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Abstract

Despite recent international efforts to increase antiretroviral treatment (ART) coverage, more than 5 million people who need ART in developing countries do not receive such treatment. Shortages of human resources to treat HIV/AIDS (referred to herein as HRHA) are one of the main constraints to further scaling up ART. Planning expansion of ART depends on the ability to predict how many HRHA will be needed in the future. We investigate whether taking into account positive feedback from the current supply of HRHA to future HRHA need substantially alters predictions. This feedback occurs because an increase in the number of HRHA implies an increase in the number of individuals receiving ART and – because ART is a lifelong treatment and is effective in prolonging the lives of HIV-positive people – a rise over time in the number of people requiring ART.

We formulate a discrete-time Markovian model to project HRHA need in three geographical regions in the developing world: sub-Saharan Africa (SSA), non-sub Saharan African low- and middle income countries (NSSA), and one specific country in SSA, South Africa (SA). To run the model, we use recently published estimates of ART coverage, HIV prevalence, HIV incidence, health worker emigration rates, mortality rates of people needing ART, and numbers of HRHA required to treat 1,000 ART patients.

We find that feedback is a significant determinant of HRHA needed for universal ART coverage. Our model shows that with feedback SSA requires 1.4 times, NSSA requires 0.8 times, and SA requires 3.3 times the size of their *entire existing HRHA population* to be added *every year for the next 10 years* to achieve universal ART coverage by 2017. Without feedback, the regions would require 0.6, 0.3 and 1.5 times the size of their respective HRHA populations to be added each year until 2017. Beyond 2017, sustaining universal coverage requires further HRHA increases until the system reaches steady state.

We further find that ART coverage is sensitive to HRHA inflow and emigration, and that universal ART coverage is unlikely to be achieved and sustained with increased HRHA inflows alone, but will in many settings require decreased HRHA outflows, substantially reduced HIV incidence, or changes in the nature or organization of care.

Introduction

Despite recent international initiatives to scale up antiretroviral treatment (ART) (Clinton Foundation 2007; Global Fund to Fight AIDS, Tuberculosis and Malaria 2007; Médecins Sans Frontières 2007a; President's Emergency Plan For AIDS Relief (PEPFAR) 2007), more than 5 million people in developing countries who needed ART in December 2006 did not receive it (World Health Organization (WHO) 2007), leading to large numbers of potentially avoidable deaths (Hogg et al. 1999; Bärnighausen 2007). In June 2006, the General Assembly of the United Nations committed itself to the goal of achieving universal access to HIV care by 2010 (United Nations 2007). In many developing countries, the binding constraint to increasing ART coverage is not drugs, laboratory equipment, or facilities, but human resources to treat HIV/AIDS (HRHA) (Clark 2006; Hosseinipour 2002; Institute of Medicine 2007; Kober, and Van Damme 2004; Marchal, De Brouwere, and Kegels 2005; Marchal, Kegels, and De Brouwere 2004; Médecins Sans Frontières 2007b; Ooms, Van Damme, and Temmerman 2007; Van Damme, Kober, and Laga 2006). Realistic estimates of the number of health workers required to achieve and maintain universal ART coverage in future years are necessary to devise appropriate strategies for health worker education, training, and retention (Bärnighausen 2007).

Estimating the number of additional HRHA currently needed to achieve universal ART coverage in developing countries is relatively easy, using, for instance, recent empirical estimates of the number of health workers needed to provide ART to 1,000 patients in developing countries (Hirschhorn, Oguda, Fullem, Dreesch, and Wilson 2006) and estimates of current unmet need for ART (WHO 2007). Such static estimation of HRHA need is, however, only of limited value for a number of reasons. First, while most of the other inputs needed to provide ART, such as antiretroviral drugs and medicines to prevent and treat opportunistic infections, laboratory equipment to measure CD4 counts, and health care facilities, can be relatively quickly scaled up if sufficient funds are available, HRHA cannot be increased quickly, because of long education and training times (Bossert, Bärnighausen, Bowser, Mitchell and Gedik 2007). Any estimation of HRHA need must thus span a period of many years.

