Development Of HIV Model And Its Simulation

D. K. Chaturvedi, Dayalbagh Educational Institute
Pritam Singh, Dayalbagh Educational Institute
S. K. Gaur, Dayalbagh Educational Institute
D. S. Mishra, Dayalbagh Educational Institute

Available at: https://works.bepress.com/dk_chaturvedi/8/
Development of an HIV Model and Its Simulation


This article discusses model development for HIV-infected populations using the system dynamics technique. The technique has an advantage over conventional modeling techniques as it independently assumes causal relationships that involve qualitative and quantitative variables to model socioeconomic problems of a complex nature. The model has been simulated and the results have been compared with the available data.

Introduction

The HIV problem is a very complex and ill-defined one from the modeling point of view. Keeping in view the complexities of HIV infection and its transmission, it is difficult to make exact estimates of HIV prevalence. It is more so in the Indian context, with its typical and varied cultural characteristics, and its traditions and values with special reference to sex-related risk behaviour. However, it is possible to have a rough estimate with a range that may be used for planning HIV/AIDS prevention and control programmes. These estimates can also be useful for mapping specific vulnerable groups and areas so as to plan targeted interventions in major urban and other areas in the state. Applications of the data from sero-surveys of HIV in a sentinel population is considered for the model development of HIV for finding an approximate estimate of the magnitude of HIV in the community (Cahill 1983, Geng 1985).

In the model development the following factors have been helpful in the understanding of the problem:

\textit{Journal of Health Management, 3, 1 (2001)}
Sage Publications New Delhi • Thousand Oaks • London
1. There are two types of HIV viruses, currently known as HIV-1 and HIV-2. HIV-1 is dominant in nature worldwide and transmits at a faster rate, whereas HIV-2 is less easily transmitted and the time period between the initial infection and illness is longer. According to Prof. Max Essex of the Harvard AIDS Institute, out of the two categories of HIV viruses, AIDS contracted in Western nations is mainly through homosexual contacts and intravenous drug use spread by HIV-1 B, whereas in South Asia and Sub-Saharan Africa it is caused by other varieties of viruses, HIV-1 A, C and E, and are contracted almost entirely by heterosexual contacts. Hence, the risk of HIV infection increases up to 10 times because of sexually-transmitted diseases (STD) (Feldman and Johnston 1986).

2. It has been reported that women are twice as likely as men to contract some kinds of STDs. Also HIV infection rates among 15 to 19-year-old girls are three times more than those in teenage boys (Banerjee 1999).

3. The character and number of affected people vary from region to region. For example, Africa and Asia show more transmission through heterosexual sex while Latin America through homosexual sex and Eastern Europe and newly independent states through drug injections (Gupta 1986).

4. In India and China HIV has infected 5 per cent of the people who are engaged in high-risk behaviour. Overall, about 6.4 million people are currently believed to be living with HIV in Asia and the Pacific—just over a fifth of the world’s total population (Banerjee 1999).

This is an alarming situation and to stop/reduce the rate of infection is a great challenge. Hence, there is a genuine need to develop a model for the HIV-infected population, considering almost all the factors affecting its behaviour so that one can study the effect of each and every variable on the behaviour of the HIV-infected population or the rate of change of HIV infection for strategic planning and control.

This article highlights the system dynamics methodology and presents its applications for modelling and simulation of the HIV-infected population. The system dynamics modelling technique offers a number of advantages over conventional modelling techniques, especially for modelling systems where an exact model cannot be obtained using conventional techniques. The diagrammatic tools used in the model development encourage the modeller and give better understanding of and quick insight into the system, which is quite complex in nature and difficult to model due to the inherent non-linearity in it. The results obtained by the model developed here is compared with the data given by National AIDS Control Organisation (NACO), India (Government of India 1999). The model is simulated up to A.D. 2003.

