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Simulation of the Heterosexual HIV/AIDS Epidemic in Japan by a Fuzzy Mathematical Model

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A study with a mathematical model was conducted for the objectives of analyzing heterosexual human immunodeficiency virus (HIV) transmission in Japan and identifying effective countermeasures against HIV/acquired immunodeficiency syndrome (AIDS) epidemics in communities in which the transmission is mainly through commercial sex workers (prostitutes). A fuzzy mathematical model which examined 4 groups (highly and moderately sexually active males, and highly and moderately sexually active females) was developed to simulate the heterosexual HIV/AIDS epidemic in Japan. The simulation generated bell-shaped epidemic curves for the numbers of male and female AIDS cases. At the early stage of the epidemic, the calculated incidence of male and female AIDS cases was similar to the reported incidence in each sex, respectively, in Japan. The results obtained with the scenario which assumed rapid spread of condom usage among highly sexually active females disclosed that this countermeasure had the biggest effect. The results obtained with either the scenario which assumed the spread of condom usage among males who travel outside of the community, or which assumed a decrease in the number of commercial sex workers from other communities, disclosed that these countermeasures had little preventive effect. The results suggest that countermeasures designed to decrease heterosexual HIV transmission inside of the community are the most effective, even if the inflow of HIV from outside communities does not decrease.

Key Words: AIDS; epidemiology; fuzzy theory; mathematical model; sexually transmitted disease

Some Asian countries have been spared the present worldwide human immunodeficiency virus/acquired immunodeficiency syndrome (HIV/AIDS) epidemic (WHO, 1995). In Japan, the reported cumulative number of HIV-infected persons and AIDS patients was 3,524 and 1,154, respectively, at the end of 1995 (Soda et al., 1996). Many of these cases are in haemophiliacs, and the number of HIV/AIDS cases resulting from infection through heterosexual intercourse is not large. However, the number of haemophiliac HIV cases does not show any increase, while the number of heterosexual HIV/AIDS cases has become the 2nd largest group and shows the most rapid rate of increase (Tables 1 and 2). Countermeasures against an

Abbreviations: AIDS, acquired immunodeficiency syndrome; CSW, commercial sex worker; HIV, human immunodeficiency virus; TFN, triangle fuzzy number.

Table 1. Cumulative reported number of AIDS and HIV-infected persons by risk factors

Risk factors	AIDS			HIV		
	Japanese	foreigner	Total	Japanese	foreigner	Total
Heterosexual (male)	135	35	170	283	84	367
Heterosexual (female)	23	20	43	118	381	499
Homosexual	148	31	179	294	56	350
Intravenous drug users	2	3	5	3	8	11
Materno-infant	5	2	7	4	5	9
Haemophiliacs	582	0	582	1806	0	1806
Others	12	4	16	29	8	37
Unknown	82	72	152	72	373	445
Total	987	167	1154	2609	915	3524

HIV/AIDS epidemic through transmission by commercial sex workers (CSWs) or prostitutes are thus an urgent issue in Japan.

Countermeasures against infectious diseases are well known among experts in the field of public health. However, the most effective countermeasure against one infectious disease is not necessarily identical to that for another infectious disease. The effectiveness of countermeasures depends upon many factors which relate not only to the disease itself but also to human behavior, and it is particularly difficult to identify the most effective countermeasure against an HIV/AIDS epidemic, as it is related to the complex human behavior of sexual activity.

Simulation with a mathematical model is one of the scientific methods of analyzing epidemics of infectious diseases and of evaluating countermeasures against them. Many mathematical models have been developed and applied to the HIV/AIDS epidemic since its initial occurrence (Knox, 1986; Anderson, 1988, 1989; De Gruttola et al., 1988; Dietz et al., 1988; Gupta et al., 1989; Van Druten et al., 1990; Jager et al., 1992). Mathematical models which simulate HIV transmission through heterosexual intercourse require analysis of multiple groups (multigroup transmission model). The models should also assume an "open" model which assumes the inflow of HIV from outside of the community, and to examine the internal spread of HIV among at least 4 groups (highly promiscuous and less promiscuous males, and highly promiscuous and less promiscuous females). However, the more complex the models become, the more data are necessary. This defect may play a part in the infrequent usage of mathematical models of HIV/AIDS transmission among public health decision makers.

In this study, we applied fuzzy theory to a mathematical model of heterosexual HIV/AIDS epidemics in order to compensate for this fact. We used the reported numbers of HIV-infected persons and AIDS patients in Japan to confirm the effectiveness of countermeasures against the transmission of HIV/AIDS.

Methods

Mathematical model

Overview

In the model, we assume HIV/AIDS transmission through heterosexual intercourse in a community. This model consists of the following 4 groups: (a) highly sexually active males (Group 1); (b) highly sexually active females (Group 2); (c) moderately sexually active males (Group 3) and (d) moderately sexually active females (Group 4). Individuals in Group 1 are males who have regular sexual intercourse with CSWs. They are assumed to have sexual intercourse with those in Groups 2 and 4, and with CSWs outside of the community when they travel or stay in the foreign country. Those in Group 2 are female CSWs, who work at specialized Japanese-style bath rooms or work at other sex-related services. This group includes

Table 2. Reported incidence of AIDS by sex and year

Year	Male	Female	Total
1985	6 (0)	0 (0)	6 (0)
1986	5 (0)	0 (0)	5 (0)
1987	9 (1)	5 (4)	14 (5)
1988	16 (4)	3 (3)	19 (7)
1989	15 (3)	1 (0)	16 (3)
1990	28 (7)	3 (1)	31 (8)
1991	38 (9)	0 (0)	38 (9)
1992	49 (20)	2 (1)	51 (21)
1993	73 (26)	14 (8)	87 (34)
1994	120 (39)	17 (7)	137 (46)
1995	140 (61)	28 (19)	168 (80)
Total	499 (170)	73 (43)	572 (213)

The number of heterosexial cases is indicated in parentheses. Haemophiliacs are excluded.

CSWs who always live in the community and those who come into the community from outside communities where HIV/AIDS is epidemic. Individuals in Group 3 are assumed to have sexual contact with those in Groups 2 and 4, and those in Group 4 to have sexual contact with those in Groups 1 and 3. Figure 1 is a diagrammatic representation of this multigroup transmission model.

