 persons in cohort 2, each interviewed three times at 1-year intervals, demonstrating marked diminution in needle-sharing activity. At each interaction, the same 52 people were interviewed, and these diagrams depict those who said they shared needles and the contacts with whom they shared them.

either cohort. In addition, the size of the largest connected components diminished appreciably for all relationships in both cohorts, and for sex and needle-sharing relationships in cohort 2. In general, mean degree (the number of contacts per respondent, a straightforward measure of centrality) remained constant or diminished in both cohorts for all relationships and for each of the four types of contact individually. The largest degree observed was unchanged in cohort 1, but diminished appreciably for all relationships, and for each relationship individually, in cohort 2. The pattern for information centrality (a measure of the mean distance of a participant from any other participant) was inconstant. Statistical tools for testing the patterns and the differences are not available [26], but taken together, these changes suggest a diminution in group interaction (smaller and fewer components) and a decrease in intragroup interaction (lowered centrality).

Table 4. Changes in measures of connectivity in the subgroups at three time periods (T1, T2, T3) spaced 1 year apart.

	No. groups														
	Any contact			Sex			Needle			Drug			Social		
	T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3
Cohort 1															
Cliques (size 3)	15	9	1	1	0	0	0	2	0	13	5	1	6	2	0
2-Cliques	77	51	56	37	30	30	13	10	10	32	22	23	45	43	44
2-Plex (n = 3)	5142	3267	4400	2161	1127	1847	221	208	203	1231	958	582	1200	795	1221
2-Plex (n = 4)	26	8	4	0	0	1	0	1	0	19	5	4	1	0	0
Cohort 2															
Cliques (size 3)	2	0	2	0	0	0	0	0	0	1	0	0	2	0	0
2-Cliques	64	53	55	42	24	20	7	7	3	36	25	29	47	44	44
2-Plex (n = 3)	3884	1873	2544	757	311	289	203	52	10	1170	390	978	1667	852	1138
2-Plex (n = 4)	2	3	2	0	0	0	0	0	0	0	0	2	1	0	0

Cliques are groups within which all three persons are connected to each other. 2-Cliques are groups of size 3 within which all persons are two steps or fewer from each other. 2-plexes of size 3 are groups within which all persons are connected to at least one other person in the group. 2-plexes of size 4 are groups within which all persons are connected to at least two other members of the group (see text for full definitions).

Direct measures of connectivity, so-called 'microstructures' or 'cycles', provide a more consistent view of structural events (Table 4). With only a few exceptions, all measures of small subgroup formation or of the density of activity within such small subgroups demonstrate a diminution in cohesion over the years. Such diminution is exemplified by the pattern of 2-cliques (groups of three people who are connected to each other by two or fewer steps). In every instance, for both cohorts and for all relationships together and each separately, the number of 2-cliques diminishes. Of particular note is that for most uniplex relationships in both cohorts there were virtually no k-plexes of size $n = 4$, $k = 2$, meaning that there were no groups of four people within which each person was related by needle-sharing or sexual activity to two of the others. The sole exception was within the drug-sharing network of cohort 1, but these k-plexes fell in number from 19 to four over the 3 years of observation. The decline or absence of these microstructures for sexual or needle-sharing relationships has direct relevance to the likelihood of disease transmission.

HIV-positive persons

In the larger study of 595 respondents, we identified only 17 who were HIV-positive. Seven out of 17 HIV-positive respondents appeared in the subgroups discussed here. The remaining 10 were either interviewed fewer than three times or were not named as contacts within these groups. Of these seven, only two appeared (one time each) in sex or needle-sharing networks. None of the HIV-positive persons occupied a position of centrality either in the subgroup as a whole, or within a specified clique or microstructure. During the entire period of the study, we identified only one episode that suggested actual transmission of HIV, despite the presence of well-documented risk-taking behaviors on the part of known positive persons and the continuing low-grade introduction of HIV into this community [17].

Discussion

A sizeable group at risk for HIV, documentation of behaviors that foster viral exchange [12], and the absence of significant endogenous propagation of the virus [17] provoke a re-examination of purely behavioral explanations for the HIV epidemic. Personal risk-taking plays an obvious role in viral acquisition, but disease spread, and in particular the explosive epidemic witnessed in some areas, may bear a less straightforward relationship to personal behavior. In cross-sectional analyses of this study population, we previously determined that HIV-positive persons occupied a peripheral location in the overall network, since more than half of them were not part of a large connected component of over 3600 people [13] and the remainder who were in this connected component were of low centrality [18]. Such a configuration stands in sharp contrast to the high centrality of HIV-positive persons who were part of a network of injecting drug users in the high prevalence area of Bushwick (Brooklyn, New York, USA) [14]. Such preliminary observations suggested that social network structure may facilitate or obstruct transmission within a population and that the dynamics of network change may be crucial for understanding the dynamics of transmission.