Principal Symbols

Level Variables

\[ I_P \] — HIV infected population level (number of persons)
\[ B_D \] — Blood demand level (blood bottles consumed)
\[ T_F \] — Total population level (number of persons)
\[ A \] — Awareness level (per cent)

Rate Variables

\[ R_{HIV} \] — HIV prevalence rate (persons/1,000)
\[ S_D R \] — Rate of blood demand (blood bottles consumed/year)
\[ D_R \] — Crude death rate (number of persons died/year)
\[ B_R \] — Crude birth rate (number of persons born/year)
\[ R_A \] — Rate of awareness level

Auxiliary Variables

\[ I_E C \] — Information, education and communication (process that informs, motivates and helps people to adopt and maintain healthy practices and lifestyles, and prevents them from acquiring infection and ill health).
\[ R_H \] — Number of persons involved in a rehabilitation programme and the facilities provided to HIV-infected persons for their comfort.
\[ S_P \] — Susceptible population (number of persons)
\[ R_D \] — Efforts for research and development for HIV medicines, simple and easy test facilities for HIV, and also help in rehabilitation.
\[ M_P A \] — Manpower available to educate people on AIDS (number of persons involved in the education and
awareness programmes on HIV multiplied by their working hours [man-hours].

BSF  —  Number of blood testing/screening facilities for reducing transfusion of infected blood.

Constants

K1-K10  —  Constants
DT  —  Step size in simulation (that is, small fraction of time) DT. The model involves a first-order differential equation, that is:

\[ \frac{dy}{dx} = f(x) \Rightarrow y = f(x) DT + \text{constant.} \]

Dot Extension

J  —  Jth time instant
K  —  Kth time instant
L  —  Lth time instant
JK  —  Interval between Jth and Kth time instants

System Dynamics Technique for Modelling the HIV-infected Population

System dynamics methodology offers an innovative approach for modelling and simulation of dynamics of social/socioeconomic problems under a variety of situations to facilitate quick learning and understanding the problem/system and its behaviour.

J.W. Forrester originally developed this methodology for industrial applications. It explains the causalities and identifies the feedback loop that helps understand any system while modelling, and simulating its dynamics under the relevant operating conditions (Forrester 1968; Goodman 1980; Koenig and Blacwell 1961).

Even in socioeconomic systems with explicit interconnection structure, quick and useful insights can be gained through this methodology by first identifying the presence of cause-effect relationship in each pair of variables of interest and then characterising the direction (+ or -) of the causality under certain particular conditions, that is, all else remaining constant, on other variables by making reference to relevant literature or domain experts.

Casual loop diagrams and flow diagrams are thus developed among variables subclassified as level (or state) variables, flow-rate variables, auxiliary variables and exogenous variables and parameters. Dynamical equations characterise system dynamics in terms of discrete time difference and algebraic equations, which can be directly and readily simulated on the computer, ordinarily using simple Euler's forward method of numerical integration. In relatively more sophisticated procedures one can use a state-of-the-art solution technique such as the fourth-order Runge-Kutta method, as desired by the systems analyst (Chaturvedi and Sarsangi 1992, 1993; Press et al. 1992).

Variable Identification

The first step in model development using the system dynamics technique is the identification of key variables. The variables identified for the HIV-infected population model are examined here.

Risk

There is sufficient risk of HIV to take the form of an epidemic if adequate care is not taken. Population groups considered to be at high risk of HIV infections because of their behaviours and selected as sentinel groups for HIV sentinel surveillance (HSS) include men who have unprotected sex with many men (MSM), injecting drug users (IDU), and heterosexuals (HET) who have unprotected sex with multiple sex partners of subgroups female sex workers (FSW) and sexually-transmitted-disease (STD) patients. Lower-risk HET subgroups used in HSS systems include blood donors, military recruits and antenatal clinic (ANC) attendants. In addition, TB patients have been included in some HSS systems (Conwell 1991; Dossiers 1988; Sabatier 1988; WHO 1990).

Female Sex Workers (FSW) Studies in Thailand indicate that there are many different types of FSW—from the direct brothel worker to the occasional freelancer who may be picked up at bars or other locations. The average HIV risk for each type of FSW varies directly with the average number of different sexual partners each type may have on a daily or weekly basis (Khorshed 1992).
Injecting Drug Users (IDU) Similarly, not all drug users inject drugs, and not all injecting drug users routinely share their injecting equipment (WHO 1990). Hence, the relative size of each specific IDU subgroup must be estimated when HIV prevalence is estimated for the total IDU population.

Blood Donors If the blood demand level increases in a particular zone then donors will also increase in that zone. In most developed countries blood donors are mostly voluntary and the HIV infection risk in such donors is low or zero. However, in many Asian countries, depending on the utilisation of paid donors, this risk is high (Dossers 1988). In addition, the HIV prevalence rate among blood donors usually decreases markedly when appropriate methods are implemented to screen out donors with possible high-HIV-risk behaviours.