The 1st stage of HIV/AIDS epidemic

At the 1st stage, there is no HIV-infected person nor AIDS patient in the community. It is assumed that some of the males who travel out of the community are infected with HIV through heterosexual intercourse with HIV-infected CSWs there, and that they return to the community. The probability of HIV infection is a function of the number of CSWs with whom they have had sexual intercourse, the prevalence rate of HIV among these CSWs, and the probability of HIV transmission per CSW. It is also assumed that some individuals of Group 1 are infected with HIV through heterosexual intercourse with HIV-infected CSWs who come into the community from outside communities, even though the individuals from Group 1 do not go outside of the community. The probability of the infection is a function of the number of CSWs with whom they have sexual intercourse, the rate of CSWs from outside communities among individuals in Group 2, the prevalence rate of HIV among these foreign CSWs, and the probability of HIV transmission per CSW. Mathematical formulas are shown in the Appendix (Jager and Ruitenberg, 1992).

Spread of HIV infection and occurrence of AIDS patients

We assume that newly infected individuals in Group 1 begin to transmit HIV to susceptible persons in Group 2 or 4 through heterosexual intercourse. The probability of the infection of susceptible persons is a function of the number of sex partners, the prevalence rate of HIV in the group of the sex partners, and the probability of HIV transmission per sex partner. In the same way, it is assumed that newly infected

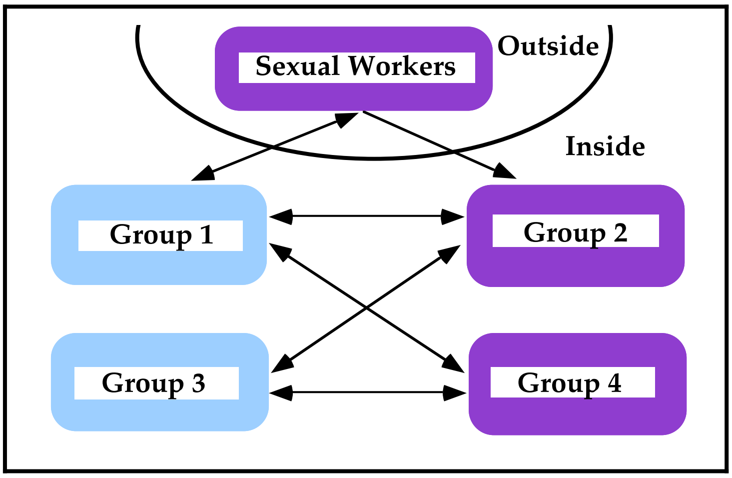

Fig. 1. Multigroup transmission model. HIV transmission among 4 groups. Group 1: highly sexually active males; Group 2: highly sexually active females; Group 3: moderately sexually active males; Group 4: moderately sexually active females. The arrows in the figure indicate HIV transmission. The arrow from the "Sexual Workers" to the "Group 2" indicates not only HIV transmission but also the inflow of commercial sex workers from outside to inside.

Table 3A. Summary of data: baseline estimates and ranges

Data		Baseline estimate	Range	References
Probability of HIV transmission				
From male to female	(person-year)	0.05 (mean)	0.012 (SD)	14, 15, 18, 41
From female to male	(person-year)	0.01 (mean)	0.0024 (SD)	14, 15, 18. 41
Incubation period of HIV				
Median (Weibul distribution)	(year)	10		5, 31, 33
Shape parameter (Weibul distribution)	(year)	2.29		5, 31, 33
Pathogenicity rate	(%)	85		7, 22, 33, 44, 46
Rate of continuance of infectivity	(%)	50		Assumed
Case fatality rate	(/year)	0.15		7, 42, 45
Mortality rate of health individuals	(/year)	0.001		21

Pathogenicity rate, rate of persons who develop AIDS among HIV-infected persons.

individuals in Group 2 or 4 transmit HIV to susceptible persons in Group 1 or 3. In the community, the number of HIV-infected persons gradually increases with the repetition of these heterosexual (male-to-female and female-to-male) acts of intercourse.

Many HIV-infected persons gradually develop AIDS, and cease to transmit HIV to susceptible persons. However, it is assumed that some of them do not develop AIDS and continue their infectious status. The incidence of AIDS among newly HIV-infected persons is a function of the rate of persons who develop AIDS among the infected persons (hereafter, "pathogenicity rate") and the probability density which indicates development of AIDS after an incubation period.

HIV-infected persons and AIDS patients die of many causes, most of them related to AIDS. We assume that the mortality rate of HIV-infected persons is the same as the rate of susceptible persons, but that the rate in AIDS patients is much higher than that in susceptible persons.

Table 3B: Summary of data: baseline estimates and ranges

Data		Baseline estimate	Range	References
Population of				
Highly sexually active male*		300,000	150,000 – 600,000	21, 25
Highly sexually active female*		10,000	5,000 – 15,000	21, 25
Moderately sexually active male*		4,200,000	3,900,000–4,350,000	21, 25
Moderately sexually active female*		4,090,000	4,085,000–4,095,000	21, 25
Individuals of G1 who travel abroad*		20,000	10,000 – 30,000	39
Individuals of G1				
who have sexual intercourse abroad*	(%)	10	5–15	25
Prevalence rate of HIV among CSWs abroad	(%)	20		4, 36, 50
Rate of foreign CSWs				
among CSWs in a country*	(%)	5	3–10	25
Prevalence rate of HIV among foreign CSWs	(%)	5		28
Frequency of sexual intercourse				
Between G2 and G1 (person/month)*		20	10–25	25, 28
Between G3 and G2 (person/year)*		6	3–12	25, 28
Between G1 and G4 (person/year)*		0.01	0.005–0.02	Assumed
Between G3 and G4 (person/year)*		0.001	0.0005–0.002	Assumed

*Triangular fuzzy number.
CSW, commercial sex worker.

Through these processes, HIV/AIDS becomes epidemic in the community. (Mathematical formulas are shown in the Appendix.)

