The United Nations and the Quest for the Holy Grail (of AIDS)

Team 787

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Abstract

The HIV/AIDS pandemic has grown to immense proportions, establishing itself as the fourth leading cause of death worldwide. In response, worldwide interest in HIV treatments has grown, but uncertainty in how to go about funding these treatments remains. Nations must choose between the most effective combinations of sexual education, antiretroviral treatments (ARV) and HIV vaccine research. Our paper aims to quantify the effects of each of these treatments in order to best confront AIDS.

We propose an iterative deterministic model for measuring the progress of HIV through 2050. In this model, the HIV-population at each time is a function of the previous HIV-population, plus the net new cases for that year. Hence, the crux of our model is developing expressions that accurately predict the infection and death rates due to HIV. Our model is adapted to account for the three main factors in HIV transmission: unprotected intercourse, non-sterile drug needles and births of children to HIV-positive mothers. Furthermore, we analyze country-specific parameters, such as a prevalence of HIV among certain populations (such as homosexuals) as well as condom usage and risky sex rates. We model the influence of advanced treatments (such as ARV and vaccines) on countries varying in each of the input parameters described. Additionally we investigated the impact of multiple drug resistance on combating HIV in developing nations.

We first approach historical data to evaluate our model in relation to recent historical trends. Using data extrapolated from South African antenatal clinics, we demonstrate our model's capacity for creating accurate predictions from the specified input parameters.

Our goal is to assess which methods minimize the number of HIV cases in both the short and long run, and use this data to guide policy decisions which will best approach the HIV pandemic. We found that condom usage, ARV therapy and an HIV vaccine all have significant effects on the course of HIV development. Current aid efforts including sexual education which reduced risky sex and promoted condom use were very valuable.

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They have helped contribute to the leveling off of the outbreak in South Africa. We predict that these trends will continue, and that the scope of the HIV outbreak is in the first stages of receding. ARVs, however, receive a mixed review. After a review of the literature, we determined that no consensus exists on how ARVs affect transmission rate. We modeled that, if, as some sources have proposed, ARV does not decrease the transmission rate of HIV, its widespread use may actually increase the scope of an outbreak. However, if it decreases transmission rate, it can be an important factor in containing HIV. We also conclude that vaccines provide the greatest promise for the long term treatment of HIV.

We also propose an economic model for distributing resources. Even in the presence of an upcoming HIV vaccine, we reveal that there are important economic considerations that promote ARV usage. We finally recommend universal sexual education, distribution of ARVs based on infection profiles and adequate endowment for research into finding a vaccine, the holy grail of HIV.

Contents

1 Introduction

Since its recognition in the early '80s, the HIV/AIDS epidemic has killed an estimated 25 million people (UNAIDS 2005). Rates of infection continue to increase across the world, especially in Eastern Europe and Asia. HIV also continues to spread in many other areas of the world, with the greatest concentration in Africa. The statistics involved in the African AIDS crisis are staggering: in some regions on the continent, it is estimated that as many as one out of three people may have HIV/AIDS.

Global mobilization in response to AIDS is very much a work in progress. Compounding the recency of the discovery of the virus, HIV rates in many countries worldwide have only recently become regularly monitored. Hence a large body of historical data on which to extrapolate does not exist, and institutions to provide global support are not entirely in place.

The magnitude of the HIV/AIDS outbreak is a clear indicator of the need for global action. Current foreign aid has been focused around AIDS prevention through sexual education, including the promotion of abstinence and safe sex. These programs have included education about condom usage, which has been of varying success. Some notable gains have been made, for example in South Africa, where the condom usage rate is now over 50%.

However, HIV/AIDS remains a major factor in public health. Despite the slow of new cases in South Africa, AIDS is a major cause of death. To account for AIDS, the life expectancy of the average citizen in South Africa is reduced by 19 years, from 66 to 47 (Economist 2002). Hence, current efforts focus on developing improved prevention in hopes that the infection rate can be decreased to a manageable level.

HIV/AIDS prevention can take several forms. The current frontline defense against the virus internationally is safe sex education, including condom instruction and distribution. However, future aid will most likely take one of two forms: large-scale anti-retroviral therapy (ARV) and, eventually, an HIV/AIDS vaccine. The effectiveness of vaccine therapies on disease has been well demonstrated in the past. Vaccines are largely attributed with the virtual elimination of diseases such as smallpox and polio. The major difficulty is the actual development of a vaccine. Though there are over 17 vaccine therapies in various stages of testing, thus far HIV has proven rather diffcult to properly immunize against. ARV is a much newer viral therapy that has never been tried as a large scale preventative defense tactic. It is well established that ARV increases the lifespan of infected individuals by delaying the onset of AIDS. The effectiveness of ARV as a large scale treatment would hinge not on extending lives but on reducing the transmission rate of infected individuals taking ARV. However, there is no consensus about ARV's effect on transmission rate (see Anderson 1992 as well as Krieger, 1991 and Royce 1997).

This paper aims to examine each of these possible prevention techniques, and determine their effectiveness in fighting the HIV/AIDS epidemic worldwide. We will focus on several countries selected for the diversity of the origin of their outbreak and their ability to be extrapolated to other outbreaks. South Africa has a large HIV/AIDS population, but little drug use. India has an enormous population and a small but growing AIDS presence. Russia has a large HIV-positive injected drug community. The United States has a fairly small HIV population (clustered among its homosexual population) which is limited by the high safe sex rate. We will also examine HIV/AIDS population trends assuming no treatment methods are added to the status quo.

2 Experimental

2.1 Overview

An important factor in the continuation of an epidemic is known as R_0 (Velasco-Hernandez 2002). R_0 is a measure of the reproductive rate of the disease. An R_0 of 1 implies that each HIV carrier infects one other person before death. An epidemic spreads only if R_0 is greater than 1. A treatment is only considered preventative if it decreases the reproduction rate. (Hence, a hypothetical treatment which extends the lifespan of a victim, but does not lower his transmission chance may in fact be detrimental to the elimination of the disease). The idea of mapping an epidemic in terms of R_0 lends itself to the creation of an iterative deterministic model. In this paper, we describe the creation of such a model. In each iteration, the number of new HIV/AIDS cases is a function of the previous state of the system, along with the expected rate of disease transmission. Hence,

$$R_0 \propto \frac{d(total\#aids)}{d(time)}.$$

As R_0 changes extensively over time, we discuss results in terms of trends and total HIV-positive populations, instead of quantitative values of R_0.

The model determines the change in HIV/AIDS victims based on both new cases of HIV as well as deaths of previous HIV victims due to AIDS. In order to accurately model HIV/AIDS transmission, many factors need to be taken into account. There are three primary vectors for the transmission of HIV: unprotected sexual intercourse, use of 'dirty' (reused) drug needles and childbirth by HIV-positive mothers. These factors are balanced against the death rate in order to determine the net number of new HIV cases. We use a feedback-based model for death, where the number of AIDS deaths is based on the expected lifespan of an HIV victim and the number of victims who contracted HIV at specific previous timepoints.

In its most complex form, the model is able to account for new cases from birth, dirty needles and intercourse as well as impact from a hypothetical vaccine and ARV treatment simultaneously.

2.2 Basic Model

In mathematical terms, the general system of the previous section can be written as:

$$\#aids(t) = newInfections(t) + \#aids(t-1) - deaths(t)$$

where t is the number of years, $\#aids(t)$ is the total number of HIV/AIDS victims at time t[1]. Our initial point, t_0, is the year 2000. Values at indices $t < 0$ are taken from historical data. As the model is elaborated, the use of historical data will be discussed in more detail. As stated in the overview, the net number of new infections is determined by both new HIV carriers as well as deceased AIDS patients.

2.2.1 New Infection Rate (due to unprotected sex)

The basic form of the model assumes that HIV transmission only occurs during sex, that is, $newInfections(t) = intercourseT(t)$, where $intercourseT(t)$ is the number of new HIV victims due to unprotected sexual intercourse[2]. This assumption will be refined later in the paper, where we describe models for other methods of transmission.

