Influence of Mathematical Modeling of HIV and AIDS on Policies and Programs in the Developing World

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Background: **A number of simulation models have been developed to explore the dynamics of the AIDS epidemic. There seems to be minimal impact of these models on policies and programs.**

Goal: **To describe the major findings from simulation modeling and the impact of these findings on policies and programs.**

Study Design: **A literature review to summarize the major findings that are supported by more than one modeling group.**

Results: **Simulation modeling has contributed to improved understanding of a number of issues including the demographic impact of AIDS, the value of targeting prevention efforts to high-risk behavior, the importance of controlling STDs, the benefits of early intervention, and the need for combined interventions.**

Conclusions: **Modeling has played a major role in increasing our understanding of the dynamics of the epidemic and in demonstrating how much we still need to learn. Its impact on policies and programs has been limited. The need for better translation of modeling findings to policy action will be even greater in the future.**

SINCE THE BEGINNING of the AIDS epidemic, a number of individuals and groups have developed simulation models to investigate the dynamics of AIDS. These efforts have ranged from relatively simple extrapolative models to large, complex simulation models. Among the simple models that have been widely used are EpiModel, developed by the Global Program on AIDS (GPA),[1] and the AIDS Impact Model (AIM), developed by The Futures Group International.[2] In relation to AIDS in the developing world, four major modeling efforts stand out: SimulAIDS, a Monte Carlo model of heterosexual transmission of AIDS developed initially by Bertran Auvert and colleagues during Project SIDA in Zaire[3–5]; iwgAIDS, a complex continuous simulation model of all the known modes of HIV transmission developed by Steve Seitz and others with funding from the US government[5–7]; the series of models developed at the Imperial College, London University and Oxford University by Roy Anderson and colleagues that simulate the heterosexual spread of HIV[8–18]; and STDSIM, a Monte Carlo model of the sexual transmission of HIV and four other sexually transmitted diseases (STDs) developed by Dik Habbema and colleagues at the University of Erasmus with funding from the European Commission.[19,20]

The aims of these modeling efforts have been varied. Some have sought to understand the basic dynamics of the epidemic, whereas others have investigated the impact of large-scale changes in behavior. The dissemination of modeling results has been similarly varied. The modeling work of Anderson and colleagues,[8–18] for example, has produced a large number of formal publications, whereas very few publications have been produced by the iwgAIDS group, though that model has been applied to a number of different data sets.

It would seem that such great effort should produce information that significantly influences policies and programs. The purpose of this article is to review the evidence and to try to answer the question: What has been the influence of simulation modeling on HIV and AIDS policies and programs?

This review is based on the assumption that epidemiologic and socioeconomic modeling results should influence policies and programs. Although some modeling may investigate the basic dynamics of HIV and AIDS, all the modeling efforts described here have gone well beyond that by reporting the impacts of different types of behaviors and interventions on the spread of HIV. The only reason for undertaking such studies is to increase the knowledge base on which we can design policies and programs. However, the link between modeling results and program decisions will rarely be a direct one. Program managers need to review results from different modeling studies and from other sources. The results of modeling studies will contribute to the knowledge base and, thus, influence rather than directly determine decisions. If modeling results are not used, it may not be the fault of the modeler, but rather a failure of others who act as intermediaries between the scientific community and the program managers. These

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intermediaries are often responsible for compiling and synthesizing scientific information and presenting it to program managers, donors, and other decision makers in a form that they can use. The influence of modeling results is determined by a variety of factors, including whether the modeling research addresses issues of concern to program managers, results are consistent across different models, results lead to feasible actions, and whether intermediaries are functioning to translate scientific results for program managers.

Policy and Program Implementation Process

To organize the discussion of the effects of simulation modeling on policies and programs, it is useful to consider the various steps in the policy process and how the results of modeling have contributed at each step. The major steps in the process may be described as[21]:

1. *Problem identification and need recognition.* Before there will be any policy response to AIDS, the epidemic must be recognized as a problem. Furthermore, it must be considered to be serious enough to warrant government intervention. There is a clear distinction between recognizing AIDS as a problem and deciding that there is a need for formal policies to address it. In most countries in Africa, the first AIDS cases were reported in the mid-1980s, but work on comprehensive policies did not begin until the 1990s. Governments responded to the emerging problem with a variety of incremental steps before recognizing the need for a comprehensive policy. The response generally started with a medical approach, evolved to a public health approach, and finally became a multisectoral response.
2. *Information collection, drafting, review, and approval.* Most countries that developed national AIDS policies established drafting committees or steering committees charged with overseeing the development of the first draft. These drafting committees typically seek expert advice through interviews with experts, commissioning of expert papers about key topics, or by including experts in technical subcommittees. These experts are the key conduits through which information derived from scientific research, such as simulation modeling, is provided to policy makers. Policies regarding AIDS are usually approved at one of three levels: the Minister of Health, the cabinet, or the parliament. Most guidelines and operational policies are approved by the minister of health. Comprehensive policies or those involving politically sensitive issues are generally approved by the cabinet or parliament.
3. *Implementation.* Once policies are adopted, they must be implemented. The process of developing implementation guidelines can be every bit as time consuming as the process of developing the policy. Often, many hard decisions that were avoided when policies were drafted need to be resolved when plans and guidelines are developed.
4. *Monitoring, evaluation, and research.* As programs are implemented, there is a continuing need both for monitoring to determine if implementation is proceeding according to plan and for evaluation to determine if the desired results are being achieved. These results are used to modify plans and programs in an attempt to constantly improve performance.

Influence of Simulation Modeling on Policies and Programs

There are several stages in the policy and implementation process where information generated by modeling can be influential. However, it is difficult to identify the amount of influence that modeling has had. National policies and plans rarely provide detail about why certain issues or programs were chosen and others were not. One useful source is the documents of donors that describe the rationale behind their decisions. Perhaps the most comprehensive of these documents is the book published by the World Bank, *Confronting AIDS*,[22] and the supporting papers prepared for the book.[23] Also, strategy documents from USAID describe the rational for its programs.[24] *The UNAIDS Best Practice Collection* is not useful because few of these documents present the reasons for selecting each program. Even the strategic planning guides from UNAIDS, which do present a recommended list of priority programs, do not discuss the reasons for the selection. My experience with programs in Africa and Latin America has provided much of the information in this article, although this may bias the conclusions toward those areas where this work has focused, particularly building political support.

The results of simulation modeling are particularly useful at certain stages of policy development and implementation. These include problem identification, need recognition, and implementation. In the following sections, the influence of modeling in each of these key stages is discussed.

Problem Identification and Need Recognition

Identifying that a health problem exists generally necessitates the collection of data about the number of cases and number of deaths caused by the disease. With HIV and AIDS, modeling plays a role by projecting the future number of AIDS cases and deaths that will result from current infection levels.

The most widely used model of this type was EpiModel. This model was produced by GPA to project the number of deaths that would result in the next 5 years as a result of current HIV infections. The model has been used not only for this purpose, but also to project future levels of prevalence. These projections made by GPA experts or local technicians have played a key role in alerting national decision makers to the magnitude of the AIDS problem. EpiModel is no longer widely used, but a successor program is being developed by UNAIDS that will take advantage of the additional data now available in most countries.

Several organizations have projected AIDS deaths for a number of countries as part of a larger effort to prepare population projections (US Census Bureau,[25] United Nations,[26] World Bank[27]). The number of AIDS deaths has generally not been reported by these organizations, but the impact of AIDS on life expectancy has been reported. For example, the US Census Bureau estimates that life expectancy at birth in Zimbabwe has already been reduced from 63 to 39 because of AIDS. Such alarming trends have captured the attention of the media and many politicians.

Under several USAID-sponsored projects (RAPID, POLICY, AIDSCAP, PASCA) AIM has been used to make projections of the future numbers of people infected with HIV, AIDS cases, and AIDS deaths. These projections have been used in awareness-raising efforts designed to increase political support for AIDS programs in a number of countries including Uganda, Kenya, Ghana, Ethiopia, Zambia, Zimbabwe, the Côte d'Ivoire, Madagascar, Honduras, and Panama. In several of these countries, this information has contributed to increased support for AIDS programs.

All of these models either assume a trend in HIV prevalence or use a simple curve-fitting procedure to project prevalence. They convert prevalence estimates to incidence and then calculate the expected number of AIDS cases and deaths. Perhaps because of the simplicity of these models, they have been widely applied. The information generated by these models has played a major role in alerting decision makers to the full magnitude of the epidemic, which has allowed countries to begin a serious response before large numbers of AIDS deaths occur.

