Preliminary Version

The Impact of Social Interactions on the Spread of HIV Infection among Injection Drug Users: A Cellular Automaton Model[1]

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The research below is about modelling complex social systems, and in particular applications of Cellular Automata. This is a collaboration of variety of initiatives such as MoCSSy, CSMG, IMPACT-HIV at the IRMACS centre in Simon Fraser University and the BC Centre for Excellence in HIV/AIDS.

This project was supported by the MITACS NCE of Canada and Maplesoft.

[1]IDU, HIV, social influence, transmission dynamics, herd immunity

Abstract

Injection drug users (IDU) who share needles are at high risk for contracting human immunodeficiency virus (HIV) infection. Social and behavioral influences that promote needle sharing can, therefore, impact HIV transmission. HIV spreads rapidly in IDU communities and interventions that target needle-sharing have had variable results. We constructed a cellular automaton model to study the dynamics of the HIV epidemic in an IDU community, in the presence of influences that promote or discourage sharing of used needles. Peer influences are tracked by a counter associated with each individual, who begin or stop sharing needles once a threshold level of influences from neighbours is reached. The simulated epidemic exhibited a strong nonlinear response to social influence on needle-sharing behaviour. An epidemic phase diagram for the parameter space of social influences revealed two states for HIV prevalence. The endemic state above the phase transition curve is characterised by stable HIV prevalence of approximately 35%. Parameter values below the phase transition curve lead to the extinct state. This is similar to a *herd immunity* effect, as the epidemic in this region of the parameter space is eventually driven to extinction. The behaviour of the system implies that public health interventions aimed at reducing needle sharing may have little effect if coverage is limited. If coverage exceeds the phase transition threshold, interventions are expected to be highly effective in stemming HIV epidemics in IDU communities.

We used the computer algebra system Maple for all simulations in this project.

1 INTRODUCTION

Injection drug users (IDU) who share needles are highly vulnerable to HIV infection, since sharing needles and paraphernalia contaminated with the HIV virus is a particularly efficient mode of viral transmission [16]. Since sharing used equipment is common, the number of new HIV infections is high in many IDU communities. [23].

Interaction with IDU can influence susceptible individuals to begin injection drug use [15]. Furthermore, these same social influences may play a role in encouraging IDU to share needles and hence become at risk for HIV infection [14]. For these reasons, sharing of injection equipment is a central issue in controlling the spread of HIV among IDU.

In this paper, we present a cellular automaton (CA) model to study the impact of social interactions, influencing needle-sharing behaviour, on the spread of HIV in an IDU community. Cellular automata can be used to study the effects of complex social interactions at the individual level [9], on the evolution of an epidemic at the population level. Due to their flexibility, cellular automata can serve as virtual laboratories for testing a nearly endless number of social scenarios.

Our CA model is based on an epidemic compartmental framework. Compartmental models employ differential equations and defined groups of individuals, such as susceptible, infectious and recovered, to study epidemic dynamics. A recognised limitation of compartmental models is that groups are homogeneous, with average contact rates imposed on individuals within a

group. To address individual variation in behaviour, various stratification approaches have been applied but these are seriously limited in capturing the range and variability of individual behaviours, which typically drive epidemics.

We developed the CA model to evaluate the impact of individual interactions on the dynamics of linked HIV and risk-behaviour epidemics in the IDU community. A Mover-Stayer-type of compartmental model was chosen as the basic framework, as it has been used previously to represent the spread of drug use as an epidemic [20].

The model is general and can be adapted to various urban IDU communities. Our model was validated for the Downtown Eastside (DTES) HIV epidemic in Vancouver [24]. Vancouver's DTES is among the poorest neighbourhoods in Canada with a large population of IDU. It has experienced an explosive HIV epidemic in the 1990s, which remains a significant public health concern in spite of interventions.

2 DESCRIPTION OF THE MODEL

2.1 Model Structure

In the CA model, a cell represents an individual interacting with its neighbours. Each cell is identified as a member of one of five states or compartments. The states are defined in Table 1. Note that in this model a stayer could be conceptualized as a community nurse, a drug counsellor, etc. So they are a small proportion of the population.