We model HIV transmission due to sex as related to the number of instances of intercourse times a base rate of transmission per sex act(taken from the results of Smith 2005). Note that the base transmission rate male→female is twice as high as the rate female→male. We denote the number of instances of intercourse by ρ. ρ represents a general risk factor. Each expected instance of typical heterosexual sex represents a ρ of one. Hence, using numbers from the European Study Group on Heterosexual Transmission of HIV, we assume an average intercourse rate of 3 times per week, or about 160 times per year. Taking into account heterosexual anal intercourse causes an increase of the risk factor to 200 (or more).

Since we are assuming primarily heterosexual intercourse, we keep the HIV/AIDS population of each gender separately. For example, the number of men that get HIV at time t is related to the number of females that have HIV at time t-1. Likewise, only men without HIV can get HIV, so the rate is dependent on the percentage of HIV-free men. These factors are multiplicative because of linear independence. Note that we use the symbol ♂ to denote a function (or

[1] To facilitate readability, function and variable names are given descriptive names whenever possible.

[2] We realize that terms such as these are a delicate subject, but we feel that being direct provides a valuable level of clarity.

variable) that includes only men, and ♀ to denote a function including only women. For example, $intercourseT_{♂}(t)$ is the number of men who contract HIV due to heterosexual intercourse. Hence we represent our $intercourseT$ rates as

$intercourseT_{♂}(t)$=percent unaffected men *number of affected women * (1-condom use) * risk constants

That is, for men:

$$intercourseT_{♂}(t) = \rho * riskSexCons_{♂} * (1 - condomRate) * \#aids_{♀}(t-1) * (1 - \%aids_{♂})$$

and for women:

$$intercourseT_{♀}(t) = \rho * riskSexCons_{♀} * (1 - condomRate) * \#aids_{♂}(t-1) * (1 - \%aids_{♀})$$

Assumptions made in Section 2.2.1

- Condom usage is constant over time. This assumption is not implicit in the model (for condomRate could easily be made a function). However, it provides a worst case scenario (i.e., it maximizes the impact of HIV). It is very unlikely that condom usage would decrease (as it is a function of social education and it is unlikely for a person who uses condoms regularly to stop) if sexual education programs follow the status quo. It is far more likely that condom usage will increase as education programs become increasingly well funded and organized. Static condom usage rates also allow other model parameters (such as ARV usage) to result in clearer trends and makes the model overall more robust.

- Condoms are 100% effective. This assumption is very close to reality (condoms are over 99% effective) and is a useful simplification that results in very little accuracy loss.

- All sexual acts have the same chance of infection. This is close to true since the chance of infection is very low. When the replacement rate is approximately 1 over the course of a lifetime (which almost always turns out to be true), the difference between the transmission rate in a monogamous relationship versus having multiple sexual partners becomes small.

2.2.2 Death Rate

Tragically, most carriers of HIV will eventually die of AIDS. (Recall from the introduction that AIDS has caused the South African average lifespan to decrease by 19 years). On average, it takes 9 years for an HIV infection to become AIDS(Morgan 2002). We assumed that regular sexual activity stopped when symptomatic AIDS occurred, but this may not be the case. Hence, the number of years of activity after HIV infection should be between 9-10 years. We denote this parameter as $averageDeath$. We used the low-end estimate to tighten the

feedback loop in the model. Our key assumption is that all HIV victims will die of AIDS. Hence, we use a feedback loop to represent the death rate:

$$deaths(t) = newInfections(t - averageDeath)$$

Assumptions made in Section 2.2.2

- Each HIV carrier will die of AIDS. This is a major simplifying assumption, which prevents the necessity of keeping track of population ages. Overall it will cause a (slight) increase in the average lifespan of the HIV carrier, and hence is a worst case scenario estimate. This assumption is also tempered by our treatment of ARV. While ARV increases lifespan, we assume that the average age of HIV contraction + the new lifespan cannot be over the life expectancy. This minimizes the impact of this assumption.

- Each HIV carrier dies after being infected for exactly $averageDeath$ (that is, 9) years. This simplifies the model by reducing individual variation. As we look at the population in aggregate, it makes sense to give our parameters the mean values.

2.3 Additional Model Parameters

2.3.1 HIV Transmission Due to Reproduction

A major social impact of HIV/AIDS is the creation of an orphan population whose parents have both died of AIDS. This can be fairly common in such countries as South Africa, with large percentages of HIV infected adults. However, the birth of HIV-infected babies does not greatly impact the rate of new HIV cases. This is because they die before they are able to participate in any of the forms of HIV transmission (intercourse, drug needle use and childbirth). The values used for risk of transmission at childbirth was up to 35% in undeveloped countries and around 1-5% in the first world (UNAIDS 2005). Transmission due to childbirth was calculated as:

$$birthT(t) = birthRate * \#aids_{\varsigma}(t-1) * riskBirth$$

Assumptions made in Section 2.3.1

- All children die before contributing to the spread of HIV/AIDS. Given that the average lifespan of an HIV patient is about 9 years from the point of contraction (which, in this case, is at birth), it is extremely likely that this assumption has negligible effect.

- Women with AIDS are as likely as other women to have a child. This is likely nearly true, because in undeveloped countries, awareness of HIV is fairly low, while in the first world the chance of contraction of the disease by the child is low. However, because of the previous assumption, this assumption has very low impact on the model.

2.3.2 HIV Transmission Due to Infected Drug Needles

Drug needle sharing is an important factor in HIV transmission in many countries, including India and Russia. Incorporating drug needles, we create a new expression for the infection rate:

$$newInfections(t) = intercourseT(t) + needleT(t)$$

We calculate the needle transmission rate based on a drug risk factor ρ_D, which is equal to the approximate number of drug injections an average drug user has per year. We also assume the dirty needle rate is a constant 35% (UNAIDS 2005). We also account for the gender inequality in drug use, which is an 80/20 male/female split. We take the risk of infection from a single drug use ($riskDrugCons$) from the European Study Group. Hence, the drug transmission rate is:

$needleT(t)$ =number of drug users HIV negative * chance of sharing a drug needle with someone HIV positive * risk factors and constants

$$needleT(t) = \rho_d * riskDrugCons * \#HIV^{-}DrugUsers_{\sigma'} * .35 * \%HIV^{+}Drug$$

Assumptions made in Section 2.3.2

- Constant dirty needle rate. Again, this is a worst case scenario analysis.
- For each individual drug use, the chance of HIV transmission is the same. This assumption follows the same logic as the last assumption in section 2.2.1.

2.3.3 HIV Transmission Due to Homosexual Intercourse

In most countries affected by HIV, HIV/AIDS is not associated with the homosexual community. Rather, much more common carriers of the virus are (heterosexual) sex workers. In the United States, however, a disproportionate portion of HIV victims are homosexual. In the model, transmission due to homosexual intercourse was computed very similarly to $intercourseT(t)$. The major change was the that the homosexual population was modeled, and it was assumed that members of the homosexual community had solely homosexual sex. Also, due to the form of sexual intercourse among homosexual men, a different risk per sexual act constant was used (also taken from the European Study Group).

$intercourseT_H(t)$=percent unaffected gay men *number of affected gay men * (1-condom use) * risk constants

$$intercourseT_H(t) = \rho * riskSexCons_H * (1 - condomRate) * \#aids_H(t-1) * (1 - \%aids_H)$$

2.3.4 Antiretrovirals

The foremost effect of antiretrovirals, or ARVs, is not to prevent the transmission of HIV but rather to extend the lifespan of infected individuals. As mentioned in the introduction, there is not yet scientific consensus on the effect of ARV on the transmission of HIV. Hence, we incorporated this effect as an input parameter of our model ($arvFactor$). $arvFactor$ can vary between .25 (from one estimate which states that ARV reduces transmission by 75%) to 1 (if it has no effect on transmission rate). Another input parameter was $arvPortion$, the percentage of HIV-positive individuals that received ARV treatment. We implemented ARV by assuming that large-scale treatment would begin at a given year (usually around 2015), representing the deployment of an infrastructure which was constructed in the years preceeding the ARV program. This presents ARV as a form of treatment as a vaccine would be: a large scale, top-down, governmentally supported attempt to control the spread of HIV. We also assume that ARV patients have a slightly decreased amount of risky sex, due to the increased sexual education caused by repeated contact with health personnel (over the course of their treatment).