National decision makers are not necessarily convinced of the need for action by projections of large numbers of AIDS deaths. They have many other health problems to consider, such as malaria, measles, and tuberculosis. Decision makers must be shown that AIDS has serious impacts on social and economic development that make it different from other diseases. Models have contributed to this process. Projections of the number of AIDS orphans have been made by UNICEF, the US Census Bureau, and by country programs using EpiModel or AIM. The astonishing number of orphans that will be created by AIDS in the coming decade has served as a powerful stimulus to action in many countries.

Several economists have developed macroeconomic models to show the impacts of AIDS on the gross domestic product and the gross domestic product per capita.[28–30] These models have shown contrary results. Some have projected severe macroeconomic impacts of AIDS, whereas others have projected that these impacts will be slight. This confusion has limited the impact of these studies, though many donors continue to think that better studies of the economic impact would illustrate clearly to national decision-makers the costs of doing nothing.

The AIM model has been used to project the healthcare impacts of AIDS in terms of increased expenditures for care, the large portion of hospital beds devoted to patients with AIDS, and increases in tuberculosis cases as a result of AIDS.[31–33] Other models have also addressed the problem of AIDS and tuberculosis.[34] This interaction is increasingly seen as one of the major healthcare impacts of AIDS.

Little modeling work has been done to show the other potential socioeconomic impacts of AIDS. Models have not addressed the impact on the family, firms, or economic sectors, though these issues are of great interest to policy makers.

Simulation modeling has been useful in showing that interventions can make a difference, a message that dispels the notion that there is little we can do. Almost all of the complex simulation models have been used to make this point. However, because few have been used to model country-specific situations in detail, this point has had more influence on donors than on national decision makers.

Models have also shown that early intervention makes a difference. This point has been used to urge nations to develop effective prevention programs even before the epidemic becomes severe. Some countries, such as Senegal, have responded to this argument with effective actions. Overall, the time from the identification of the first AIDS case and the initiation of a national AIDS Control Program has declined from 4.7 years during 1980 to 1984 to the establishment of programs an average of 1 year before the identification of the first AIDS case during 1990 to 1994.[23]

Information Collection, Drafting, Review, and Approval

A key component of most policies is goals that describe in quantitative terms what the policy is trying to achieve. Goals can be set for political purposes, where catchy slogans are adopted (e.g., "Health for all by 2000") with little idea of whether the goal can actually be achieved. Goals can also be scientifically based and used to provide real program direction and evaluation. Modeling can be essential to setting quantitative goals by illustrating what levels of improvement might be expected realistically and what programs would be needed to achieve that result. There are few examples of such goals for AIDS, however. The Program of Action of the International Conference on Population and Development[35] does call for a 25% reduction in new HIV infections among the 15-year to 24-year age group by 2005 to 2010. This goals seems to have been derived from several modeling studies that showed such a reduction could be achieved with a combination of programs for behavior change, condom promotion, and STD control. However, there is no evidence that this goal has had any influence on national policies or donor funding. In the USAID strategic plan for health and population, the goal relating to AIDS merely calls for a "reduction in the number of new HIV infections."

Implementation

One of the key roles of simulation modeling should be to help high-level decision makers and program planners decide what should be done and what resources are needed to achieve the goals. There are no examples of country programs that routinely use simulation modeling to guide key program decisions. Any influence of modeling on these decisions has resulted from published results based on hypothetical data sets or on data pertaining to particular countries. The general lessons learned from such modeling exercises may be picked up by programs in other countries. The following describes some of the key findings from simulation modeling that have been published and the impact these findings have had on national and donor programs:

Targeting. This is perhaps the one concept where modeling has had the most influence. Simply stated, the concept of targeting is that "targeting interventions to those most likely to become infected and most likely to transmit infection is the most effective strategy." A number of simulation models have shown this concept to be true for all epidemic stages. Among donors and program managers, there is general acceptance that targeting is an appropriate strategy early in the epidemic, though there is less agreement about the value of targeting in generalized epidemics.

Importance of controlling STDs. Research of risk factors for HIV infection first showed the enhancing effect of STDs on HIV transmission. Subsequent modeling studies have shown that controlling STDs can contribute significantly to reducing HIV transmission. Nevertheless, donors and country programs generally cite the research regarding risk factors rather than modeling efforts as the rationale for including STD control programs in their prevention efforts. However, the European Union has been interested in the information that modeling could provide to fund a large effort that would develop a comprehensive STD simulation model (STDSIM, University of Erasmus). It is not clear what effect this effort has had on European Union funding decisions. A major boost to STD programs was provided when the results of the Mwanza STD research were published. This research showed that improving the treatment of symptomatic STD in rural areas of Tanzania could significantly reduce HIV incidence. The "hard" data provided by this research is consistently cited as a reason for including STD control in all AIDS prevention programs.