0 — Stayer Fixed cell with no change of state (will never use drugs).
1 — Susceptible Either a non-user or an injection drug user who does not share needles. Can transition to SIDU state.
2 — SIDU HIV^- A sharing injection drug user who is HIV^-, but regularly shares needles. Such an individual can become infected by an HIV+ SIDU neighbour and become a SIDU-HIV. SIDU can quit needle-sharing and transition to the Susceptible state.
3 — SIDU-HIV HIV^+ drug user who shares needles. A SIDU-HIV who stops needle-sharing transitions to the HIV state.
4 — HIV HIV^+ individual infected through sharing contaminated needles, and subsequently ceases sharing needles. May be influenced to begin sharing needles and transition back to SIDU-HIV.

Table 1: Definition of States in the CA Model

Figure 1 shows the two types of interactions possible in the model. Solid arrows show routes for *social influences*. Social influences do not have immediate effects, but accumulate over time to a threshold to trigger behaviour change. Dashed arrows represent the *transmission* of either behaviour change or HIV (see Figure 1). Boxes numbered 0 to 4 represent groups of Stayers, Susceptibles, SIDU, SIDU-HIV and HIV, respectively.

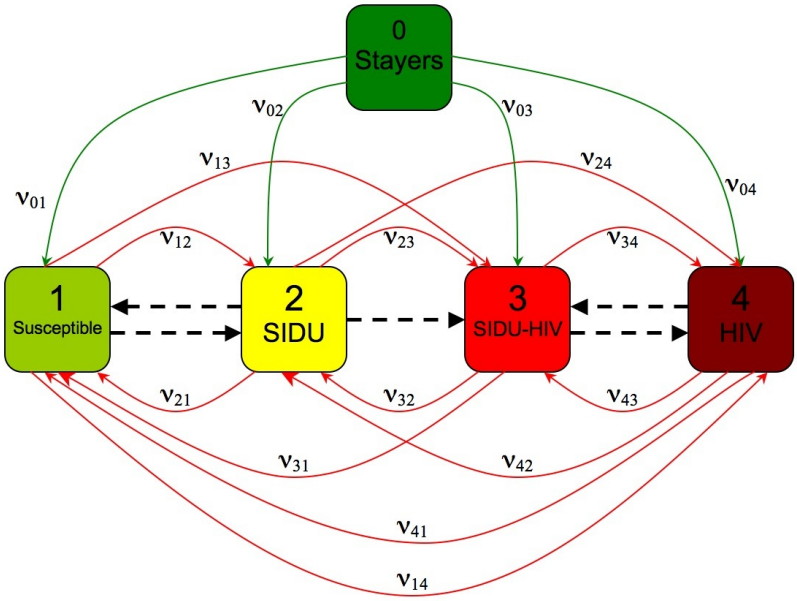

Figure 1: Model Structure

2.2 Influencing Needle-sharing Behaviour

Two types of influences are possible in the model. An individual can influence neighbours by discouraging or encouraging them to share needles. In fact some of the individuals exert a positive influence (α) and discourage other individuals in the community from sharing needles. Other individuals have a negative influence on the other individuals in the model (β) by encouraging them to share needles. In this model, α and β are conceptual parameters that capture a multitude of influences present in the environment. These influences can be social ones such as someone physically offering another individual to share needles. At the same, these influences are considered to be environmental, for instance, an individual may be triggered to share needles by the mere presence of sharing needles in their environment.

The Susceptibles and HIV groups in the model are non-transmitters of HIV. Both groups can include non-users or IDU who currently practice safe injection by not sharing needles. All individuals can influence their neighbours and all, except Stayers, can receive influences from neighbours. Stayers cannot encourage needle sharing. Susceptibles, SIDU, SIDU-HIV, and HIV

can either encourage or discourage needle sharing. Individuals can also exert influences on peers from the same compartment (not shown in Figure 1).