To model ARV, we calculated the HIV transmissions due to ARV patients and other HIV victims separately in order to account for changes in the transmission rate of ARV patients:

$$newInfections(t) = \\ intercourseT(t) * (1 - arvPortion) + intercourseT(t) * arvPortion * arvFactor$$

We assume 100% adherence (except when talking about resistant strain development, see below).

2.3.5 Drug Resistance

A risk involved in antiretroviral therapy is the creation of treatment-resistant strains of HIV. This occurs when an ARV patient follows his treatment regimen incompletely. It occurs because selection pressures on the virus eases, allowing HIV to once again replicate in greater numbers. If the newly replicating HIV strain has evolved to become more capable in replicating in the presence of ARV, a resistant strain is born.

We model drug resistance using the parameters given in the prompt. ARV-resistant infections are tracked separately, so that, while ARV-resistant carriers may continue to take ARV, they will not benefit. The number of new ARV-resistant strains that develop as a direct result of missing ARV treatments is modeled as:

$$newInfections_{resistant}(t) = \%\text{ aids victims on ARV *(1-adherence rate)*chance to mutate}$$

We assume that 85–95% of ARV patients adhere to treatment(Rutenburg 2006). This data refers to ARV pilot programs; in a system that is well organized (like the one we suggest), the ARV adherence rate may be even higher.

2.3.6 The Holy Grail, or, The AIDS Vaccine

When one hears mention of 'The cure for AIDS', usually that reference is referring to a vaccine which prevents HIV infection. We model an HIV vaccine by assuming that, as increasing amounts of immunization occur, a growing portion of the population is unable to contract HIV. This is in direct contrast to the way in which ARV affects HIV/AIDS rates. For example, in one of the equations from section 2.2.1 (repeated here):

$$intercourseT_{\female}(t) = \rho * riskSexCons_{\female} * (1 - condomRate) * \#aids_{\male}(t-1) * (1 - \%aids_{\female})$$

The term which determines which portion of the population is able to catch HIV

$$(1 - \%aids_{\female}) \text{ becomes } (1 - \%aids_{\female} - \%vaccinated)$$

The vaccination rate for both men and women are the same. Hence, no gender subscript is needed.

To simulate the number of vaccinated individuals within the population at any point in time ($\%vaccinated$), we fitted the percentage of vaccinated individuals in the population over time with a logistic curve. We assumed that a vaccine will be available by the year 2015 and that the government of each country will employ a well regulated vaccine program to achieve steady state vaccination by 2030. The curve started at 0% and plateaued at a steady-state level - identified by the second dose of the tetanus toxoid rate for that country as reported by the WHO (2002). The logistic curve was used to trace the percentage of vaccinated individuals in the population over time for several reasons:

- the initial rate of increase in the % of the population vaccinated was assumed to be low as initial awareness about the vaccination will be low and as infrastructure is put in place to facilitate vaccine distribution
- the rate of increase in the percentage of the population vaccinated will increase as awareness builds and as infrastructure becomes established
- the eventual rate of increase in the percentage of the population vaccinated will decrease as more people become vaccinated and therefore, there will be fewer people left to be vaccinated

Assumptions made in Section 2.3.6

- Vaccines are 100% effective. It is impossible to predict exactly how effective any given vaccination will be. Hence, when we refer to a vaccine, we mean a completely effective vaccine. This may in fact take the form of a cluster of multiple drugs.
- The vaccine distribution program is well-organized, for example run strictly by a government.

2.4 Country Choice, and Country-Specific Parameters

To determine the countries that were the most critical in terms of HIV/AIDS from 2006 to 2050, five indicators were employed when analyzing past data:

- Trends in HIV/AIDS prevalence rates
- Demographic of HIV/AIDS-infected population
- Level of HIV/AIDS education and awareness
- Routes of HIV transmission
- Integrity and availability of current and historical HIV/AIDS statistics

Trends in HIV/AIDS prevalence indicated the extent of HIV/AIDS infection and the rate at which the incidence of infection was increasing in the population. This statistic was critical in ascertaining whether HIV/AIDS was confined to at-risk groups or had spread to the general population as well as from urban to rural areas. Countries demonstrating high levels of HIV/AIDS infection and sharp rates of increase in prevalence were the most critical. These countries were followed by those that had high levels of HIV/AIDS infection and low rates of increase in prevalence. For such countries, antiretroviral therapy was deemed to have the greatest impact. Given the high levels of infection in the population, extending the lifespan and enhancing the quality of life of HIV/AIDS victims was crucial to maintaining economic productivity, reducing the number of orphans and reducing the strain on social services. For countries with low levels of infection and sharp rates of increase in prevalence, increasing the lifespan and improving the quality of life of HIV/AIDS victims was less critical. Emphasis was placed on stemming the spread of HIV/AIDS through more extensive HIV/AIDS education, more widespread condom use and more comprehensive drug prevention, drug rehabilitation as well as harm reduction programs.

The demographic of the HIV/AIDS-infected population indicated the total number of HIV/AIDS victims and the distribution of HIV/AIDS infection among different age groups. This statistic was important in quantifying the impact of HIV/AIDS infection on economic productivity and forecasting the number of orphans in the country. In countries with huge populations, such as India,

minor increases in HIV transmission could translate into huge numbers of people becoming infected. Consequently, countries with big populations were at greater risk of suffering from the economic and social impacts of a HIV/AIDS outbreak. In addition, countries, where the young (aged 15–35) bore the brunt of new HIV infections, were deemed to have a more critical HIV/AIDS situation. Such countries were more likely to suffer from large dips in economic productivity and more complex social problems. The young not only constitute a significant proportion of the workforce but also have the highest fertility rate. Consequently, there would be a vast increase in the number of orphans if the infection rate among the young increases. For example, in South Africa, one in three women aged 20–34 (UNAIDS) were infected with HIV. Given this high infection rate among young women, South Africa is expected to have 2 million orphans by 2010 (Economist.com).

The level of HIV/AIDS education and awareness was key in predicting the rate of infection. In countries with a low level of HIV/AIDS education and awareness, the use of condoms was lower and the extent of unprotected casual sex greater. Consequently, the risk of infection was significantly higher among individuals in the population. For example, in sub-Saharan Africa, which accounts for only 10% of the world population but constitutes 60% of people living with HIV, two-thirds of young women (aged 15–24) lack comprehensive knowledge of HIV transmission (UN AIDS).

HIV transmission routes were critical in identifying the major factors causing the rise in HIV/AIDS prevalence in a particular population. Identifying the major factors in turn advanced the selection of an appropriate solution to reduce the rate of infection. Certain factors could be more easily addressed and landmark reductions in the rates of infections could be achieved with relatively little effort and low capital (for example by providing condoms). Other factors, such as an extraordinarily large number of young drug users in the Russian Federation, revealed an endemic social problem that was more difficult to address. Countries, where more diverse routes of HIV transmission was observed and more complex social factors present, were considered to have a more critical HIV/AIDS situation.

Integrity and availability of HIV/AIDS statistics were essential in tracking the spread of HIV/AIDS infection in the population. Such data was also critical in calibrating the model so that it closely mirrored historical trends and was therefore, more likely to predict the spread of HIV/AIDS accurately. Consequently, countries which had a comprehensive record of HIV/AIDS statistics were favored over those which had little HIV/AIDS data available. Integrity of data was also a selection criterion. Countries such as China, where government suppression of HIV/AIDS data was suspected in the past, were omitted from the study.