Second, the number of HRHA needed to achieve universal ART coverage in the future is not independent of the current HRHA numbers. The more HRHA are available, the larger the number of people who currently receive ART will be, and because ART is a lifelong treatment and is effective in prolonging the lives of HIV-positive people in developing countries (Braitstein et al. 2006; Merson, Dayton, and O'Reilly 2000; Herbst, Cooke, Bärnighausen, Kany Kany, Tanser, and Newell 2008), the larger the number of people who require ART in the future will become – that is, there is positive feedback from HRHA numbers to HRHA need.

Third, HRHA themselves are at risk of contracting HIV and becoming patients in need of ART, especially in countries with generalized HIV epidemics (Connelly et al. 2007; Ncayiyana 2004). In many developing countries, large numbers of health workers in need of ART are not receiving it (Chen and Hanvoravongchai 2005; Shisana 2007; Tawfik and Kinoti 2003). We would expect that the probability of a health worker receiving ART increases with increasing numbers of HRHA. ART will increase the life expectancy of HIV-positive HRHA, and thus decrease the need for HRHA over time – that is, there is negative feedback from HRHA numbers to HRHA need.

We project the ART coverage that can be achieved under varying assumptions about HRHA inflow from the health worker education system and outflow because of emigration or deaths. We also investigate the effects of changes in HRHA HIV incidence and HRHA ART coverage on population ART coverage.

Methods

Model: conceptual description

Our model is a simple, discrete-time, Markovian deterministic system with two main population pools (Law and Kelton 2000): HRHA and people needing ART. In order to investigate whether changes in HRHA HIV incidence or HRHA ART coverage appreciably change the long-term need to add HRHA to the pool of existing health workers, we divide HRHA into four subpopulations: HIV-negative HRHA, HIV-positive HRHA who do not (yet) need ART, HIV-positive HRHA who need ART but are not receiving it, and HIV-positive HRHA needing and receiving ART. Time increments are yearly.

We chose a deterministic rather than a stochastic system, because our model asks questions at the regional or the national level. At these levels, data characterizing the statistical properties of random quantities are not available; we thus judged that deterministic point estimates were better than introducing additional stochastic mathematical structure into the model without evidence to guide the selection of such a structure. We chose a Markovian system (that is, where the state of the system, people needing ART and HRHA, at time $t + 1$ depends only on the state of the system at time t and not on previous states), because a Markovian system is comparatively simple to implement and sufficient to investigate feedback structures, such as the feedback from health workers providing ART to ART need.

Model: details

The patient population needing ART, starting from a given initial size at time $t = 0$, evolves as follows. At the beginning of each period t, new infections occur at a given annual rate. The newly HIV-positive people then enter a fixed latency period of 10 years (compare Boerma et al. 2006) during which they are exposed to general population mortality, but do not yet need ART. The proportion of HIV-positive people who survive the latency period enters the population needing treatment at the beginning of each period. The previous period’s treated and untreated population sizes are then reduced using their respective annual mortality rates.

Given the current number of HRHA, the number of patients treated is computed assuming a fixed HRHA-to-patient ratio of 1 team to 1,000 patients. A recent review of staffing patterns in ART programs in developing countries found that one to two doctors, up to three pharmacy staff, and two to seven nurses were needed to provide ART to 1,000 patients (Hirschhorn et al. 2006). The ratio used in this model employs the lower bound of the number of doctors needed to provide ART to 1,000 patients: by scaling our estimates of HRHA need by a constant factor, we can easily translate them into the need for nurses or pharmacy staff. In our model, however, one HRHA represents a team of health workers sufficient to provide ART to 1,000 patients. The precise makeup of the team is irrelevant to our model. The only assumptions for our results to hold are that the provision of ART by health workers is as effective in reducing mortality as the provision of ART during the first phase of ART scale-up in low-income countries (Braitstein et al. 2006) and that health workers are internationally mobile.