Assumed countermeasures

We assume 4 types of countermeasures, as follows: (a) spread of the usage of condoms among males who travel outside of the community; (b) spread of the usage of condoms among CSWs in Group 2; (c) spread of the usage of condoms among males in Groups 1 and 3 and (d) decrease of the number of CSWs from other communities. The speed of the spread of condom usage and of the decrease of the number of CSWs is assumed to be either rapid or slow. Consequently, there are 8 scenarios, which incorporate rapid or slow change of the 4 factors affecting the HIV transmission route. The outcome of each of these countermeasures is evaluated by measuring the number of AIDS cases generated in the model. The decrease of frequency of heterosexual intercourse among persons at risk is a preventive strategy against HIV/AIDS epidemic, and similar to the spread of condom usage. However, it is known that the latter is more effective than the former, and we assumed the spread of condom usage in this model (Mann, 1994). (Mathematical formulas are shown in the Appendix.)

The community assumed in this model simulates the young population of a metropolitan area (Tokyo, Kanagawa, Saitama and Chiba) in Japan. The reported numbers of HIV-infected persons and AIDS patients, and demographical and social data in this area are incorporated in order to make simulation with the model realistic and to enhance the evaluation of the effect of each countermeasure.

Data

We collected and synthesized data from published and unpublished sources (Tables 3A and 3B) (Lui et al., 1988; Bacchetti and Moss, 1989; Jason et al., 1989; Anderson et al., 1991; Kuo et al., 1991; Ministry of Justice in Japan, 1991; Padian et al., 1991; Weniger, et al., 1991; European Study Group on Heterosexual Transmission of HIV, 1992, 1994; Haverkos et al., 1992; Phillips et al., 1992; Selwyn et al., 1992; Stone et al., 1992; The Italian Seroconversion Study, 1992; Chang et al., 1993; Kamakura et al., 1993; Kihara et al., 1993; Japan Health and Welfare Statistics Association, 1994). Where data were incomplete, we used a fuzzy number. The interval of confidence of the fuzzy number was estimated by a Delphi survey, experts' opinions and project team consensus. In this model, the unit time is assumed to be a year, because we compare the calculated results of the model with the reported number of HIV/AIDS cases in the surveillance, and these numbers are combined into an annual total. Furthermore, there are some other data which are reported as annual statistics.

Size of population

The number of persons aged 20–39 years is about 8,600,000 (4,500,000 males and 4,100,000 females) in the metropolitan areas mentioned above (Japan Health and Welfare Statistics Association, 1994). We used these numbers. The numbers of individuals in Groups 1, 2, 3 and 4 were not studied directly. One Delphi survey estimated that about 20% of young males (25th and 75th percentile; 10% and 30%; respectively) have several sexual partners in a year, and that the number of female CSWs is about 10,000 (3,500 and 15,000, respectively) in the metropolitan area (Kamakura et al., 1993). We used the triangular fuzzy number (TFN) for these parameters (Table 3B).

It is known that about 2,500,000 Japanese males aged 20–39 years travel abroad in a year (Ministry of Justice in Japan, 1991). We estimated the number of individuals in Group 1 who travel abroad by extrapolation of the following 2 rates against this value: the rate of Group 1 to the total of Groups 1 and 3, and the rate of the number of males in the metropolitan area to all Japanese males. This estimated TFN of the number of individuals in Group 1 who travel abroad was (10,000, 20,000, 30,000).

We assumed that the rate of CSWs from outside communities entering Group 2 was not constant, that this rate rapidly increased in the early stages of the HIV/AIDS epidemic, and then gradually decreased with course of the epidemic (see ***Assumed countermeasures*** above).

Sexual activity

Since the beginning of the epidemic of HIV/AIDS, many studies of sexual activity have been carried out in Western countries (De Buono et al., 1990; ACSF investigators, 1992; Johnson et al., 1992; Mann, 1992a; Ward et al., 1993; Lemp et al., 1994). However, it is not appropriate to use these data in this study, because the sexual activity within one community is quite different from that in another community, and this difference may be especially great when cultures differ.

Studies of the sexual activity of lay people or CSWs in Japan are very few. One study disclosed that 50% of young Japanese males who had stayed abroad more than 2 years had the experience of having sexual intercourse with some unspecified number of females during their stay (Jitsukawa and Okamoto, 1994). The before-mentioned Delphi survey estimated that about 25% (10% and 40%) of young Japanese males who travel abroad have sexual intercourse with native females there (Kamakura et al., 1993). We assumed that about 10% of individuals in Group 1 who travel abroad would have sexual intercourse with a CSW there without condom usage. This parameter was also assumed as the TFN (5%, 10%, 15%). Another study revealed that the mean number of customers per foreign female CSW in a month was 18.8 ± 23.8 (mean ± SD) (Kihara et al., 1993). We assumed that about one female sexual worker, independently of her nationality, has about 20 customers in a month. This parameter (person/month) was assumed as the TFN (10, 20, 25).

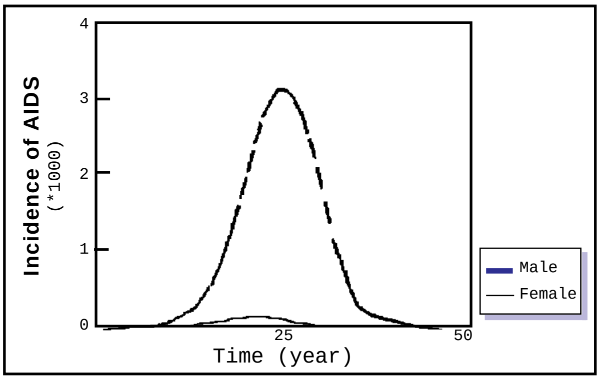

Fig. 2. Basic model (Models A and B).

In addition to these parameters, there are some sex parameters with which we must estimate real values, i.e. the frequencies of sexual intercourse between individuals in Groups 2 and 3, Groups 1 and 4 and Groups 3 and 4. However, we could not find any studies giving estimates of these values. We assumed these values as the TFN, and estimated their magnitudes based on experts' opinions and project team consensus. The assumed TFNs for the frequency (person/year) of sexual intercourse between individuals in these Groups are shown in Table 3B.

We assumed that there was no use of condoms at the early stage of the HIV/AIDS epidemic, and that the use of condoms either rapidly or slowly increased with the epidemic (see ***Assumed countermeasures*** on p. 87).