Based on these five indicators, a country from each of the following continents

(Africa, Asia, Europe, North America and Australia) was selected:

2.4.1 South Africa

According to UNAIDS, HIV prevalence among pregnant women had reached its highest level in 2004 with 29.5% of women attending antenatal clinics testing positive for HIV. In the country's worst-affected province, KwaZulu-Natal, prevalence had reached 40%. Prevalence also remained exceptionally high – between 27% and 31% – in Eastern Cape, Free State, Gauteng, Mpumalanga and North West provinces. In South Africa, AIDS had been taking a devastating toll on human life. Death registration data showed that deaths among people 15 years and older increased by 62% from 1997–2002, with deaths among people aged 25–44 more than doubling. These statistics revealed the staggering extent to which HIV/AIDS was impacting South Africa's productivity and threatening social stability.

2.4.2 India

Although levels of HIV infection had stabilized in some states such as Tamil Nadu, it was increasing in at-risk population groups in other states. Prevalence among pregnant women was still low in the poor and densely populated northern states of Uttar Pradesh and Bihar (UNAIDS). However, relatively minor increases in HIV transmission could translate into huge number of people becoming infected. According to data from the National AIDS Control Organization 2003–2004 Annual Report, 85.69% of new infections occurred through heterosexual sex as women were being infected by husbands who frequented sex workers. 30% of street-based sex workers did not know that condoms prevented HIV infection. In the northern states, HIV transmission was concentrated among drug injectors and their sexual partners. There was a sharp rise in HIV infections among drug injectors in the southern state of Tamil Nadu, where 39% were HIV infected in 2003 compared with 25% in 2001. Overall, 2.24% of new infections occurred through injecting drug use.

2.4.3 Russian Federation

Each year, people aged 15–29 years accounted for more than 75% of new HIV diagnoses (UNAIDS 2005). The extraordinarily large number of people injecting drugs lay at the heart of the country's epidemic. At the end of 2004, there were 340 000 registered injecting drug users in the Russian Federation, though the actual number of injectors could be 4–10 times as high. In 2005, unsafe drug injecting practices still accounted for most HIV transmissions, with an estimated 30–40% of injecting drug users using non-sterile needles. Moreover, most drug injectors were sexually active and if infected with HIV, they could transmit the virus sexually to their casual or regular partners. Studies in Togliatti and Nizhny Hovgorod found that more than 80% of male injectors had not used condoms regularly over a 1 month period.

2.4.4 United States of America

Based on UNAIDS/WHO data, at the end of 2003, there was an estimated 1.04–1.2 million HIV cases up from 850 000–950 000 for 2002. The increase reflected the fact that people with HIV were living longer due to antiretroviral treatment, as well as the failure to adapt and sustain prevention successes. The majority of people living with HIV were men who had sex with men. Sex between men accounted for 63% of newly-diagnosed HIV infections in 2003. In addition, injecting drug use remained a prominent channel for HIV transmission. 20% of Americans living with HIV in 2003 were infected in this manner. Heterosexual intercourse, however, was the main mode of transmission for women living with HIV with an estimated 73% acquiring the virus through this manner.

2.4.5 Australia

Having declined by about 25% from 1995–2000, the number of new HIV diagnoses edged up again and reached 820 in 2004 (UNAIDS 2005). An estimated 14 800 people now live with HIV with 31% of those infections occurring in 2003, possibly reflecting a resurgence of risky behavior. 68% of all HIV infections since the epidemic began could be attributed to sex between men. The proportion of total HIV infections accounted for by heterosexual intercourse had risen from 7% before 1996 to over 23% by 2004. 50% of heterosexual sex-related infection had been in persons from a high prevalence country (33%) or whose partners were from a high prevalence country (27%).

3 Results

3.1 Historical Fitting

It is difficult to test the validity of an HIV/AIDS model due to the scarcity of past data. We validated our model by examining historical HIV rates from antenatal clinics in South Africa between 1995 and 2005(see Figure 1). Antenatal data from South Africa is one of the most complete sets of HIV counts worldwide, and hence is likely among the most accurate. Our model was able to fit the data with a high degree of accuracy with three minor changes, a slight decrease in the lifespan of the average HIV patient (to 7 from 9; this probably occurred because HIV detection tests have become more sensitive over time), an increase in the risky sex rate constant (which is very unsurprising, given that these numbers predate a majority of sexual education efforts) and increasing condom use rate over time (which is actually a better indicator of past trends).

3.2 Results by Country

In general, the model predicted the following trends in HIV/AIDS population:

- An increase in condom usage leads to a decrease in HIV/AIDS cases.

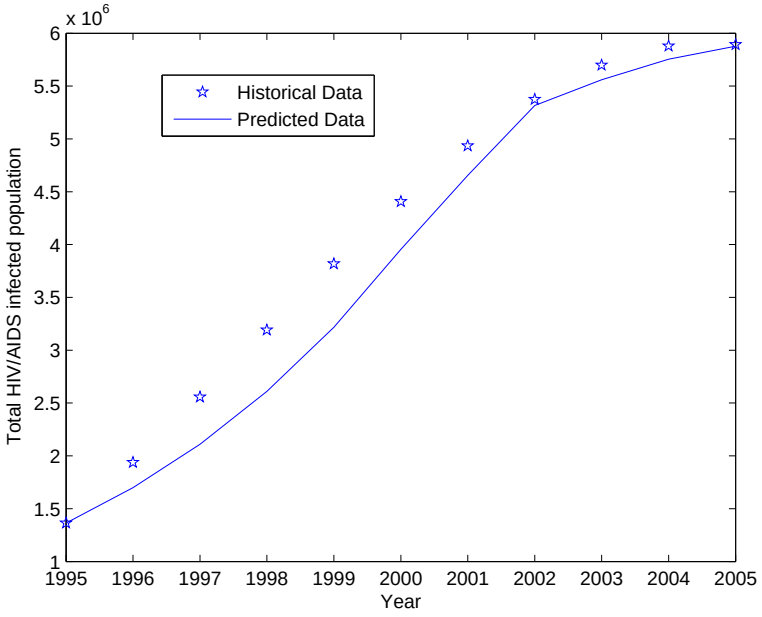

Figure 1: Comparison of model to South African historical data

- An increase in the average lifespan of an HIV/AIDS patient leads to an increase in the number cases.
- A decrease in the transmission rate leads to a decrease in the number of cases.
- Distribution of an antiretroviral (ARV) drug reduces the number of HIV/AIDS cases due to sexual acts only if ARVs cause a decrease in the per-act transmission rate.
- Steady distribution of an AIDS vaccine leads to a steady decrease of HIV/AIDS cases to a baseline level.

3.2.1 South Africa

The model (see figure 2) predicted a decrease in HIV/AIDS cases prior to 2015 for all variations. The number of cases when excluding ARV and vaccines approached a steady state of approximately 3 million cases. It is important to note that the level of injection drug use in South Africa was found to be negligible and was not included as a parameter for new HIV/AIDS patients.

When ARV treatment was introduced to the population, there was a dramatic shift in the steady state level of HIV and AIDS for both scenarios. Increasing

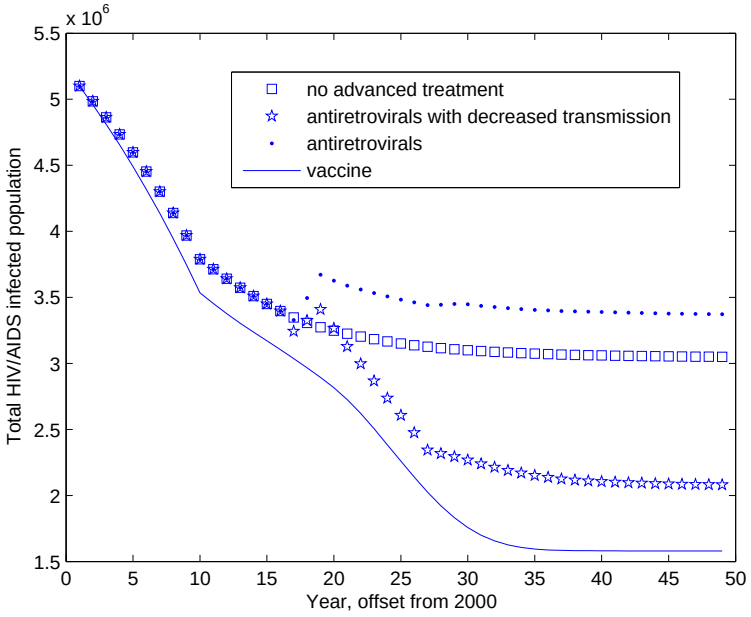

Figure 2: Prediction of HIV/AIDS epidemic in South Africa

the life span of the AIDS patient with no effect on the transmission rate resulted in a new steady state level of approximately 3.4 million, greater than the steady state with no advanced treatment. However, when ARV with a decrease in transmission rate was considered, the number of HIV/AIDS cases approached a constant level of approximately 2.1 million. Thus, the decrease in transmission was found to have a drastic effect on the number of HIV/AIDS cases in 2050, but was not enough to eradicate the disease. The model also predicted a sudden increase in cases at approximately 2020 for both ARV scenarios. This deviation results from the assumption that the delivery of ARV drugs instantaneously increases the life span of all HIV/AIDS infected individuals in the population, therefore lowering the death rate at that time by a substantial amount. Thus, the deviation is an artifact of our assumptions.