The evolution of HRHA in the model is similar, in principle, to the evolution of the population needing ART, but more detailed. The size of the HIV-negative HRHA pool decreases in each period because of mortality and emigration. The remaining number of HIV-negative HRHA is further diminished because of new HIV infections. At the same time, new HRHA are added to the subpopulation of HIV-negative HRHA at a given annual rate, yielding the HIV-negative HRHA population at the start of the next period. During the latency period from HIV infection to ART need, the size of the HIV-positive HRHA pool is decreased because of mortality and emigration. HRHA who neither die nor emigrate during the 10 years from infection to need for treatment are added to the subpopulation of HIV-positive HRHA needing ART.

The HRHA who need treatment at the beginning of a period are split into two subpopulations: those who received treatment during the previous period and those who did not. Both subpopulations are reduced by their respective mortality and emigration rates. The number of HRHA needing treatment in the current period is computed as the sum of the HRHA needing treatment who have remained in the subpopulation from the previous period and the HIV-positive HRHA who have newly become in need of ART.

Model: parameter estimates

Table 1 presents estimates for model parameters for three regional base cases, as derived from published studies. We divided all developing countries into two separate base cases, sub-Saharan Africa (SSA) and non–sub Saharan African (NSSA), because the HIV epidemic (WHO 2007), health worker emigration (Docquier and Bhargava 2007), and mortality (World Bank 2007) are very different in these two sets of countries. We added a third base case, the country of South Africa (SA). We included SA as a separate base in order to apply our model to a country with substantially higher HIV prevalence, HIV incidence, and HRHA emigration rates than both the SSA and the NSSA averages.

Whenever rate estimates for parameters such as HIV incidence, mortality or emigration were available in the literature, we converted the rates into annual probabilities, because we model time as consisting of discrete one-year-long units.

< Table 1 >

The initial estimates of the number of people receiving ART and the number of people needing but not receiving ART in the three base cases are from a recent joint publication by WHO, the Joint United Nations Programme on HIV/AIDS (UNAIDS), and the United Nations Children’s Fund (UNICEF) (WHO, UNAIDS, and UNICEF 2007). Estimates of mortality among people receiving ART were based on a review of mortality in 18 ART programs in low-income countries (Braitstein et al. 2006). Estimates of mortality among people needing ART but not receiving it were taken from a study in South Africa (Badri, Lawn, and Wood 2006).

In developing countries in the early phases of the HIV epidemic, people with high educational attainment, such as health workers, were at higher risk of HIV infection than the general population (Hargreaves and Glynn 2002). However, recent studies of HIV infection among health workers have found HIV prevalence in health workers to be similar to the prevalence in the general population (Connelly et al. 2007; Shisana, Hall, Maluleke, Chauveau, and Schwabe 2004). Therefore for the initial split into HIV-negative and HIV-positive HRHA subpopulations, we assumed that HIV prevalence and HIV incidence among health workers equaled the prevalence and incidence in the general adult population in the three regional base cases. We calculated the annual probability of HIV acquisition for SSA and NSSA countries using estimated numbers (by world region) of people who were newly infected with HIV during 2007 and estimated numbers of people who needed to be excluded from the population at risk of HIV incidence in 2007 because they had already contracted HIV (UNAIDS and WHO 2007). We derived our estimate of the annual probability of HIV acquisition for SA from the 2005 *South African National HIV Prevalence, HIV Incidence, Behaviour, and Communication Survey* (Rehle, Shisana, Pillay, Zuma, Puren, and Parker 2007; Shisana et al. 2005).

