Modelling the HIV-AIDS Epidemic in Southern Africa

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Abstract
L'epidemia di HIV-AIDS in Sud Africa è una crisi nazionale che sta mobilitando ricercatori da un'ampia gamma di discipline, compresa la modellizzazione epidemiologica. Questo articolo introduce l'epidemia sudafricana di AIDS, descrive una recente collaborazione con l'Istituto Pasteur su una "micro-simulazione" e analizza possibili strade per una collaborazione con il CILEA in questo campo.

The HIV-AIDS epidemic in South Africa is a national crisis that is mobilising researchers from a wide range of disciplines, including epidemiological modelling. This article introduces the South African AIDS epidemic, describes recent collaboration with the Pasteur Institute on “micro-simulation” computer modelling, and looks at possible avenues for collaboration in this area with CILEA.

Keywords: Modellizzazione epidemiologica, Micro-simulazione, Supercalcolo.

HIV-AIDS: a national crisis for South Africa
Recent results published in the “South African National HIV Prevalence, HIV Incidence, Behavioural and Communication Survey, 2005” (published by HSRC Press, available online at www.hsrc.ac.za) show that in 2005, 11% of the South African population aged 2+ was HIV positive, or approximately 5 million out of a population of about 42 million. This astonishing HIV prevalence is the result of a steady rise since about 1990, as seen in figure 1, a graph of prevalence in pregnant women (mainly poor and Black) attending state antenatal clinics, plotted against time. Antenatal clinic prevalence is an important indicator of the epidemic. It is commonly accepted that the prevalence in this group is similar to that in Black women in general in the equivalent age group, although this is disputed by some experts. Nationally, antenatal clinic prevalence was 30% in 2005, and in KwaZulu-Natal a staggering 40%.

As is the case for pregnant women, the situation looks worse than the national average when one looks more closely at sections of the population, for HIV prevalence is not evenly distributed by region, age, gender and race. In KwaZulu-Natal, the worst affected province, overall prevalence for age 2+ is 16.5%. Nationally, women have a higher prevalence (13.3%) than men (8.2%). Furthermore, HIV prevalence depends strongly on age, with the highest levels amongst the sexually-active, mostly young, adult population. Nationally, in the 15-49 age group, HIV prevalence is 16%, and prevalence generally peaks in the late 20's for women and early 30's for men, as shown in figure 2. HIV prevalence affects mainly the Black African majority race group (13.3%), and is much lower in the minority race groups (less than 2%).

The role of epidemiological modelling
Faced with an epidemic of this magnitude, epidemiological modelling has an important role in research and strategic planning, to improve understanding of the dynamics and impact of the epidemic, and to help to design treatment and prevention strategies.
In addition to modelling the epidemic in the population, computational modelling is being applied to the interaction of the virus with the immune system, bio-medical action of treatment, and HIV-tuberculosis co-infection.
Fig. 1 - National antenatal clinic prevalence plotted against time.

Fig 2 - HSRC population survey of HIV prevalence, showing distribution by age and gender.
Modelling at different scales could be combined, for example, at the small scale, virus-body interaction in an individual, and at the large scale, each individual a member of a population. This would require supercomputing power for large systems.

A “micro-simulation” models a population as a collection of individuals. Each individual is a distinct agent with a set of characteristics, such as age, gender, marital status, relationship status, sex worker or client status, and HIV status. Specific relationships with other individuals are formed, tracked and dissolved, and the history of an HIV infection is followed. By contrast, a “macro-simulation” represents a population as a set of interacting groups. The number of individuals in a group is specified, but nothing is known about specific individuals or their relationships.

The Pasteur HIV-AIDS micro-simulation model

A micro-simulation project is currently underway as a collaboration between the author, and the Pasteur Institute’s Epidemiology of Emerging Diseases Unit in Paris, France. Funding for the project has been provided by the International AIDS Society, the France-South Africa International Cooperation Programme and the South African Centre for Epidemiological Modelling and Analysis. The objective is the development of a micro-simulation code applied initially to the Zambian HIV-AIDS epidemic, with extension to the South African epidemic. The object-oriented code, written in C++, is called “PHEM”, for “Pasteur HIV-AIDS Epidemic Micro-simulation”. From a demographic point of view, it models a stable population in which proportions of men and women in different age groups, as well as proportions married, remain constant with time.