Military Recruits (MR) In the military young men may increase their general patronage of sex workers and thereby increase their overall risk for acquiring an HIV infection (Cornwell 1991).

Antenatal Females (AF) HIV serological surveys of males and females in Sub-Saharan Africa suggest that HIV prevalence found in antenatal females is a reasonable surrogate for HIV prevalence in the sexually-active population. HIV prevalence rates were found to be much higher in young antenatal girls compared to other young girls and boys. Prevalence rates were found to be much lower in pregnant women aged between 25 and 39 compared with non-pregnant ones in the same age group (Feldman and Johnson 1986).

Tuberculosis Patients TB patients have been included as sentinel groups in many HSS systems, but due to lack of sufficient data it is not possible to incorporate this variable in the present model.

Migration Migration and mobility have increased the chances of the disease spreading to other areas/persons (Thomas 1994).

Low-income Groups It is found that the low-income group population often engage in sex. In India the population of this group is enough to affect the behaviour of HIV infection (Government of India 1999). Therefore, it is an important variable to consider in modelling.

Awareness Level The awareness level of HIV in the community has significant influence on the risk factors and on how to control the HIV-infected population.

To raise awareness of HIV in the people at large, an IEC campaign can be used. IEC is a process that informs, motivates and helps people to adopt and maintain healthy practices and lifestyles, and prevents them from acquiring infection and ill health. IEC has the following components: mass media, advocacy at various levels, intersectoral collaboration, training, involvement of NGOs and research. IEC is an effective tool for changing the behaviour of an individual, but this process of behavioural change is very slow and gradual (Banerjee 1999; Thomas 1994). India is not only a vast country, but also a country of culture and linguistic diversities. This poses a great challenge for developing suitable IEC strategies and approaches. A survey was conducted by NACO in 1998 to find the awareness level of the population within the age group of 15 and 49 years in rural and urban areas of some states of India (Times of India 1998). Its results are tabulated in Table 1.

**Table 1**

<table>
<thead>
<tr>
<th>Awareness Levels of HIV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>State</strong></td>
</tr>
<tr>
<td>Delhi/Haryana</td>
</tr>
<tr>
<td>West Bengal</td>
</tr>
<tr>
<td>Maharashtra</td>
</tr>
<tr>
<td>Tamil Nadu</td>
</tr>
</tbody>
</table>

Funds

Different agencies of the UN have been actively collaborating with national governments on different aspects of HIV/AIDS prevention and control. Besides this, WHO and the World Bank are also supporting these programmes (Ahuja 1997; WHO 1993, 1994).

Research and Development

R&D groups may develop a simple and easy testing facility for HIV. This also help in rehabilitation. It could also suggest new methods for IEC to educate society, and could develop vaccines for the same (Banerjee 1999).

These are the few variables which are quite useful in the model development of HIV-infected population. The complete list of the variables...
of interest is given in the Appendix. The causal links have been developed between the pairs of variables under ceteris paribus conditions. These links were then combined to get a causal loop diagram.

Causal Loop Diagram

Figure 1 shows the causal loop diagram with four positive loops and three negative feedback loops for the HIV-infected population model. It identifies not only the direction of causality but also the strength of relationships involved on the basis of knowledge acquired through relevant literature.

The four positive causal loops are made between the following variables:

1. Risk, susceptible population (SP), rate of HIV infection (RIP), HIV-infected population (IP).
2. Risk, RIP, IP.
3. Risk, IEC, rate of awareness (RA), awareness level (A).
4. SP, RIP, IP.

Similarly, the three negative causal loops are made between the following variables:

1. Risk, IEC, awareness, blood screening facility, RIP.
2. Total population (TP), SP, RIP, IP, Risk, IEC, RA, A, rehabilitation (RH), death rate (DR).
3. TP, man power available for IEC, RA, A, RH, DR.