The implementation of a well regulated vaccine program starting in 2015 predicted a gradual decrease in disease cases over the next twenty years. The total number of HIV/AIDS infected individuals is predicted to decrease to less than 2 million by the year 2030. A significant portion of the disease eradication occurs between the years of 2020 and 2025. Therefore, the most effective way of combating AIDS was found to be by distribution of a vaccine, while the administration of an ARV drug provides an increase in longevity and quality of life for people already infected with HIV or AIDS.

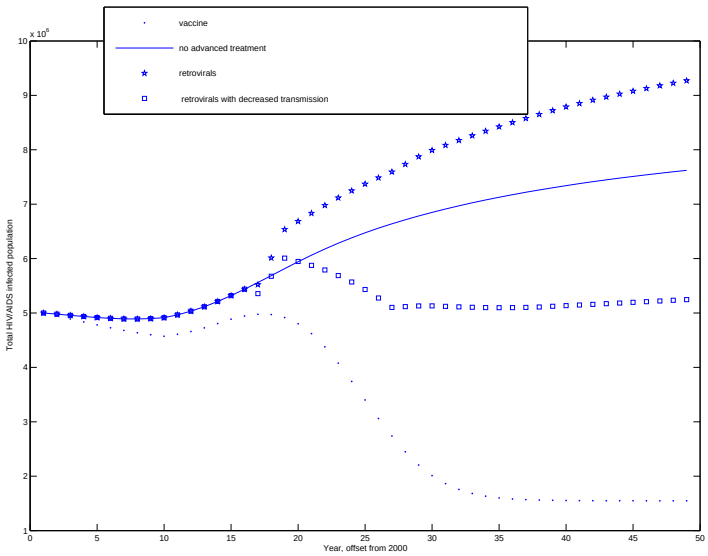

Figure 3: Prediction of HIV/AIDS epidemic in India

3.2.2 India

The model (see Figure 3)indicates a steady increase in HIV/AIDS cases over the next 45 years. The number of cases when excluding ARV and vaccines illustrates a gradual climb, reaching almost 8 million by 2050. This differs from the observed trend in South Africa most notably because of the significant drug usage in the Indian population.

The introduction of ARV treatment that increases only the lifespan of each infected individual results in an even faster increase in the number of HIV/AIDS cases every year. The projected number of cases is predicted to exceed 9.2 million by 2050 and may still be increasing at a significant rate in this scenario. However, considering the decrease in transmission from ARV drugs, the effect of increased life expectancy after onset of HIV is negated and the number of HIV/AIDS cases begins to decline. The number of cases when the transmission rate is decreased is predicted to level off at a little over 5 million in the year 2050. It is important to note that there is a small sudden jump in the number of cases in the years around 2020 (as was the case with South Africa), which is a consequence of one of our assumptions.

The most effective method of treatment was once again found to be a vaccination program, possibly supplemented with an ARV drug treatment program to reduce the social cost of carrying the disease. The model predicated that the

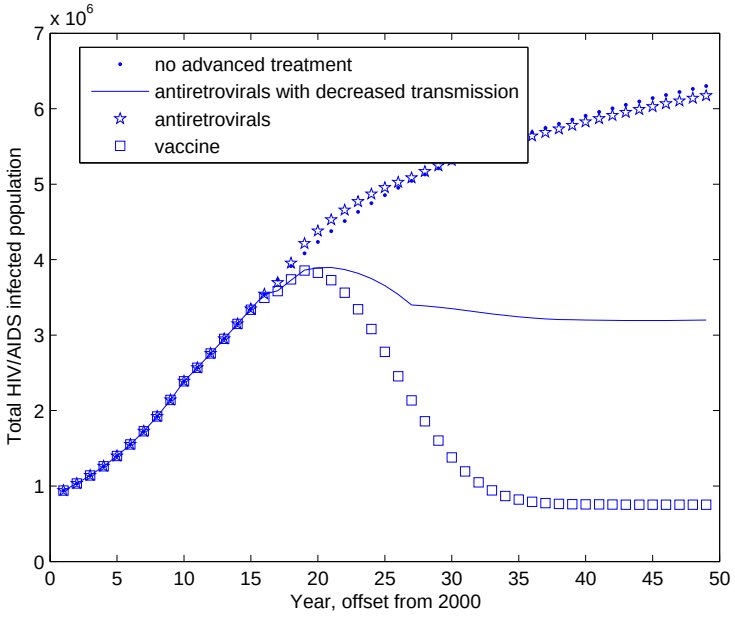

Figure 4: Prediction of HIV/AIDS epidemic in the United States

total number of HIV/AIDS cases will be approximately 2 million people in 2030 and plateau soon after that. The most significant decrease once again occurs 5 to 10 years after the implementation of the vaccination program from the years 2020 to 2025.

3.2.3 United States

In the United States, HIV/AIDS is predominantly spread through homosexual interaction. The model predicted the number of HIV/AIDS cases to exceed 6 million by the year 2050 if no advanced treatment is available (Figure 4).

An interesting observation in the United States is that, unlike the other countries we have examined, the distribution of ARV drugs that do not effect transmission rate does not increase the number of HIV/AIDS patients over the years. In this case it would seem ARV therapy has a positive impact on society by increasing life expectancy of an HIV/AIDS patient while maintaining the same level of growth of new cases.

The use of ARV drugs that decrease transmission rate is once again seen to curb the number of HIV/AIDS cases in the population. The model predicted that the number of cases will remain fairly constant at slightly over 3 million cases after the year 2030.

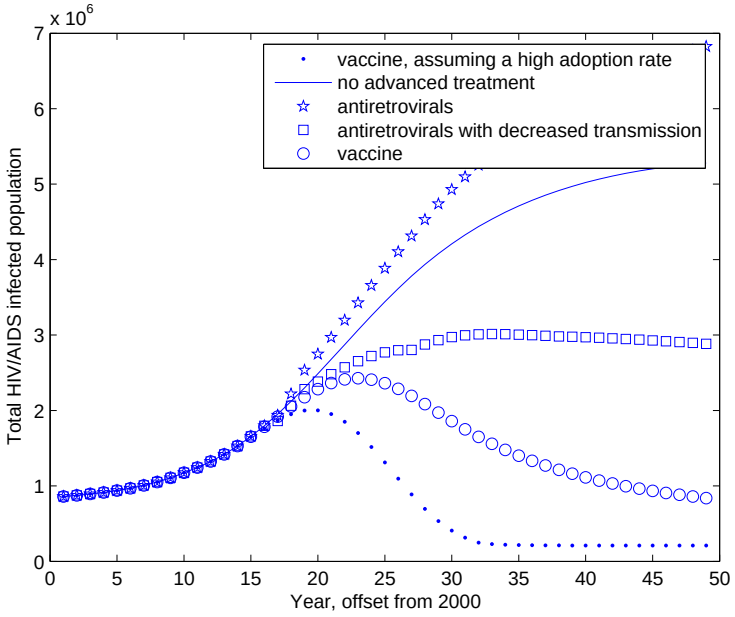

Figure 5: Prediction of HIV/AIDS epidemic in the Russian Federation

Once again, a well regulated vaccination program is predicated to essentially eradicate the virus in the country. It is predicted that there will be an almost constant decrease in HIV/AIDS cases between 2020 and 2030. By the year 2035 the number of cases are predicated to be minimal.