The model employs a novel approach to represent the effect of prolonged social relationships between members of a community where injection drug use is prevalent. In such an environment, a person is more likely to experiment with drug use after a lengthy relationship with an IDU. In the model, this is represented by a social counter linked to each cell, which records and accumulates influences from neighbouring cells at each time step. No counters are linked to Stayers becasue they cannot transition to other states. Equations for counters of the other cells are as follows:

$$C_1(t) = C_1(t-1) + R_0 v_{01} + R_1 u_1 + R_2 v_{21} + R_3 v_{31} + R_4 v_{41}$$

$$C_2(t) = C_2(t-1) + R_0 v_{02} + R_1 v_{12} + R_2 u_2 + R_3 v_{32} + R_4 v_{42}$$

$$C_3(t) = C_3(t-1) + R_0 v_{03} + R_1 v_{13} + R_2 v_{23} + R_3 u_3 + R_4 v_{43}$$

$$C_4(t) = C_4(t-1) + R_0 v_{04} + R_1 v_{14} + R_2 v_{24} + R_3 v_{34} + R_4 u_4$$

where $C_i(t)$ denotes the social influence count for an individual of type i for $i = 1, \ldots, 4$ at time t and R_i is the number of neighbours of type i for $i = 0, \ldots, 4$. The parameter v_{ij} denote the influence of individual i for $i = 0, \ldots, 4$, on individual j, for $j = 1, \ldots, 4$ ($i \neq j$). The value $|v_{ij}|$ can be defined as the probability that an individual of type j changes his/her behaviour and becomes of type i in one unit of time. Influences between individuals of the same type are denoted by u_i for $i = 1, \ldots, 4$. Influences v_{ij} can be positive or negative (discouraging or encouraging needle-sharing behaviour) with values in the interval $(-1, 1)$.

2.3 Transmissions

Since the spread of injection drug use is linked to the spread of HIV infection, the model represents two linked epidemics. Transmission of the HIV virus and the transmission of needle-sharing behaviour are both associated with change of state transitions. However, they arise by different mechanisms.

Transmission of the HIV virus takes place from one individual of type 2 to another individual of type 3 with a fixed probability at each time step. While sharing of contaminated needles is a social interaction, actual transmission of the virus depends on physical and biological constraints. Therefore, a SIDU in contact with SIDU-HIV neighbours, can contract the virus according to an estimated per contact probability of viral transmission. This probability is based on estimates of the biological transmission rate through contaminated needles and the estimated rate of needle-sharing among injection drug users. Since recovery from HIV infection is not possible, HIV transmission is one-directional (from SIDU-HIV $\rightarrow$ SIDU). Sexual transmission is not included in the model. It is assumed that viral transmission occurs only through needle sharing between SIDU-HIVs and SIDUs. Susceptibles cannot contract HIV and HIVs cannot

transmit the virus.

In contrast, acquisition of needle-sharing behaviour is the cumulative result of social influences from several individuals over a period of time. Social influence plays no direct role in the SIDU to SIDU-HIV transmission. Transmission of needle-sharing behaviour is bi-directional, as individuals may start or stop sharing needles at any time.

2.4 Rules for Updating Cells

Cells are updated according to rules described in Table 2. At each time step, all cells in the lattice are updated simultaneously. The parameters τ_i denote the life expectancy of an individual of type i for $i = 0, \ldots, 4$. At each time step, dead cells of type 0 to 4 are replaced. New entries into the population are based on the initial proportions of cell types.

0 — Stayer
a). Dies after τ_0 time steps.
1 — Susceptible
a). Dies after τ_1 time steps.
b). If not dead and $C_1(t) \leq -1$ then transitions SIDU.
2 — SIDU
a). Dies after τ_2 time steps.
b). If not dead, then for each SIDU-HIV in its neighbourhood and for each contaminated needle shared, SIDU is infected with probability p and becomes SIDU-HIV. If the SIDU neighbour was first infected ≤ 2 months ago, $p = 0.05$, if between 2 and 84 months ago, $p = 0.001$, otherwise $p = 0.01$.
c). If not dead and not infected and $C_2(t) \geq 1$ then becomes Susceptible.
3 — SIDU-HIV
a). Dies after τ_3 time steps.
b). If not dead and $C_3(t) \geq 1$ then becomes HIV.
4 — HIV
a). Dies after τ_4 time steps.
b). If not dead and $C_4(t) \leq -1$ then becomes SIDU-HIV.