Flow Diagram

A flow diagram is nothing but an elaborate diagram of a causal loop diagram, which clearly shows the level variables, rate variables, and auxiliary and exogenous variables. Therefore, it is quite helpful in writing dynamo equations. Figure 2 shows the corresponding flow diagram with infected population (IP), blood demand (BD), total population (TP) and awareness (A) as the four level or state variables; the rate of change of HIV infection (RIP), birth rate (BR), death rate (DR), rate of blood demand (BDR) and rate of awareness (RA) as the five flow-rate

![Figure 1: Causal Loop Diagram for HIV-infected Population Model](image-url)
variables; the total risk due to various factors (risk), delay in AIDS death, rehabilitation measure (RHI), IEC and susceptible population (SP) as the five auxiliary variables, funds allocated for HIV control, R&D activities and rehabilitation measures (fund), FSW, military recruits (MR), low-income status (LIG), migration (M), injecting drug users (IDU), efforts from NGOs and people in red light areas are the exogenous (externally supplied) variables and parameters.

**Dynamo Model**

Dynamo equations for characterising higher-order dynamics of the HIV-infected population model are given by the following equations. Equations 1 to 16 can be directly simulated in terms of the time profile of level variables, flow-rate variables and other illustrative characteristics for given values of exogenous variables and parameters.

**Level Equations**

There are four level equations to find the accumulated value corresponding to each level (state) variables.

\[ L_{IP,K} = L_{IP,J} + DT\times RIP,JK \]  \hspace{1cm} (1)

\( L_{IP} \) - infected population (per 1,000)
\( RIP \) - rate of infection (per 1,000)

Equation 1 represents a level (state) equation for infected population at the \( K^{th} \) time instant, which is equal to the infected population at the \( J^{th} \) time instant and the increment in it. The increment in the infected population can be determined by the rate of prevalence between the \( J^{th} \) and \( K^{th} \) time instants and the step size (time increment) \( DT \). Similarly, other level equations can also be written as follows:

\[ L_{TP,K} = L_{TP,J} + DT\times (BR,JK - DR,JK) \]  \hspace{1cm} (2)

\( TP \) - Total Population in (Million)
\( BR \) - Birth rate (per thousand)
\( DR \) - Death rate (per thousand)
I. BD.K = BD.J + DT*BD.R,JK
   BD - Blood Demand (units/thousand of population)
   BD.R - Blood Demand Rate

L. A.K = A.J + DT*RA,JK
   A - Awareness Level (in percentage)

Initial Values of Level Variables

To start the simulation it is necessary to give some starting (initial) conditions. Therefore, for all the above-mentioned level variables initial values are given as below from the data book of the year 1998-99 of the Ministry of Human Resources and Development, Government of India (Government of India 1999). In the year 1984, for the first time, six HIV-infected persons were detected in India. The total population at that time of India was 746.8 million. Assuming that the awareness level at that time was negligible (0.01):

   IP = 0.006
   TP = 746.8
   BD = 0.6157
   A = 0.01

Flow-rate Equations

Flow-rate variables are required to control the accumulated value of level variables. There are three rate variables (equations 5 to 7), one for each level variable (infected population [IP], awareness [A] and blood demand [BD]). The total population (TP) has two rate variables, one for controlling the inward flow (birth rate [RR]) and the other for controlling outward flow (death rate [DR]), as shown in equations 8 and 9:

R.I.P.KL = (9.8 + SP.KRISK.K)
   SP—Susceptible population (million)

R.A.KL = 10.C.KK1
   RA—Rate of awareness (per cents)

R.BD.KL = TABLE (BUT, TIME.K, 0, 16, 2)
   BDR - Blood demand rate (units/1,000 population)

BR.KL = TABLE (BRT, TIME.K, 0, 16, 2)
   BR—Birth rate (per 1,000)

NDR.KL = DR.K - RH.KK14

Auxiliary Equations

The auxiliary equations (10 to 22) are needed for simplifying the calculations:

2. SP.K = TP.K - IP.K.K10e-3
3. FSW.K = TP.K.KFSW
4. FSW—Female sex workers (persons)
5. RISK.K = (FSW.K.KJ + MR.K.KK4 + M.K.K5 +
   BD.K.K10)/kk

As mentioned earlier, the risk mainly depends on female sex workers (FSW), military recruitment (MR), migration (M), injecting drug users (IDU), low-income groups (LIG), awareness level of HIV in society, blood demand (BD) and research activities going on for HIV (K&L). The constants are decided on the basis of experience and then optimised while refining the model's behaviour.