3.2.4 Russian Federation

The model predicted a steady increase in HIV/AIDS cases to approximately over 5 million cases in 2050 when excluding the availability of any advanced treatment (Figure 5). This is similar to the trend observed in India, however the predominance of HIV/AIDS transmission through injecting drug use in Russia is much greater and therefore plays a much larger role in spreading the virus.

The model also predicted a much larger increase in HIV/AIDS cases when ARV treatment that increased life span was introduced. It was predicted that an increase in lifespan of HIV/AIDS infected individuals would eventually lead to over 7 million HIV/AIDS cases by the year 2050, much greater than the scenario where no advanced treatment was available. Moreover, the rate of increase of the number of cases was also observed to be much greater at every year. However, a slightly different result was seen once again for the case of ARV treatment that decreases transmission. The number of HIV/AIDS cases increases initially but

levels off much quicker than the two previous scenarios. The number of cases remains fairly constant at approximately 3 million cases after the year 2030. Ideally, ARV treatment that lowers transmission rate is an effective short term solutions that keeps the number of HIV/AIDS cases from exploding.

The implementation of a well regulated vaccine program is once again predicted to be of great effect in eradicating the virus. At the normal vaccination rate for a Russian adult, the number of HIV/AIDS cases peaks at approximately 2 million cases in the year 2020 (5 years after the implementation of the vaccine program) and then gradually decreases, approaching approximately 1 million cases by the year 2050. It can be immediately observed from the plot that the implementation of a vaccine program in Russia is not as effective as for our previous countries. This is because of an unusually low adoption rate for vaccines (37%) in Russia. Figure 5 also demonstrates the predicted effect of a vaccine adoption rate. The model predicted that this will result in a much faster eradication of the HIV/AIDS virus. Thus, Russia can significantly thwart the number of HIV/AIDS cases if resources are spent on increasing the vaccination rate among its adult population.

4 Analysis

All of the models predicted that vaccination of the population will be the most effective method of HIV/AIDS eradication. In South Africa, where drug use is not as prevalent as the other countries, the effect of the vaccine is large from the onset and the number of HIV/AIDS cases decreases rapidly. The distribution of the vaccine in the other countries also has a similar effect but the rate of decrease depends on the vaccination adoption rate and drug use in the country. In Russia, where the adoption rate is only 37%, the number of HIV/AIDS cases remains high till the year 2050 compared to if they had a higher adoption rate. Moreover, the plot does not definitively level off as was the case for the other countries, possibly because of the large incidence of drug use in the country. It is important to note that the rate of spread through drug use is considerably greater than through sexual acts and could be the predominant factor in maintaining such a high level of HIV/AIDS in Russia. In contrast, the number of cases in South Africa reaches a minimum and plateaus by 2035.

The effect of ARV therapy in reducing transmission rates of HIV/AIDS has been an object of debate among scientists. An underlying theme in all our predictions is that if ARV drugs do not influence the transmission rate of the disease, the results of its introduction could be catastrophic. Increasing the life span of HIV/AIDS patients essentially provides more time for each individual to spread the disease. Our model predicted that the number of HIV/AIDS cases would be much greater over the next 45 years for all countries in this case than any other scenario. Thus, we stress the importance of properly understanding

the effect of HIV/AIDS therapy on infected individuals in an effort to prevent future breakouts of the disease. However, the United States is an exception.

The United States brings an interesting mix to our cocktail of countries. 63% of HIV/AIDS cases in the US are among homosexuals (UNAIDS), thus reflecting a very different pattern of transmission to the other countries. Moreover, the implementation of an ARV program with no effect on transmission rate does not increase the number of HIV/AIDS cases in the future. This is in contrast to all the other countries that are examined, which generally display an increase in infected individuals due to increased lifespan. A possible reason for this observation is that we assume in our model that the use of ARV therapy implies that individuals are more informed and therefore slightly less likely to perform risky sexual acts. This does not seem to have enough of an effect on the people of the other countries modeled. In the United States this results in enough of a reduction in sexual acts to counterbalance the effect of an increase in lifespan. Thus, the number of people infected stays roughly the same over time as when no advanced treatment is available making the use of ARV drugs beneficial to society. This is because people can now live longer without increasing the spread of the disease as compared to when no advanced treatment is available.

When considering the decrease in transmission due to ARV use (Note, this number is also debatable) we observed a negating effect to the increase in life span. The ARV drugs were predicted to effectively curb the spread of HIV and AIDS in every case, causing the number of cases to remain fairly constant after the year 2030.

One of the least expected results of our model was the decrease in HIV/AIDS cases in South Africa. The model predicated that the incidence of HIV/AIDS has peaked and is now on a downward turn. This however, is not completely unexpected as HIV/AIDS has been present for the longest time in South Africa and general awareness about the disease has increased. Over the course of years an equilibrium point is reached as reproduction rate may decline. Eventually the number of new cases equals the number of deaths due to AIDS and the population of infected individuals remains fairly constant.

India presents a very different situation. The incidence of HIV/AIDS in India is a fairly recent development and is still under manageable proportions. However, the model predicted that if left unhindered, the spread of HIV/AIDS will very quickly reach uncontrolled levels as has been seen for Africa. This is in complete agreement with recent studies of the effect of AIDS in India (Economist 2004). Thus, once again we stress the importance of AIDS education programs and the distribution of effective ARV drugs when effective.

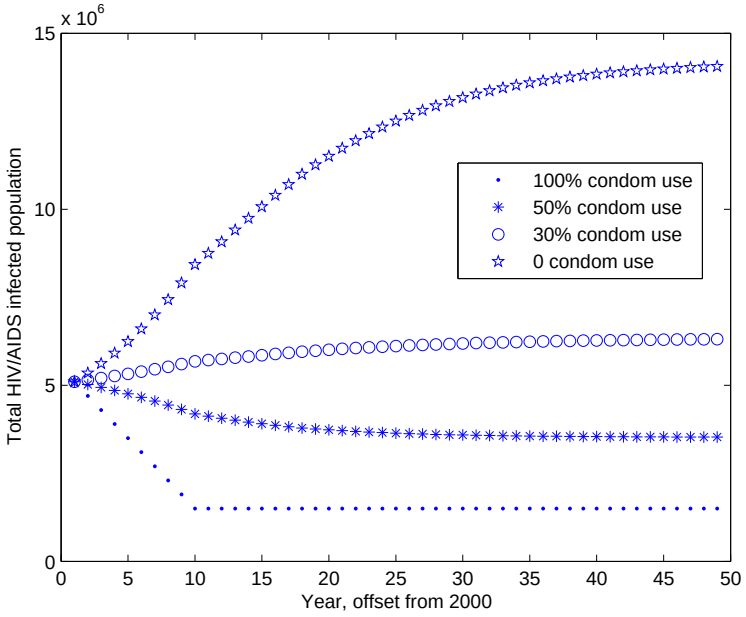

Figure 6: Effects of condom usage rate on model outcome

4.1 Analysis of Sensitivity and Individual Parameters

In this section, we briefly evaluate the sensitivity of our model. We inquire into the effect of changes to our model's parameters and whether the effects are what we would expect. To do this we test key variables in our model and hope that these changes follow intuitively from our assumptions of the nature of AIDS.

The parameters we tested are *condomRate* (percentage of sexual acts performed with condoms) and *arvPortion* (percentage of HIV/AIDS population that have access to ARV drugs). We also tested the effect of differences in transmission rate decreases due to ARV treatment and drug resistance.