In the present analysis of network dynamics, membership varied substantially from year to year, a not unexpected finding in view of the activity and the nature of relationships within the group. In general, sexual connections appeared to be more durable than other types of relationships, and drug-using partners were the most changeable. Persons with large networks had greater changeover of partners than those with small networks. In our context, with an interval of a year between interviews, it is perhaps surprising that there was any stability at all, and that stability actually increased for a number of subgroups (particularly those recruited in the second year of the study). In the absence of shorter duration information, it is difficult to assess the role of such turnover *per se* in transmission, but the tendency toward increasing stability fits with *a priori* expectations in an environment of low transmission by providing fewer opportunities for contact.

In the cohort recruited during the first year of the study, risk configuration (the riskiness of the social context) and risk behavior (the risks people took) were stable over the period of observation. In the cohort recruited during the second year of the study, both these measures changed in the direction of diminished risk, with a particular diminution in needle-sharing (Fig. 2). For either cohort, the dynamics of risk are consonant with the lack of significant transmission.

Even more striking are the changes that took place in the simple microstructure of these groups (Table 4). Cliques of size 3 (a triangle) were uncommon in cohort 1 and virtually absent from cohort 2 (in fact, there were no such structures in the sex and needle-sharing networks of cohort 2). There were no cliques of size 4 (a square with diagonals) or cliques of greater size in any of the subgroups examined. Similarly, all subgroups in both cohorts exhibited a significant diminution in the number of 2-cliques that occurred over time. These latter structures are complex (Fig. 1) and their consistent decrease is evidence of attenuation of complex interactions among small groups of people. The structure designated '2-plex ($n = 3$)' (three people in a line) are obviously plentiful, but they too decreased in general over time, especially in cohort 2. The structure called '2-plex ($n = 4$)', (a square) were also virtually absent from the sex and needle-sharing networks. Higher order structures (for which the complex nomenclature is more appropriate) were not present in any of the groups.

Thus, the structure of these groups was largely devoid of the types of interactions that would heighten the potential for viral transmission, either by the sexual or needle-sharing route, as suggested by Friedman *et al.* [14]. Coupled with stability or diminution in risky behaviors and risk configuration, and with the suggestion of increased segmentation of networks, it appears that the social network context observed in Colorado Springs from 1988 to 1992 did not facilitate transmission of HIV. As noted, amongst those HIV-positive persons who were present in these subgroups, we know of only one episode of probable transmission. We may have missed other such episodes and it is possible that some transmission took place. But intense scrutiny of HIV reports during the study [17] and subsequent surveillance in Colorado Springs (unpublished data) with particular attention to respondents who were part of this project suggest that such transmission must have been rare. Although attrition in this study is a potential source of bias, the absence of transmission in the total study group of 595 suggests that those who remained in the study may not have deviated appreciably from those who did not. Thus, although these data do not provide a quantitative approach to attributing HIV transmission (or lack of it) to risk behavior versus network change, structural factors appear to play an important role in inhibiting epidemic takeoff.

The network structure described here provides a marked contrast with that demonstrated in a recently described outbreak of syphilis [29]. In that outbreak, the investigators documented a marked increase in the number and complexity of microstructures during the period of most active transmission of syphilis. Subsequent ethnographic follow-up revealed continued sexual activity amongst the persons involved, but suggested significant alteration of structure. Although such observations are obviously not in parallel settings, nor relate to the same disease process, they do suggest an important contribution of network structure to the dynamics of transmission.

Because our research coincided with ongoing community-wide intervention efforts [12,17], the observed changes may have resulted from such intervention efforts, or possibly from client contact associated with the study itself. Both are difficult to rule out, and it is possible that program or study factors may have influenced the personal behaviors to which they would have been targeted. The differences in the risk taking of the two cohorts, in the presence of a constant program effect (no special campaigns) speaks against such impact. In addition, it is unlikely that program intervention would have had a direct effect on the observed changes in network structure. The fact that such change may take place spontaneously in a group at presumptive risk is a cautionary note for evaluation of an intervention's impact.

We can only speculate about what the social network structure may have been in New York and San Francisco during the late 1970s, or in areas of the world where heterosexual transmission plays an important role. We might surmise that such networks consisted of large connected components, that the proportion of potential risk interactions in a person's environment was high, that people availed themselves of these risks, that short-term network stability was low, and that complex microstructures abounded. We might also suggest that the diminution of homosexual transmission of HIV has resulted not only from well-documented changes in personal behavior [3], but may also have resulted from changes in micro- and macronetwork structure.

Despite the overall size of this study (595 respondents and nearly 6000 named contacts), it is a sample of one. The replication of this and other study designs in areas of differing prevalence and differing trajectories, coupled with frequent acquisition of information about change, will provide a broader perspective about the nature of transmission. What may be generalizable from this study is the approach: consideration of personal risk-taking in a dynamic social context may advance our understanding of the HIV epidemic.

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