HIV transmission, pathogenicity and mortality

The probability of HIV transmission through sexual intercourse is one of the parameters which are difficult to estimate. Earlier studies estimated this value as the probability per sexual act, while more recent studies have estimated it as the probability per sexual partner or person-year. We used the results of more recent studies, and assumed that this value was expressed as the probability per person-year. We further assumed that this value could be expressed with the normal distribution: the mean ± SD of the probability of male-to-female transmission and female-to-male transmission was 0.05 ± 0.012 and 0.01 ± 0.0024/person-year, respectively (Padian et al., 1991; European Study Group on Heterosexual Transmission of HIV, 1992, 1994; Haverkos and Battjes, 1992).

We assumed the Weibull distribution, and set 10 years as the median of the incubation period and 2.29 years as the shape parameter (Lui et al., 1988; Bacchetti and Moss, 1989; Kuo et al., 1991). According to these values, the estimated proportion of individuals who develop AIDS within 5 years is 0.15, and that within 10 years is 0.53.

Table 4. Reported and calculated incidences of AIDS cases by heterosexual infection by sex and year

Year (i)	Reported AIDS		Calculated AIDS	
	Male	Female	Male	Female
1981 (0)	0	0	0	0
1982 (1)	0	0	0	0
1983 (2)	0	0	0	0
1984 (3)	0	0	0	0
1985 (4)	0	0	0	0
1986 (5)	0	0	0	0
1987 (6)	1	4	1	0
1988 (7)	4	2	2	0
1989 (8)	3	1	4	1
1990 (9)	7	1	9	1
1991 (10)	8	0	15	1
1992 (11)	16	0	25	2
1993 (12)	31	9	38	3
Total	70	17	94	8

It is known that the "pathogenicity rate" of AIDS is relatively high in comparison to other viral infections. The Delphi survey estimated that the "pathogenicity rate" of AIDS was about 85%, so we assumed the rate of 85% in the model. It is also known that the case fatality rate of AIDS patients without proper treatment is very high (Lui et al., 1988; Jason et al., 1989; The Italian Seroconversion Study, 1989; Selwyn et al., 1992; Chang et al., 1993). We assumed that about 85% of the patients died of AIDS-related diseases within 5 years after the onset of AIDS, and that the annual case fatality rate is stable within 5 years. The annual mortality rate of members of the 4 groups was assumed to be the same as that of Japanese individuals aged 20–39 years, i.e., 0.001/year (Japan Health and Welfare Statistics Association, 1994).

Additional assumptions

In Japan, the time trend of the reported number of heterosexually HIV-infected persons has not been the same as that of heterosexual AIDS patients. The reported number of heterosexually HIV-infected foreign females increased from 1987, the beginning of surveillance for HIV-infected persons, to 1992, while the reported number of heterosexually infected foreign female AIDS patients did not increase (Tables 1 and 2). By project team consensus, we assumed that most of these AIDS patients were illegal CSWs from foreign countries, and that they either returned voluntarily or were returned to their home country because it became impossible for them to continue working for various reasons. This assumption was incorporated into the program of the mathematical model.

The program of this mathematical model is written in C language, and executed with a UNIX computer. The source program is available upon written request.

Results

Basic Model

The simulation of the mathematical model without any countermeasure showed bell-shaped epidemic curves of male and female AIDS cases (Model A, Fig. 2). However, the amplitude of the epidemic curve of the male AIDS cases was much bigger than that of the female AIDS cases. The 1st case of AIDS occurred 4 years after the 1st case of HIV infection, and the epidemic of AIDS continued for about 40 years. (We assumed that the end of the epidemic was the point in which the incidence of HIV-infected persons became almost constant.) At the early stage of the epidemic, the calculated incidence of male and female AIDS cases was similar to the reported incidence of AIDS cases, respectively (Table 4). The cumulative numbers of HIV-infected persons and AIDS patients by the end of the epidemic were about 283,900 (male: 275,619; female: 8,279) and 39,200 (male: 38,241; female: 1,066), respectively. The AIDS epidemic curves by Groups showed that the HIV/AIDS epidemic occurred in Groups 1 and 2 at the 1st stage, and that the epidemic spread into Groups 3 and 4 at the next stage. The AIDS epidemic in Groups 1 and 2 started in the 6th and 8th years, respectively, and ended in the 36th and 33rd years, respectively; the epidemic in Groups 3 and 4 started in the 11th and 25th years, respectively, and ended in the 46th and 48th years, respectively. The incidence rate of AIDS in

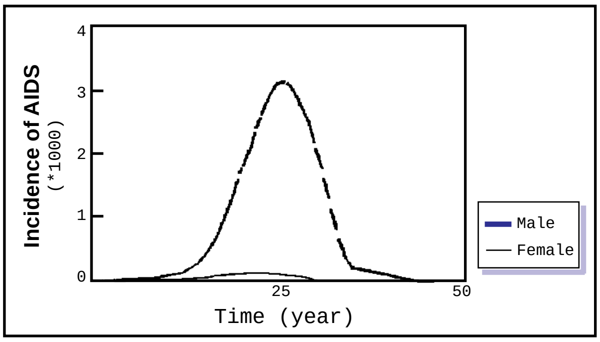

Fig. 3. Model C1.

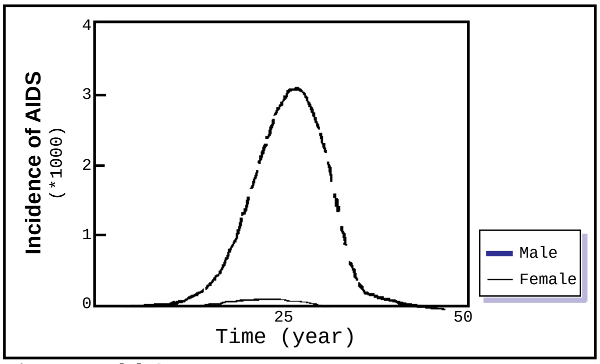

Fig. 4. Model C2.