Figure 6 shows the effects of different values of condomRate on the number of HIV/AIDS cases in South Africa. As expected, the model is quite sensitive to the *condomRate* parameter. The use of no condoms has a catastrophic effect on the number of AIDS cases, as the probability transmission is at its maximum possible value. An increase in condom usage to 30% results in a much lower rate of increase in HIV/AIDS infections, but it is not enough to curb the spread of the disease. Increasing *condomRate* to 50% results in gradual decrease in HIV/AIDS cases. Finally, complete condom use results in disease eradication in 10 years, which is the time required for previous HIV/AIDS patients to pass away. This makes intuitive sense since complete condom use prevents the spread

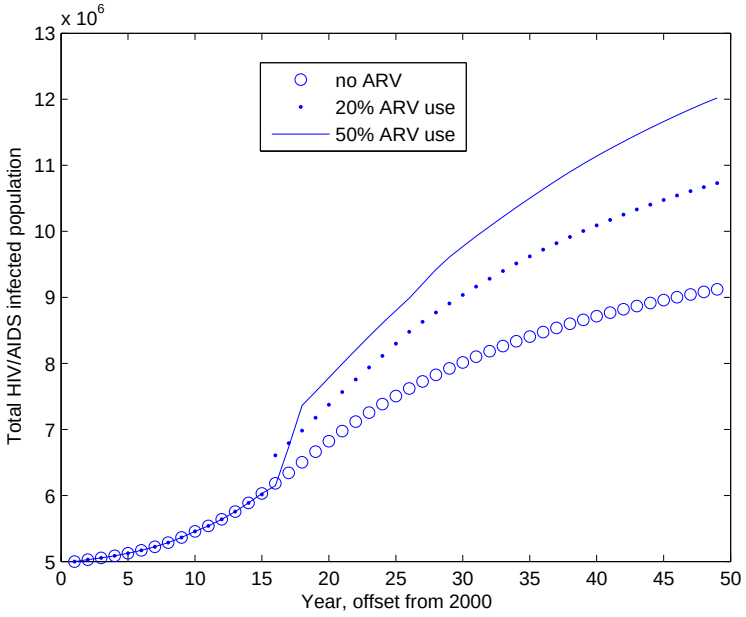

Figure 7: Effects of ARV therapy on model outcome, assuming no impact on transmission rate

of the virus, implying the number of HIV/AIDS cases for a given year are those people already infected with the virus at the time usage becomes 100% minus the number that passed away after that time.

Figure 7 shows the effect of varying *arvPortion*. The assumption made here is that ARV therapy increases the lifespan of the HIV/AIDS patient but does nothing to decrease the transmission rate. Intuitively, this leads to an increase in the number of HIV/AIDS cases as the people infected now have a longer time to spread the disease through intercourse and drug use. It is shown that fairly large changes in ARV treatment use lead to large changes in the number of HIV/AIDS cases, which is as expected. Moreover, Figure 8 presents the same data but with the assumption that ARV drugs reduce transmission rate by 25%. Comparison of the two plots demonstrate that large reductions in the transmission rate result in drastic reductions in the number of HIV/AIDS cases over the years. For example, when ARV use is 30% and there is no decrease in transmission, the number of HIV/AIDS cases approaches 11 million in 2050. When transmission rate is decreased by 75%, the number of HIV/AIDS cases decrease to a little over 8.5 million.

One final note is that all plots plateaued at a small fraction of their initial HIV/AIDS cases when condom usage was set at 100%. Intuitively, we would

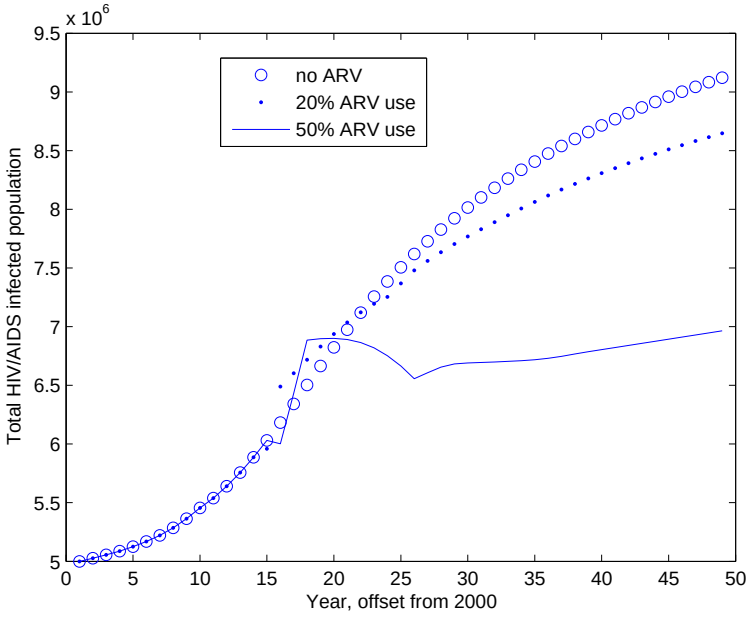

Figure 8: Effects of ARV therapy on model outcome, assuming ARV patients are 75% less contagious

expect the number of HIV/AIDS cases to approach 0 when there is no spread of the disease from sexual transmission and drug use. This discrepancy can be accounted for by the use of approximate death rates the initial iterations of our model, which did not add up exactly to our initial population of HIV/AIDS patients.

The introduction of multi-drug resistant (MDR) strains does not have a major effect on rich countries such as the United States since patients with MDR HIV/AIDS are able to purchase second and third line ARV drugs. Thus, they are able to continue their battle against the disease. However, a problem arises in poorer countries in which those infected can not afford second and third line drugs. Figure 9 shows the effects of adherence rates on the number of HIV/AIDS infected individuals when the ARV drugs effectively lower transmission rate. Treatment with ARV begins in 2020 and is swiftly followed by a decrease in the number of HIV/AIDS cases. When the adherence rate is 100%, the number of infected individuals levels off at approximately 5 million cases, which was seen in our earlier models when we assumed no MDR HIV/AIDS. As adherence rate decreases the onset of multi drug resistance is observed. This essentially results in a negation of the lower transmission rates of initial treatment with ARV drugs and therefore causes a steady increase in the number of cases in the following years as MDR HIV/AIDS is spread in the population

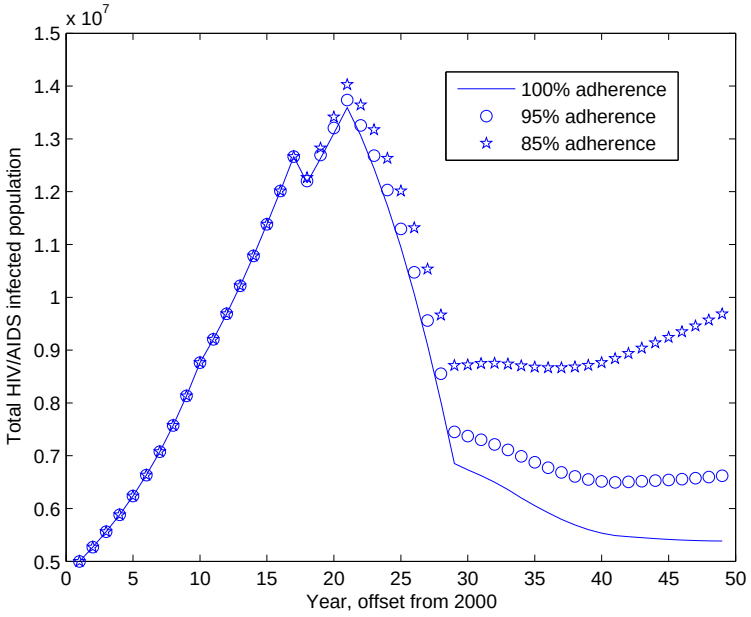

Figure 9: Effects of multiple drug resistance on transmission rate, assuming 100% ARV usage, and that ARV decreases transmission rate

without any treatment. Moreover, the onset of MDR HIV/AIDS is earlier for lower adherence rates, which is intuitively correct. Our model is sensitive to the fairly large changes in adherence rates, which is what we would expect.