Table 2: Rules for Updating Cells

2.5 Parameters and Initial Conditions

The model is constructed with the inner-city neighbourhoods of numerous large urban centres in mind that currently experience epidemics of injection drug use, HIV and other infectious diseases. In choosing parameters, we used Vancouver's Downtown Eastside (DTES) as an example. Additional parameters were defined based on estimates in the general HIV literature.

PARAMETER	VALUE	REFERENCE
HIV Transmission Rate		
Initial stage (2 months)	$p = 0.05$	This study
Clinical latency stage (84 months)	$p = 0.001$	This study
AIDS stage (12 months)	$p = 0.01$	This study
Needle-Sharing Rate		
Number of needles shared / month	120	[17]
Life Expectancy		
HIV^+	8 years	[5]
HIV^- IDU	50 years	[13]
Stayers and Susceptibles	75 years	BC Statistics Data
Initial Population		
Stayers (0)	5%	This study
Susceptibles (1)	20%	This study
Needle-sharing IDU (SIDU or 2)	45%	This study
HIV^+ IDU (SIDU-HIV or 3)	25%	This study
HIV^+ (HIV or 4)	5%	This study

Table 3: Parameters and Initial Values

Parameters and initial conditions are listed in table 3. Whenever necessary, reported parameter values were adjusted to be appropriate for conditions in Vancouver's DTES.

To our knowledge there are no estimates available of the populations that can be considered Stayers and Susceptibles in the DTES. Based on the situation in that area, we chose initial populations of stayers and susceptibles of 5% and 20%, respectively. As previously stated, a stayer could be considered as a community nurse, a drug counsellor, etc., which it refers to a small proportion of the population.

The stage of infection is an important factor to consider in the model. Infectivity varies substantially as plasma concentration of the virus changes with disease stage [6, 12]. In one study, the risk of transmission among health care workers was significantly higher when the source of the contaminated needle was a terminal AIDS patient with high levels of plasma viremia [4]. For these reasons, we chose to model infectivity as a three-stage process. In the first two months after infection and the subsequent clinical latency stage respectively, high and low transmission probabilities were used (see Table 3). Although infectivity is high during the final AIDS stage, we used an intermediate transmission probability because injection frequency is expected to decrease as the illness progressively affects general health and the user's ability to inject drugs.

The frequency of needle-sharing depends on several factors. For example, how often needles are shared depends on the type of drug injected. Using Vancouver's DTES as an example, we take into account a shift that took place around 1996 from heroin to cocaine as the predominant drug consumed in the area. Cocaine is typically injected at a higher frequency and bingeing is more common [22].

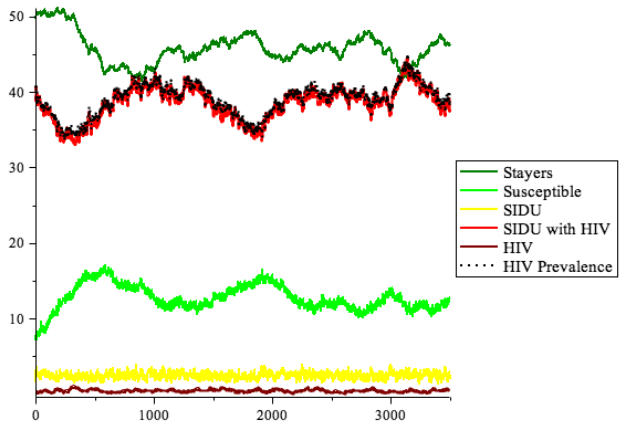

Figure 2: Epidemic is self-sustaining in the presence of social influence encouraging needle-sharing: $\alpha = 0, \beta = 0.02$.

3 Social Influence and HIV Prevalence

To simulate this model we used a two dimensional toroidal shape cellular automata, and considered the von Neumann neighbourhoods with 4 neighbours. This a diamond-shaped neighbourhood on a square grid and it is the smallest symmetric two dimensional neighbourhood, which contains only the north, south, east and west neighbours.