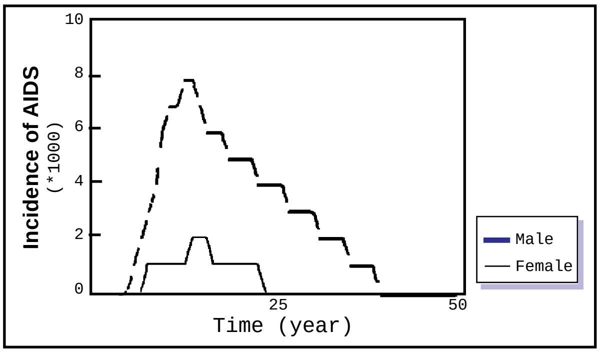

Fig. 5. Model D1.

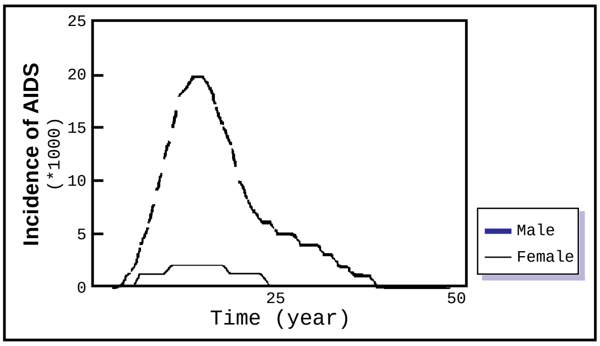

Fig. 6. Model D2.

Group 2 was the highest in the 4 Groups; the rate at its peak was about $1,000/10^5$. The rate at the peak in Groups 1, 3 and 4 was about 900, 60 and $0.08/10^5$, respectively.

The ratio of the calculated number and the reported number of HIV-infected persons at the early stage of the epidemic was 0.20 (658/3373). This ratio indicates the rate of the reported HIV-infected persons in all HIV-infected persons (hereafter "capture rate") in an HIV/AIDS surveillance.

The result shows that HIV spreads among highly sexually active males and females at the 1st stage of HIV/AIDS epidemic, that many of the highly sexually active males and females are infected with HIV during the epidemic, and that a low, but constant, number of AIDS cases occur among moderately sexually active males and females for a long time after the epidemic.

Comparison between fuzzy and non-fuzzy models

In order to study the effects of the fuzzy mathematical model, we compared the results obtained with the fuzzy and non-fuzzy models. In the non-fuzzy model, parameters which are the TFNs in the fuzzy model were treated as ordinary numbers. The baseline estimates of the TFNs are transformed to the ordinary numbers.

The simulation of this non-fuzzy model also showed bell-shaped epidemic curves of male and female AIDS cases (Model B). The cumulative numbers of HIV-infected persons and AIDS patients by the end of the epidemic were about 254,600 (male: 246,511; female: 8,078) and 35,600 (male: 34,560; female: 1,051), respectively. The AIDS epidemic curves by Groups in the non-fuzzy model were almost the same as those in the fuzzy model.

The result shows that the effect of the fuzzy model is small in simulation, and that the non-fuzzy model can be useful when highly reliable baseline estimates are available. However, in this study, all baseline estimates may not be reliable, and using only a non-fuzzy model is doubtful.

Models which includes assumed countermeasures

The models under each of the 8 scenarios were: rapid (Model C1) or slow (Model C2) spread of condom usage among males who travel out of the community; rapid (Model D1) or slow (Model D2) spread of condom usage among CSWs in Group 2; rapid (Model E1) or slow (Model E2) spread of condom usage among males in Group 1 and 3; and rapid (Model F1) or slow (Model F2) decrease in the number of CSWs from other communities.

In Models C1 and C2, the annual rate of the spread of condom usage among males who travel outside of the community was assumed to be 1.25/year and 1.05/year, respectively, and the rate in Models D1 and D2 was also assumed to be 1.25/year and 1.05/year, respectively. In Models E1 and E2, respectively, the annual rate of spread of the usage of condom was assumed to be 1.01/year and 1.002/year. These 2 values (1.01/year and 1.002/year) are values reflecting the annual rates in Models D1 and D2 adjusted by the ratio of population size of Groups 2 and 3 (10,000/4,200,000). In Models F1 and F2, the annual rate of decrease of the number of CSWs from other communities was assumed to be 0.75/year and 0.95/year, respectively.

All 8 models generated bell-shaped epidemic curves of male and female AIDS cases. The amplitudes of the epidemic curves of male AIDS cases were much bigger than those of female AIDS cases (Figs. 3–10). Among the 8 models, Model D1, rapid spread of condom usage among CSWs in Group 2, showed the

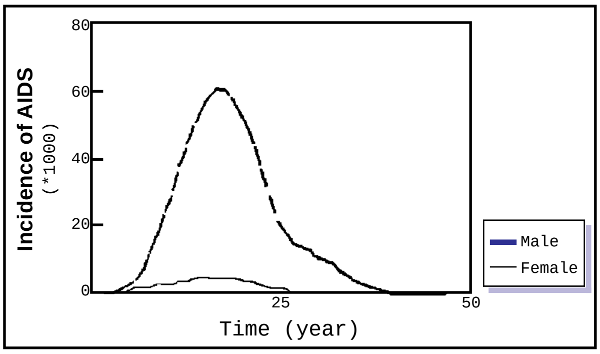

Fig. 7. Model E1.

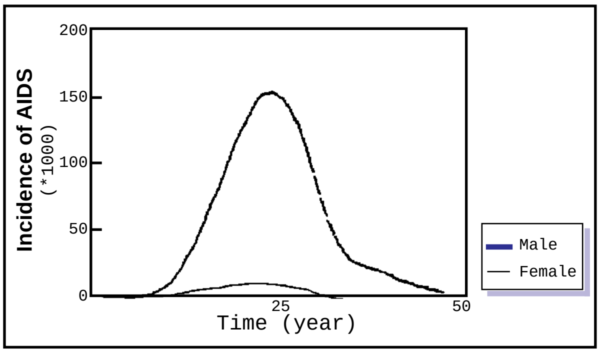

Fig. 8. Model E2.