5 Economic Model for Administering ARVs

While our group recognizes the intrinsic value of human life and human dignity as well as the right of every individual to a standard of living adequate for the health and well-being of himself and of his family (as laid out in Article 1, 3 and 25 respectively under the Universal Declaration of Human Rights), such recognition does not necessarily preclude a cost-benefit analysis for administering ARVs in countries that cannot afford ARVs. If anything, a cost-benefit analysis will at least highlight that there are economic benefits and positive externalities to providing ARVs to these countries even though the total benefits do not completely outweigh the cost of treatment. On the other hand, in the event that total benefits from ARVs do exceed the cost of treatment, a cost-benefit analysis will lend economic justification to providing specific levels of ARVs to these countries.

In this section, the economic model for administering ARVs is discussed ab-

stractly due to the absence of data.
This model employs two main techniques:

- Cost-benefit analysis
- Discount rate

This model requires several sets of data:

- GDP_t: The present value of future GDP over a period, t
- $GDP_{p,t}$: The present value of future GDP over a period, t, for different numbers of people, p, placed on ARV treatment
- $netExternalities_{p,t}$: The difference between positive and negative externalities that results from administering ARVs to p individuals for time t.

Negative externalities can result from higher rates of infection as HIV/AIDS victims enjoy increased life expectancy and therefore, have greater opportunity to spread the virus. Positive externalities can result from the cost savings that rich countries enjoy indirectly by reducing the infection rate in poor countries. For example in Australia, more than half of HIV infections attributed to heterosexual intercourse in 2000 - 2004 had been in persons who were from a high-prevalence country or whose partners were from a high-prevalence country (UNAIDS 2005). Reducing infection rates in high-prevalence poor countries might, in turn, reduce the rate of infection in rich countries.

Cost benefit-analysis for administering ARVs in a country that cannot afford ARVs comprises:

Assumptions:
Cost of ARV per year per person = $1100
r = real interest rate
Π^e = expected inflation rate = 0

Perspective from poor country that cannot afford ARVs,

$Cost_{p,t} = \sum_{t=1}^{n} \frac{1100p}{(1+r)^{t-1}}$
$Cost_{p,t}$ is the cost of administering ARVs to p individuals for length of time, t. The cost of treatment is discounted to present values.

$Savings_{p,t} = GDP_{p,t} + netExternalities_{p,t} - GDP_t$
$Savings_{p,t}$ is the total impact due to the positive effect to GDP and the benefits of externalities that result from administering ARVs to p individuals for length of time, t.

$NetBenefit_{p,t} = Savings_{p,t} - Cost_{p,t}$

$NetBenefit_{p,t}$ is the real economic benefit to the world from administering ARVs to p individuals for length of time, t.

At optimum point,
$\frac{\partial NetBenefit}{\partial p} = \frac{\partial NetBenefit}{\partial t} = 0$

At this point, the benefit yield by the world from administering ARVs to individuals in the poor country is optimal.

Perspective from rich country that is funding the cost ARVs for poor country,

After determining the optimum point (p*, t*), rich country can identify the investments that have maturity t*. If the returns on these investments are lower than the benefits yield from administering ARVs to individuals in the poor country, the capital made in these investments should be channeled instead to the procurement of ARVs for the poor country.

6 Discussion and Conclusions

6.1 White Paper

The global AIDS epidemic has killed over 25 million people since it was first recognized in the early 80's. At present, the number of infected individuals has reached over 40 million and is still increasing rapidly (UNAIDS 2005). Since there are no solutions capable of eradicating AIDS rapidly, taking steps to curb the spread of the disease is critical.

Advanced Treatment
Currently, there are two major treatments being studied–antiretroviral drugs and vaccines. Antiretroviral drugs are widely-used in well-developed countries but are not readily available in poor countries due to costs. While antiretroviral drugs have increased the life expectancy and quality of life of HIV/AIDS victims, their effect on transmission rates have been less conclusive. Vaccines, on the other hand, offer the possibility of permanently immunizing individuals to HIV. Presently, research is being carried out on 17 different HIV vaccines. However, there is much uncertainty surrounding when an effective vaccine will be found.

Given the current circumstances, we recommend funding both research into ARVs and HIV vaccines. In the short-run, ARVs are important in the effective management of the AIDS epidemic. ARVs cushion the impact of HIV/AIDS on the economic and social tapestry of a country. This is achieved by:

- Helping victims remain productive over a longer period of time, preventing

the economic collapse of countries with a large HIV/AIDS population

- Allow infected parents to live longer, mitigating the problem of a growing orphan population.

Research into ARVs, however, must not only seek to extend the life expectancy and enhance the quality of life of HIV/AIDS victims, but it must also reduce the transmission rate of HIV / AIDS. Only then will the negative externalities of introducing ARVs be reduced to a minimum.

In contrast, vaccines are important in eradicating HIV / AIDS in the long–run. Immunizing vast numbers of people will not only confer resistance to a large section of the population but also drastically reduce the risk of infection in individuals who have not been vaccinated. A vaccine also takes a smaller economic toll on a country's health care system and practically eliminates the possibility of creating drug-resistant strains as there is no need to ensure timely consumption of medication (as in the case of ARVs). As our model predicts, vaccination virtually eliminates the AIDS epidemic within 15–20 years. Consequently, adequate funding to ensure that a HIV/AIDS vaccine is found as soon as possible is critical.

The argument for international concern in HIV/AIDS is largely economic–as discussed above–but more importantly it is humanitarian as well. The economic model states that countries should prioritize their financial resources so that investments yielding lower returns than the procurement of ARVs for poor countries be allocated to the latter. From a humanitarian perspective, several factors should be considered by rich countries:

- Urgency of other funded projects
- Social impact of other funded projects on donor country and recipient country
- Infection rate

Since it is difficulty to put a cost on these factors for incorporation into an economic model, rich countries must necessarily move beyond the economic realm in championing the HIV/AIDS cause.

There are several factors when considering which countries are most critically in need of help:

- Size of the population
- Size of the HIV/AIDS infected population
- Infection rate

International organizations must focus foremost on countries with large HIV/AIDS populations and high rates of infection. This is particularly true in countries with huge populations clustered in dense urban areas. In such countries, small increases in the rate of infection translate into huge populations of HIV/AIDS victims. Consequently, these countries require a combination of ARVs – to reduce the economic and social impact of HIV/AIDS – as well as more comprehensive sexual education programs – to stem the spread of HIV/AIDS. Countries with high rates of infection and large populations (but with a small HIV/AIDS population) should be focused upon next. In such countries, the emphasis is on sexual education – to prevent the spread of HIV/AIDS to the wider population– as opposed to ARVs. These countries are followed by those that have large HIV/AIDS populations but low infection rates. In these countries, the stress will be on ARVs as there will be a pressing need to ensure the economic sustainability and social stability of the country.

6.2 Strengths and Weaknesses

Strengths

- Ability to incorporate many data sources, such as condom usage rates, drug populations and historical AIDS death rates.
- Scalable and easy to expand to account for new populational factors. Easy to adapt to new locations.
- High accuracy in fitting historical data.
- Comprehensive. Takes into consideration all the major factors concerned in HIV, including transmission factors, prevention techniques and economic considerations.

Weaknesses

- Large amount of prerequisite data required, some of which may be hard to acquire, such as historical HIV/AIDS death rates.
- Countries treated as isolated entities (does not account for migration patterns).
- Fails to account for random differences between individuals, such as the exact amount of time before death from AIDS after infection.

6.3 Future Work

There are a number of parameters that may be considered in the future to strengthen our model. Primarily we may consider population migration between countries and within countries, especially the number of people wishing to migrate to first world countries from poorer countries. We may also consider

population density as the frequency of encounters may vary in different regions of a country. Population isolation is also another important parameter that may be elaborated upon (for example, in the way that we assumed that homosexual men were a mostly closed population). We would also like to look at changes in future condom usage patterns as a result of increased education and awareness of the disease.

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