All simulations were programmed using the computer algebra system Maple and carried out on a cluster of 90 dual processor Apple G5 computers and involved an estimated computation time of about one year.

First we investigated the epidemic behaviour of the model system without social influences. With 10% initial HIV prevalence, and α and β at 0, HIV prevalence rises sharply and crashes within a short period of time. Since life expectancy of infected individuals is reduced and no new IDU can be recruited without social influence, the epidemic cannot sustain itself.

When social influence is included, the epidemic may become self-sustaining as the example shows in Figure 2. Here α is 0, so there is no discouragement of needle-sharing. The only influence present is $\beta = 0.02$, encouraging needle-sharing. In the example in Figure 3, $\alpha = 0.005$ and $\beta = 0.03$. Although there is a stronger influence to encourage needle sharing, even a modest discouraging influence is sufficient in this case for the epidemic to crash.

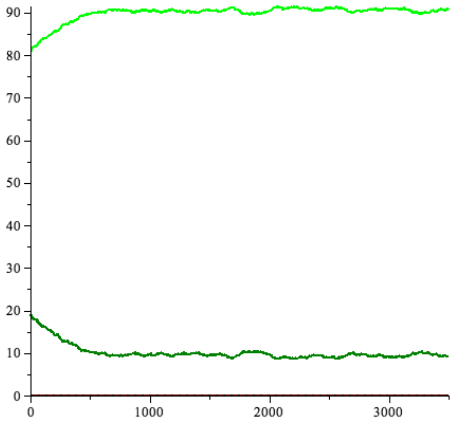

Figure 3: Epidemic is not sustained in the presence of a relatively strong social influence encouraging needle sharing and a relatively modest influence discouraging it: $\alpha = 0.005, \beta = 0.03$.

4 Epidemic Phase Diagram

To understand the global behaviour of the model, we constructed a phase diagram for ranges of α and β values (Figure 4). Points above the curve are combinations of α and β that drive the epidemic to an endemic state. Below the curve, the epidemic is not self-sustaining.

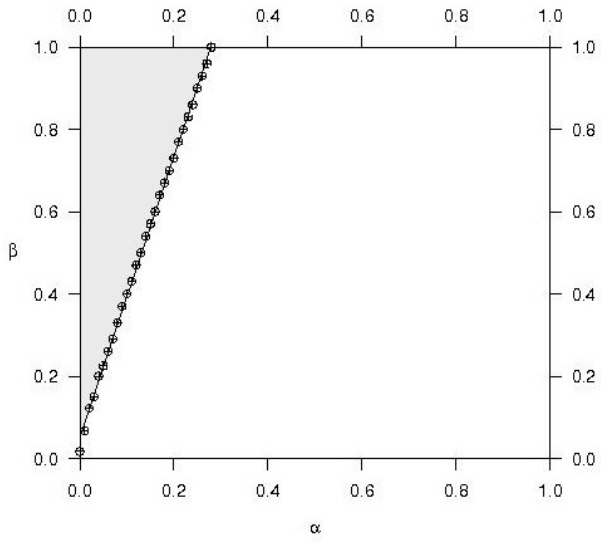

Figure 4: Phase diagram for the HIV epidemic.

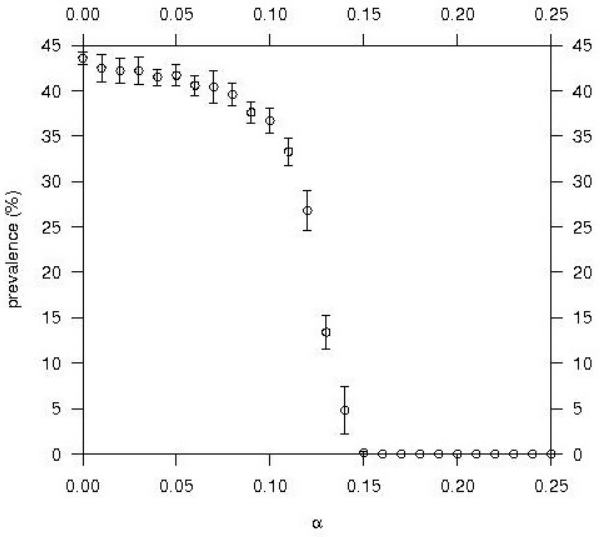

Figure 5: Horizontal cross-section of the phase diagram with $\beta = 0.5$.