Mass treatment of STDs. Mass treatment of STDs was first proposed as a strategy to reduce HIV transmission in the late 1980s. Because experiments to test this strategy are expensive, it would seem likely that simulation modeling could play a key role. In fact, several major simulation models (iwgAIDS, SimulAIDS) tested this strategy and found that it would not be effective. The models showed that mass treatment could reduce STD prevalence to low levels, but that STD prevalence would quickly recover to pretreatment levels shortly after the mass treatment ended. Despite these findings, a major trial of mass treatment was undertaken in Rakai, Uganda. The surprising results of this trial were that mass treatment did reduce STD prevalence significantly, but did not effect HIV incidence, even during the treatment phase. These results were not predicted by modeling, and several different interpretations have been offered to explain them, including the reduced importance of STDs in advanced epidemics. An application of SimulAIDS to the Rakai population, which was undertaken before these results became known, reported that STDs were the major factor in HIV spread in the area, though the authors did note that the importance of STDs diminished as the epidemic progressed.[4] Interestingly, the STDSIM model will now be used to try to duplicate the results of both the Mwanza and Rakai experiments and to explain the seemingly contradictory results.

Combination of intervention is best. Most simulation models have shown that a single prevention program (e.g., condom promotion, STD control) is by itself unlikely to produce a dramatic decline in HIV prevalence. A combination of programs is needed to reach a large enough portion of the population to significantly reduce HIV prevalence. Most national and donor programs reflect this understanding. It is difficult to determine how much these modeling results have contributed to this understanding, but it is likely that programs would have been willing to adopt a "magic bullet" approach if modeling had indicated that results could be achieved by implementing a single program well.

Early intervention yields the greatest impact. Every modeling effort that has addressed this question has found that early intervention is more cost effective than late intervention. As already mentioned, countries have been responding earlier to the epidemic than in the past. It is difficult to determine how much of this early response is due to the results of modeling and how much is due to the finding that countries that are just now experiencing the beginning of an epidemic can clearly see the consequences of a serious epidemic by looking at the hardest-hit countries in Eastern and Southern Africa. It is likely that modeling has simply supported this conclusion. However, it is also likely that if modeling had shown no benefits to early intervention, the response of many countries would have been different.

Prevalence plateau may not be a sign of program success. In most mature epidemics, HIV prevalence stops increasing at some plateau level. Modeling has consistently shown that such a plateau can be the result of the natural dynamics of the epidemic, and does not necessarily indicate the success of prevention efforts. Without this information, it is likely that many programs would be congratulating themselves on success in halting the increase in prevalence and expecting similar success in reducing prevalence without much additional effort. What is uncertain is how much the AIDS models developed in the last decade have contributed to this understanding, or whether previous experience with disease dynamics would have been sufficient to get this point across.

Rates of partner change and concurrent partnerships. The results of several modeling efforts, especially those of Roy Anderson and colleagues,[9,12,15] have shown that the rate of partner change is one of the key factors influencing the speed and size of the epidemic. Similarly, Kretzschmar and Morris[36,37] have demonstrated that the proportion of concurrent partnerships has a powerful influence on the speed and size of the epidemic. Although there is little evidence that this understanding has influenced program design to any great extent, it has certainly influenced research and evaluation efforts. Several of the key prevention indicators developed by GPA, UNAIDS, and USAID are designed to measure rates of partner change and concurrent partnerships. If these indicators are seriously applied, they will eventually influence program decisions by showing which interventions improve these indicators and which do not affect them.