A major part of the structure of PHEM is a model of the different types of sexual partnerships in the population, including the single state, and transitions between partnership states. An individual moves from a single, sexually-inexperienced state, into a marital or non-marital partnership, and may in turn move into a divorced, separated or widowed state. Proportions of the population in each state, and the transitions rates between states, are determined by data from demographic surveys.

One of the main questions to be addressed by PHEM is why HIV prevalence is so much higher in young women than young men. One hypothesis to be investigated is “healthy carriage”, in which a man in contact with an HIV positive woman receives an HIV infection confined to his skin, but otherwise remains uninfected and healthy. The superficial infection lasts a week or so, and if in this time he has contact with another woman who is HIV negative, she could become infected. The net result is that a man passes HIV from an infected woman to a previously uninfected woman, but remains HIV negative in the process. The Healthy Carriage hypothesis may explain why young women in Southern Africa have a much higher prevalence than the young men from which they draw their partners.

Because the age structure of HIV prevalence is a central research question in this project, it is important to incorporate a good model for the age preference of sexual partnerships. It has proved to be a difficult problem, since the allocation of ages of partners must simultaneously produce a good fit to observed patterns for men and women. It has been solved by developing a selection algorithm analogous to a market-bidding process.

The epidemiological model is based in the demographic structure – the matrix of sexual partnerships within the population. HIV infection spreads, and an HIV infection leads to AIDS and death, typically after 10 years. Epidemiological factors affecting the epidemic are infection probabilities, rate of sexual contacts, rate of progression to AIDS, and possibly healthy carriage. Additional aspects that could be included are condom usage, circumcision, increased infectivity due to other sexually transmitted diseases, tuberculosis co-infection, and effect of antiretroviral treatment.

Computationally, PHEM runs at present for a simulated time of 25 years in a weekly cycle, computing births, formation and dissolution of partnerships, sex work, contacts outside partnerships, HIV infections, AIDS deaths, non-AIDS deaths, and ageing. Initial results show reasonable agreement with observed HIV prevalence patterns by age and gender, but work is still in progress to produce publishable results.
The need for supercomputing power

When the PMEM code has been completed and tested, it will be interesting and necessary to scale up the size and possibly the complexity of the system. This will require supercomputing power. At present, the simulation runs on a PC with a population of 100,000. The South African population is about 42 million, and although a sample of 100,000 may give us all the results we need, there may be unexpected results that emerge if the full population is modelled. In any case it will be interesting to try. If it does turn out that the best results come from modelling the actual population size, then parallel supercomputers will be indispensable, especially if the model is ever applied to the populations of China or India!

Other extensions of the model that would benefit from supercomputing are modelling of spatial effects such as migration, increased complexity in modelling relationships and events, more detailed modelling of HIV infection and treatment, and inclusion of co-infections such as tuberculosis. Multi-scale modelling, in which each individual is in turn modelled as a virus-host system, will require supercomputing, as will an expanded socio-economic model in which the HIV epidemic is a sub-system in an interlocking web of social and economic structures.

Opportunities for Cooperation?

Parallel-processor supercomputing is very likely to be needed for HIV-AIDS micro-simulation, and consequently there is scope for fruitful cooperation between the University of KwaZulu-Natal and CILEA. This cooperation would not have to be confined to epidemiological modelling, but could extend to other areas such as physics. An obvious area of cooperation would be the provision by CILEA of supercomputing time. Another area is training, with CILEA instructors running courses in Durban, or UKZN staff and students spending time in Segrate. CILEA could provide valuable assistance with setting up UKZN’s 32-node machine, and with parallelising codes. Whatever mode of cooperation is found, there is benefit to be derived in applying CILEA’s supercomputing capacity to the AIDS crisis in South Africa, through the South African epidemiological modelling research programme.