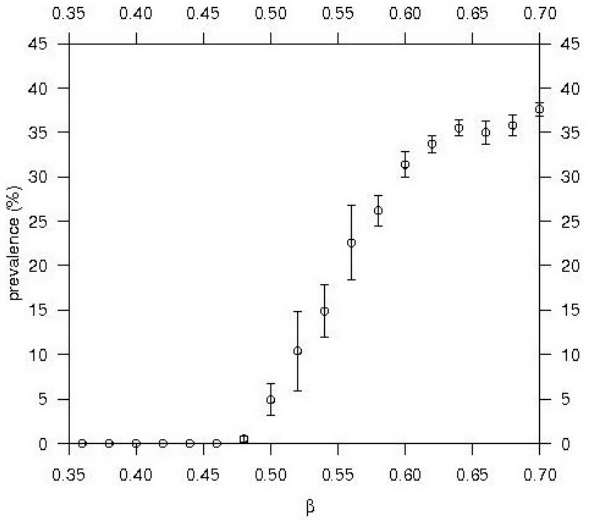

Figure 6: Vertical cross-section of the phase diagram with $\alpha = 0.14$.

5 DISCUSSION

The cellular automaton model simulations presented here imply that social factors may play an important role in driving the HIV epidemic in injection drug users. In the model community where the only mode of viral transmission is through contaminated needles, the epidemic

showed a threshold response to changes in social influence among community members. When the epidemic is sustained, HIV prevalence remained stable around 30%. We found that discouragement of needle sharing had a stronger impact than encouragement. The results of the simulations raise the possibility that targeting social interactions among drug users may have potential as a public health intervention strategy.

It is becoming increasingly recognized that complex social context plays a crucial role in determining HIV risk behaviour among IDU [19]. In a statistical study, for example, social determinants were found to be the most significant predictors of borrowing needles [21]. Although statistical associations are compelling, there is need of a comprehensive understanding of the social context and psychosocial dynamics of risk behaviour among IDU. This requires extensive qualitative studies, which include ethnographic approaches [18]. Individual assessment of risk is not the only — or possibly even the most important — factor leading to needle-sharing behaviour. It is also the product of social context, peer influence and cultural norms [3].

Cellular automata in general may be well suited to constructing models based on qualitative empirical studies and testing social theory derived from them. The structure of our model is general enough to incorporate behavioural flexibility and a broad range of interactions so it can easily be modified to test various social scenarios in future versions.

Epidemiology recognises the concept of herd immunity [2]. When a threshold number of individuals are immunized in a community, those that are not, remain protected from infection. Herd immunity is a function of transmission dynamics and it essentially means that the disease cannot grow epidemically on the network. In our model, social influence discouraging needle-sharing interrupts the network and as such serves a function similar to immunization. Combinations of α and β under the phase transition curve correspond to a type of herd immunity effect because HIV prevalence approaches 0 and the epidemic is not sustained.

The version of the model we present here does not take into account a number of factors that are likely to be important in the transmission dynamics of HIV among IDU. Sexual transmission of HIV and immigration of already infected individuals into the population are likely to be important and will be considered in future work. Another issue is the accuracy of the probability of viral transmission parameter. This is a key parameter in the model and one that is difficult to estimate. There are a number of ways of estimating transmission probability for a single needle-sharing event [8]. Statistical models exist that rely on estimates of the rate of needle-sharing [1, 11, 10]. Injuries among health care workers is another source of information [7], which is typically more accurate regarding the circumstances surrounding the injection event [4]. In future versions of the model we will also explore the impact of variation in transmission probability on epidemic dynamics.

Acknowledgements

We would like to thank Robert S. Hogg and the members of the Complex Systems Modelling Group for helpful discussions and suggestions. We also are grateful for technical support from

The IRMACS Centre, Simon Fraser University.

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