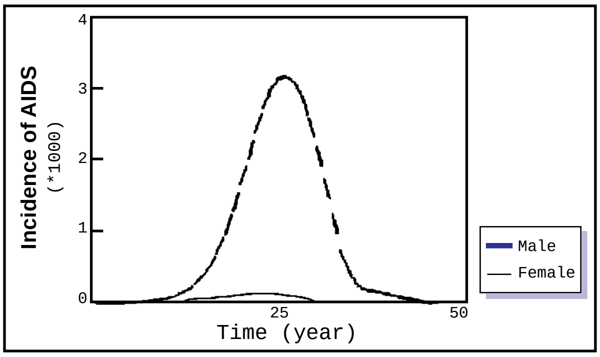

Fig. 9. Model F1.

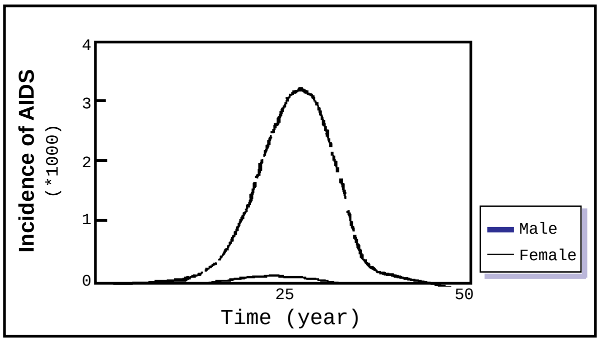

Fig. 10. Model F2.

Table 5. Cumulative numbers of HIV-infected persons and AIDS patients by models

Model	Peak of epidemic	HIV			AIDS		
		Total	Male	Female	Total	Male	Female
A	29	283,900	274,700	8,200	39,200	38,200	1,000
B	27	254,600	246,500	8,000	35,600	34,600	1,000
C1	29	28,300	274,700	8,200	39,200	38,200	1,000
C2	29	283,900	274,700	8,200	39,200	38,200	1,000
D1	14	1,200	1,100	100	150	130	20
D2	15	2,100	2,000	100	290	260	30
E1	19	6,800	6,400	400	920	870	50
E2	25	21,000	20,000	1,000	2,730	2,600	130
F1	29	283,900	274,700	8,200	39,200	38,200	1,000
F2	29	283,900	274,700	8,200	39,200	38,200	1,000

Values shown in the table are the nearest rounded whole numbers.

biggest effect as a countermeasure. The cumulative numbers of HIV-infected persons and AIDS patients by the end of the epidemic were about 1,200 (male:1,096; female:113) and 150 (male:134; female:19), respectively. The ratios of these cumulative numbers of HIV-infected persons and AIDS patients in Model D1 to Model A (the basic model) were both 0.004. Model D2, slow spread of condom usage among CSWs in Group 2, showed the 2nd biggest effect, and Model E1, rapid spread of condom usage among males in Groups 1 and 3, showed the 3rd biggest effect, followed by Models E2, C1, C2, F1 and F2 in order of the magnitude of the effect (Table 5).

The results of these 8 models showed that prevention of the inflow of HIV from outside communities is not an effective countermeasure once the spread of HIV among highly sexually active groups has taken place, and that the decrease of HIV transmission through heterosexual intercourse within the community is the most effective countermeasure, even if the inflow of HIV from outside communities does not decrease.

Discussion

This quantitative study disclosed that decrease of HIV transmission is the most effective countermeasure against HIV/AIDS epidemic in an isolated community where HIV is mainly spread through heterosexual intercourse. Even if the inflow of HIV from outside communities continues through male travelers and foreign female CSWs, the most effective countermeasures in an isolated community is decreasing HIV transmission through heterosexual intercourse within the community. This means that the promotion of the use of condoms among CSWs and their customers, detection of HIV-infected CSWs, and promotion of having steady sex partners are highly effective preventive methods. These preventative measures have already been carried out in many countries (Chin and Mann, 1990; Dumasia, 1990; Weniger et al., 1991; Mann, 1992b, 1992c; Thomas et al., 1993). However, there are also many other countermeasures against the HIV/AIDS epidemic, some of which have been carried out without objective evaluation. It is difficult to show the quantitative effect of a single countermeasure, in comparison to other countermeasures, even if the incidence of new HIV-infected persons or AIDS patients suddenly decreases in association with the expansion of HIV/AIDS countermeasures. Thus, the effects of some relatively poorly effective countermeasures may be overestimated. For example, in Japan, the high risk of HIV infection through sexual intercourse with CSWs in foreign countries has been widely announced, and leaflets/pamphlets to this effect are distributed to travelers abroad. However, there is no governmental program to promote the usage of condom among CSWs and their customers. Countermeasures targeting travelers abroad are among the preventive countermeasures, but should not be pursued without countermeasures designed to decrease the HIV transmission through heterosexual intercourse within the community.

Many mathematical models have been developed since the inception of the HIV/AIDS epidemic (Knox, 1986; Anderson, 1988, 1989; De Gruttola and Mayer, 1988; Dietz and Hadler, 1988; Gupta et al., 1989; Van Druten et al., 1990; Jager and Ruitenberg, 1992), but in only a few, the effectiveness of different countermeasures has been evaluated (Anderson, 1989; Van Druten et al., 1990; Jager and Ruitenberg, 1992). In many models, the effectiveness of only a single countermeasure is monitored, rather than comparison of various countermeasures. We are aware of no model in which the effectiveness of efforts to prevent the inflow of HIV from outside is compared with that of efforts to prevent the transmission of HIV within the community. Presently, foreign CSWs are a major infectious source of the HIV/AIDS epidemic, not only in Japan but also many other countries as well. This "open" model, which includes the inflow of HIV through foreign CSWs, is quite useful in decision-making related to countering the HIV/AIDS epidemic.

However, the comparison of effectiveness using a mathematical model is not easy, because the solutions yielded are largely affected by the values of parameters entered into the model. The more realistic the algorithm becomes, the more uncertain the parameters are. In many models, instead of a complex algorithm which includes uncertain parameters, a simple algorithm which does not include these parameters is used. In this study, we selected a complex algorithm which includes uncertain parameters, because simulation with more realistic models is known to yield more useful information for decision-making in countering the HIV/AIDS epidemic. The results of this study are almost certainly affected by the values of the parameters; when the parameteric values are changed, the relative effectiveness of various countermeasures can be changed; at least in simulation using the model. In this study, in order to compensate for this defect, we used the fuzzy theory to generate the parameteric values.