Importance of bridge populations. Morris and others[36–38] have used network models to show the importance of bridge populations to the spread of HIV. Bridge populations are those persons who have contact with high-prevalence groups (e.g., commercial sex workers, urban populations) and low-prevalence groups (e.g., monogamous wives, rural populations). If the bridge populations are small and easy to identify, then interventions with them could effectively protect large numbers of people in low-prevalence groups at a low cost. Some bridge populations are easy to identify, such as clients of commercial sex workers and persons in traveling professions. However, these populations may not be easy to reach with targeted interventions. Work is underway to characterize bridge populations in some settings and to identify characteristics that might be useful for program targeting.[38]

Focus on the young. Some modeling work, particularly that of Stoneburner and colleagues,[39] shows that as an epidemic matures, the distribution of incidence shifts toward the youngest age groups. Results from HIV surveillance studies also show an increasing proportion of incidence among the youngest sexually active age groups. This evidence has influenced most programs to identify adolescents as a key target group. Surveillance systems are being revised to focus more on tracking infections among this key group. However, as with many other issues discussed here, it is difficult to determine how much influence modeling has had as opposed to the evidence of surveillance systems.

Voluntary counseling and testing. There has been a debate in recent years about whether counseling and testing is a cost-effective strategy to prevent HIV infections. The program in Uganda has included counseling and testing for many years, and has shown the demand for these services. Self-reports of behavior change have shown that these programs do have an effect. Recently, programs in Tanzania and Kenya have reported similar results. In an interesting use of modeling, the AVERT model[40] was used to translate reported behavior change to estimates of infections averted, which were used to determine the cost per infection averted. The results showed that voluntary counseling and testing can be as cost effective as STD treatment programs. At least partially in response to these findings, voluntary counseling and testing programs are being implemented in a large number of programs.

Mother-to-child transmission of HIV. Since 1994, studies have shown that mother-to-child transmission of HIV can be reduced through a variety of programs, including treatment of the mother and newborn child with zidovudine, the avoidance of breastfeeding, and cesarean delivery. Even with the discovery that short courses of zidovudine can be effective, these treatments are expensive for high-prevalence countries. For low-prevalence countries, the treatment itself might not constitute a major expenditure, but the massive counseling and testing effort to locate HIV-infected women could be a major expense. Breastfeeding is a major transmission mode in many countries, but replacing breastfeeding with breastmilk substitutes can increase child deaths due to other causes. Several models have recently been developed to analyze the effects of different program configurations on child survival and cost per infection averted.[41–45] These programs are just starting to be used in program planning in some countries, and could make a significant contribution to program design in the near future.

Antiretroviral therapy. The demonstrated effectiveness of antiretroviral therapy (HAART) on controlling HIV infection in developed countries has led to an examination of the potential role of HAART in developing countries. Trials are underway in several countries to test the efficacy and expense of such treatments. Recently, models have begun to explore the cost effectiveness of HAART in various settings.[46] These models have had limited use to date, but promise to contribute significantly to future program planning.

Monitoring, evaluation, and research. Modeling can be used to help establish monitoring, evaluation, and research priorities and systems. The most common use is in evaluation. Simulation models can be used to determine if changes in HIV or STD prevalence are consistent with the implemented interventions or whether the changes are likely due to other factors. STDSIM has been used to evaluate the results of the Mwanza and Rakai STD studies to determine if the results are potentially consistent or contradictory.

Conclusions

Modeling has contributed significantly to the effort to control the AIDS epidemic, but not always in ways that might be expected. The relatively simple models that project HIV prevalence and the future number of AIDS cases and deaths have played a major role in building political commitment to confront the epidemic. The more complex simulation models have been used to confirm the effectiveness of specific prevention approaches (e.g., the benefits of early intervention, importance of STDs, need for a combination of interventions). Simulation models have also contributed to the understanding of the importance of targeting. However, it is difficult to point to specific aspects of today's AIDS control programs that would be different if no simulation modeling had been undertaken. Many conclusions from modeling studies have not been accepted by donors and program managers unless they have been confirmed by experiments.

Simulation modeling has pointed to new areas of importance, such as rates of partner change and concurrent partnerships, and has stimulated thinking and research in these areas that may eventually effect programs. Modeling has helped to convert measures of behavior change into cost effectiveness of infections averted (e.g., by substituting for costly experimentation in the field of voluntary counseling and testing). Simulation models are also being used to help understand the results of operations research, particularly regarding apparently conflicting results of the STD treatment trials in Mwanza and Rakai.

The translation of simulation modeling results to policy and action suffers from the same problems that affect most research. Modelers do not necessarily see it as their role to ensure that policy makers understand and use their results. Policy makers often think that modeling is not understandable, answers the wrong questions, or suggests unrealistic solutions. Better mechanisms to translate modeling results into information that is usable by policy makers are needed to enhance the impact of modeling research on HIV and AIDS policies and programs.

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