DR.K = TABLE (DR.T, TIME.K, 0, 16, 2)
   M.K = TABLE (MT, TIME.K, 0, 16, 2)
   MR—Military recruitment (persons)
   IDU.K = TABLE (IDUT, TIME.K, 0, 16, 2)
   LIG.K = TABLE (LIGT, TIME.K, 0, 16, 2)
   LIG—Low-income group (persons)
Tables of death rate (DR), military recruitment (MR), migration from other countries to India (M), injecting drug users (IDU), number of persons in the low-income group (LIG) and fund allocated by the government to control HIV are taken from the data book of the year 1998-99 of the Ministry of Human Resources and Development, Government of India (Government of India 1999).

R.D.K = funds.K.K12

Funds.K = TABLE (FT, TIME.K, O, 16, 2)

Funds—Alloted funds (Rs. in crores)

MPA,K = TP.K’K11

RH.K = A.K’KA + FUNDS.K.K13

Tables:

MRT, BRT, DRT, EDT, MT, IDUT, LIGT.

Constants

R1 to K14 are constants.

Simulation Results

The model had been simulated for the comparative growth in seropositive cases in India from 1986 to 2005. The simulation results are shown in Figures 3 and 4 and also in Table 2. The result shows that the rate of HIV seropositivity is increasing and has doubled within a brief span of six years.

Conclusion

It has almost been an accepted fact that AIDS/HIV is not a health problem alone, but a problem of such magnitude that it affects every facet of human life. The country will have serious socioeconomic consequences if the disease goes unchecked. Therefore, every sector of society, the government, non-government organisations, business, industry, leaders, policy makers, programme managers—almost everyone—should accept the seriousness of the AIDS/HIV epidemic. The commitment of all these organisations as well as individuals is very important for combating the disease. How to involve every one, however, is the biggest challenge.

The following conclusions have been drawn after simulating the model developed in this paper:

1. IEC is an important variable affecting the behaviour of the HIV-infected population/rate of HIV infection. Hence, it is necessary to make a comprehensive IEC policy at the national level to increase awareness, improve knowledge and understanding in the common man about HIV infection, and modes of transmission and methods of prevention.

2. Involvement of NGOs in the policy framework is essential for effective implementation of different programmes. Also, there is a need to improve the capabilities and skills of NGOs.

3. Funds are the next important and crucial parameter, which will affect all the controlling variables and parameters. An appropriate allocation of funds to different sectors and organisations will not only help in controlling the rate of infection of HIV but also to prolong the life of already infected persons.
Figure 1
Simulation Results of HIV-infected Population Model

- Total population (millions)
- Birth rate and death rate
- Blood donation rate
- Infected population

Figure 4
Simulation Results of HIV-infected Population Model

- Blood demand
- Awareness level
- Risk
- Rate of infected population
Future Scope

The model developed in this paper using the system dynamics technique can be quite useful for forecasting, planning and controlling aspects of HIV infection. Future work can be listed as follows:

1. Sensitivity analysis of the HIV-infected population model can be carried out for different variables and the effects of those variables can be studied.
2. Once the sensitivity analysis is over, the results can be utilised to develop control policies and to implement them in an effective way.
3. Work can be further extended by developing a fuzzy model for HIV infection because most variables of the HIV-infected model are subjective (qualitative) in nature. The qualitative information can be handled very easily using this model.

Appendix

The key variables affecting the mechanism of the HIV-infected population model are listed below.

1. Risk of getting infected from HIV
2. Susceptible population
3. Crude death rate
4. Crude birth rate
5. Total population
6. Awareness level among the people
7. Manpower available for education regarding HIV/AIDS
8. Population in red light area
9. Population in slums and low-income strata
10. Migration level
11. Female sex workers
12. Military recruits
13. Efforts in R&D for HIV/AIDS
14. Rehabilitation measures
15. Prolonging death due to AIDS by effective rehabilitation
16. Rate of HIV infection

Development of an HIV Model and its Simulation

17. Information, education and communication (IEC)
18. Blood donation level/blood donors
19. Drug-addicted population
20. HIV-infected population
21. Funds allocated for reducing HIV infection rate
22. Efforts by government and non-government organisations
23. HIV blood testing facility
24. Antiretroviral treatment
25. Prisoners, truck and auto-rickshaw drivers
26. Number of non-licensed blood banks

References


Geneva: WHO.


D.K. Chaturvedi, Pratap Singh, Man Mohan, S.K. Gaur and D.S. Mishra are at the
Faculty of Engineering, Dyal Singh Educational Institute, Dyal Singh, Ages 242
001. Tel: 0166-281220; email: dsgndeved@gmail.com.