The application of fuzzy mathematical models in engineering and industry has been favorably evaluated (Jain, 1976; Prade, 1979; Kaufmann and Gupta, 1991). However, it is difficult to evaluate their application in public health, because of the impossibility of testing the results yielded by the fuzzy models in experiments. In general, the mathematical models used in public health have uncertain effect and include uncertain values which are dependent on human behavior. The fuzzy model is one of the newest methods used to calculate these uncertain values in mathematical models. In this study, we incorporated the results of the Delphi survey, which are indicated in an actual-values range and can be interpreted as TFNs, into the fuzzy model. We used the fuzzy model to make maximum use of the results of the Delphi survey. The combination of the fuzzy model with the Delphi survey results may be an effective model for use in the public health field.

The basic model generated a bell-shaped epidemic curve of AIDS cases. Epidemic curves with this shape have been observed in epidemics of some other infectious diseases, and mathematical models of epidemiology of these diseases have yielded theoretical epidemic curves which were similar to the observed epidemic curves (Kermack and Mckendrick, 1927; Morio et al., 1985; Bailey, 1986; Cvjetanovic et al., 1986). The HIV/AIDS epidemic is still in process, and thus the entire epidemic curve of HIV/AIDS cannot be known. However, some other mathematical models have also yielded a bell-shaped theoretical epidemic curve of AIDS cases (Anderson, 1988; Koopman et al., 1991). The epidemic curves of AIDS cases in these studies and ours indicate that the incidence of AIDS patients exponentially increases at the early stage of the epidemic, begins to decrease after many susceptible persons are infected, then decreases to a low point and becomes almost constant.

The incidence at the end stage of the epidemic curve is almost null. It may not be acceptable that the incidence of a sexually transmitted disease (HIV/AIDS in this case) becomes null. This is a result of using a static population, if we use a dynamic population the incidence at the end stage of the epidemic curve must be a constant value other than zero. However, the aim of this study is to perform a quantitative comparison among 8 scenarios, so there is no reason to use a dynamic population and to make the model more complex. We used a simple static population.

Although the bell-shaped epidemic curve was shown in both males and females, in this study, the basic model disclosed a marked difference in incidence for male and female AIDS patients. There are 2 explanations for this difference by sex, which has not been described in other studies of HIV/AIDS using mathematical models. First, in the basic model, the population size of highly sexually active males is assumed to be much bigger than that of highly sexually active females (300,000: 10,000), and this assumption, of course, leads to a substantial difference between the 2 groups in incidence. Second, it is assumed that HIV-infected highly sexually active females, who are from outside of the community and develop AIDS, return to their home countries without being counted as AIDS patients; this assumption also decreases the incidence of female AIDS patients.

The epidemic curves by Groups generated in the basic model showed that the HIV/AIDS epidemic begins in Groups 1 and 2, and then spreads into Groups 3 and 4 at the next stage. These epidemic curves indicate that the HIV/AIDS epidemic in the community will be small if the epidemic in Groups 1 and 2 can be prevented. These epidemic curves are also consistent with the before-mentioned results obtained with the assumed countermeasures, in that the results for D models (assumption of the rapid/slow spread of the usage of condoms among CSWs), and E models (assumption of the rapid/slow spread of the usage of condoms among males) disclosed relatively high effectiveness.

The simulation with the basic model yielded not only the estimated incidence (and prevalence) of AIDS cases but also the prevalence of HIV-infected persons. The reported number of AIDS cases is one of the indices of the magnitude of the HIV/AIDS epidemic. In many countries, the surveillance of AIDS cases is carried out in order to estimate HIV/AIDS epidemic. However, AIDS occurs after a long incubation period, and the incidence (or prevalence) of AIDS is an index of the HIV epidemic about 10 years before (the median of the incubation period). Also, AIDS patients are seldom capable of transmitting HIV to susceptible persons because they are sick. The prevalence (or incidence) of HIV-infected persons, who do not have symptoms but are capable of transmitting HIV to susceptible persons, is a more appropriate index of the magnitude of the HIV/AIDS epidemic. In some countries, including Japan, even though the surveillance of HIV-infected persons is also carried out, the usage of these data is limited because there is no information about the capture rate (as mentioned before, the rate of the reported HIV-infected persons among all HIV-infected persons). Even when an increase in HIV prevalence is observed, it cannot be determined whether the prevalence of HIV has actually increased or whether the capture rate has merely become higher.

In this study, at the early stage of the HIV/AIDS epidemic, the calculated incidence of AIDS in the model is similar to the reported incidence of AIDS, and the calculated prevalence of HIV may be similar to the actual prevalence of HIV. The comparison between the calculated prevention of HIV and the actual prevalence of HIV is also desired, but very difficult, because it is almost impossible to get the actual prevalence of HIV. In this study, the capture rate is used to estimate the reliability of the calculated prevalence of HIV. The capture rate calculated from the prevalence of the reported and of the calculated HIV was 0.20. This value is similar to the capture rate which was calculated by the “back-calculation method” with data regarding AIDS in Japan (Hashimoto et al., 1993), and makes the data of HIV surveillance more useful.

This mathematical model simulates an epidemic of HIV/AIDS transmitted solely through heterosexual intercourse, but not through homosexual intercourse or intravenous drugs. Because a mathematical model which includes not only heterosexual intercourse but also homosexual intercourse and intravenous drug usage is very complex, we cannot get reliable data for parameters in a model. This simulation based exclusively on heterosexual transmission may limit the applications of this study. However, among the many HIV transmission routes, heterosexual HIV transmission is the one for which the effectiveness of preventive methods is most difficult to evaluate, for a number of reasons: the population at risk is large, mobility makes follow-up difficult, and it is difficult to acquire exact information regarding sexual activity. In many countries, however, the epidemic seems to involve primarily heterosexual transmission. The algorithm used in this study can be applied to data acquired in many countries, and the fuzzy model can be used even when adequate data are not available. We think that this fuzzy model is one of the tools in identifying effective countermeasures against the HIV/AIDS epidemic with potential applications in countries where heterosexual transmission of HIV/AIDS is a major issue.

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Appendix: Mathematical Formulas

The 1st stage of HIV/AIDS epidemic

At time t, the number of susceptibles, infectives and AIDS patients in Group i (i = 1, 2, 3, 4) is $x_i(t)$, $y_i(t)$, $z_i(t)$, respectively. The number of individuals in Group i is $n_i(t)$, which includes the number of susceptibles, infectives and AIDS patients. The number of infected males in Group 1 who return to the community from the outside at time t ($t = 0$) is described by,

$$y_1(0) = T_{1F} \times w(0),$$

where, T_{1F} is the transmission parameter from groups of females CSWs to Group 1 (subscripts "1" and "F" means Group 1 and females, respectively), and $w(t)$ is the number of individuals in Group 1 who go the outside of the community. The transmission parameter (T_{1F}) is a complex combination of other underlying parameters,

$$T_{1F} = \beta_{1F} \times k_{1F} \times \boldsymbol{f}_{1F},$$

where,

$\boldsymbol{f}_{1F}$ = proportion of individuals in Group 1 who have sexual intercourse with females outside of the group, the Fuzzy number,
k_{1F} = mean number of females with whom there is sexual contact at the unit time by an individual in Group 1,
β_{1F} = probability of infection from an infected females to a susceptible in Group 1 per partnership, the normal distribution function.

The number of infected foreign females in Group 2 who enter the community from the outside at time t ($t = 0$) is described by,

$$y_2(0) = \rho(0) \times v(0),$$

where, $\rho(t)$ is the prevalence rate of HIV among CSWs outside the community, and $v(t)$ is the number of CSWs who enter the community from the outside.

The HIV/AIDS epidemic at time *t* in Group 1

From time t to $t + \Delta t$, the change of the number of susceptibles to HIV in Group 1 is described by,

$$x_1(t + \Delta t) - x_1(t) = - T_{1F} \times x_1(t) \times (y_2(t)/n_2(t)) - T_{1F} \times x_1(t) \times (y_4(t)/n_4(t)) - T_{1F} \times w(t),$$

where, $(y_2(t)/n_2(t))$ and $(y_4(t)/n_4(t))$ is the proportion of HIV infectives in Groups 2 and 4, respectively.

The change of the numbers of infectives and AIDS patients in Group 1 are described by,

$$y_1(t + \Delta t) - y_1(t) = T_{1F} \times x_1(t) \times (y_2(t)/n_2(t)) + T_{1F} \times x_1(t) \times (y_4(t)/y_4(t)) + T_{1F} \times w(t) - \int_0^t \gamma\, y_1(u)du,$$

$$z_1(t + \Delta t) - z_1(t) = \int_0^t \gamma\, y_1(u)du - z_1(t),$$

where, γ is the probability of developing AIDS in infected individuals (the Weibul distribution), $\int_0^t \gamma\, y_1(u)du$ is the number of AIDS patients who was infected with HIV at the time 0 and manifested AIDS by the time t, and δ is the case fatality rate of AIDS patients.

The HIV/AIDS epidemic at time *t* in Groups 2, 3 and 4

In Group 2, $x_2(t)$, $y_2(t)$ and $z_2(t)$ are described by,

$$x_2(t + \Delta t) - x_2(t) = - T_{2M} \times x_2(t) \times (y_1(t)/n_1(t)) - T_{2M} \times x_2(t) \times (y_3(t)/n_3(t)),$$

$$y_2(t + \Delta t) - y_2(t) = T_{2M} \times x_2(t) \times (y_1(t)/n_1(t)) + T_{2M} \times x_2(t) \times (y_3(t)/n_3(t)) - \int_0^t \gamma\, y_2(u)du,$$

$$z_2(t + \Delta t) - z_2(t) = \int_0^t \gamma\, y_2(u)du - \delta z_2(t),$$

where, T_{2M} is the transmission parameter from groups of males to Group 2 (subscripts “2” and “M” means Group 2 and males, respectively).

In Groups 3 and 4, $x_3(t)$, $y_3(t)$, $z_3(t)$, $x_4(t)$, $y_4(t)$ and $z_4(t)$ are described by the formulas similar to them in Group 2.

Assumed countermeasures

At time t, under the condition of widespead usage of condoms, $x_1(t)$ and $y_1(t)$ are described by,

$$x_1(t + \Delta t) - x_1(t) = - \varepsilon_1(t) \times T_{1F} \times x_1(t) \times (y_2(t)/n_2(t)) - \varepsilon_1(t) \times T_{1F} \times x_1(t) \times (y_4(t)/n_4(t)) - \zeta(t) \times T_{1F} \times w(t),$$

$$y_1(t + \Delta t) - y_1(t) = \varepsilon_1(t) \times T_{1F} \times x_1(t) \times (y_2(t)/n_2(t)) + \varepsilon_1(t) \times T_{1F} \times x_1(t) \times (y_4(t)/n_4(t)) + \zeta(t) \times T_{1F} \times w(t) - \int_0^t \gamma\, y_1(u)du,$$

where, $\varepsilon_1(t)$ is the rate of condom usage in Group 1 when in the community, and $\zeta(t)$ is the rate of condom usage in Group 1 when outside the comunity.

In Group 2, $x_2(t)$ and $y_2(t)$ are described by,

$$x_2(t + \Delta t) - x_2(t) = - \varepsilon_2(t) \times T_{2M} \times x_2(t) \times (y_1(t)/n_1(t)) - \varepsilon_2(t) \times T_{2M} \times x_2(t) \times (y_3(t)/n_3(t)),$$

$$y_2(t + \Delta t) - y_2(t) = \varepsilon_2(t) \times T_{2M} \times x_2(t) \times (y_1(t)/n_1(t)) + \varepsilon_2(t) \times T_{2M} \times x_2(t) \times (y_3(t)/n_3(t)) - \int_0^t \gamma 0 y_2(u)du,$$

where, $\varepsilon_2(t)$ is the rate of condom usage in Group 2 when in the community. In Groups 3 and 4, $x_3(t)$, $y_3(t)$, $x_4(t)$ and $y_4(t)$ are described by the formulas similar to them in Group 2.

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