We assumed that initially 15% of HIV-positive HRHA were in need of ART. This number falls within the range of the proportion of HIV-positive people needing treatment found in studies across Africa (1% - 34%) (Williams, Korenromp, Gouws, Schmid, Auvert, and Dye 2006) when ART need is defined as a CD4 count of less than 200 cells per microliter (WHO 2004).

We used a recently published dataset, *Medical Brain Drain: Physicians Emigration Rates 1991-2004*, to derive annual probabilities of HRHA emigration (Docquier and Bhargava 2007a). Docquier and Bhargava use annual reports on physician immigration by 16 countries belonging to the Organisation for Economic Co-operation and Development (OECD) and data on physician numbers from the *World Development Indicators* to derive annual estimates of doctors’ emigration rates for 192 countries

(Docquier and Bhargava 2007b). We took estimates of the number of doctors from the same dataset (for each country-year) as the weighting factor to calculate a weighted average annual emigration probability for SSA and NSSA. We used the most recent estimate of the probability of annual doctor emigration available for the SA base case (i.e. for the year 2004) (Docquier and Bhargava 2007a).

In addition to emigration, we assumed that health workers leave the HRHA pool because they retire or die. We derived a combined annual probability of either of the two events from an estimate of the work lifetime of HIV-negative HRHA. We calculated the work lifetime as the difference between the weighted average life expectancy across the countries included in each of the base case regions (where the weighting factors are the country population sizes from the *World Development Indicators* (World Bank 2007)) or a retirement age of 60, whichever is lower, and an assumed average health worker age of 30. Estimates of new health workers added annually to the HRHA pool were inferred by assuming the current HRHA populations in the three regions were in steady state given the rate at which HRHA currently leave the pool.

Descriptive results

If the HRHA inflow and emigration rates remain at base-case levels, in 10 years ART coverage will have dropped in all three regional base-case scenarios, most substantially in SA, less in SSA, and least in NSSA (Figure 1). Table 2 shows results for the three regional base-case scenarios and for univariate sensitivity analyses when individual model parameters are varied. Table 3 shows the number of HRHA that need to be added to the existing HRHA population each year to achieve universal ART coverage in 10 years.

< Figure 1, Table 2, Table 3 >

Result 1: In all three base cases, the positive feedback from HRHA numbers to HRHA need (due to the effect of ART on mortality) is significant. At higher levels of ART coverage the feedback effect becomes larger; at near-universal coverage it is the main determinant of HRHA need.

Under base-case assumptions, ART coverage is lower for the model with feedback than for the model without feedback (by 3-7 percentage points). For the model with feedback, outputs are listed in Tables 2 and 3. Without feedback, 22-35% ART coverage is obtained by year 10 (30% in SSA; 35% in NSSA; 22% in SA) as well as in steady state. With feedback, as shown in Table 2 and Figure 1, coverage in year 10 drops to 19-28% (25% in SSA; 28% in NSSA; 19% in SA) and remains approximately at that level in steady state. At or near universal coverage, the feedback effect is the main determinant of HRHA need. Without feedback, the HRHA inflow rate required to achieve universal coverage in year 10 is 788 HRHA per year in SSA (or 0.6 times the size of the current HRHA population in the region), 199 HRHA per year in NSSA (or 0.3 times the size of the current HRHA population), and 494 HRHA per year in SA (or 1.5 times the size of the current HRHA population). With feedback, as shown in Table 3, this rate is 2.5 times higher in SSA (that is, 1,931 HRHA per year or 1.4 times the size of the current HRHA population in the region), 2.7 times higher in NSSA (that is, 532 HRHA per year or 0.8 times the size of the current HRHA population), and 2.2 times higher in SA (that is, 1085 HRHA per year or 2.2 times the size of the current HRHA population). The feedback effect also significantly affects the sustainability of universal ART coverage beyond year 10. For instance, without feedback, universal coverage with 1,287 HRHA per year is sustainable beyond year 10 for SSA (119% coverage in steady state). Similarly, universal coverage is easily sustainable with rates of 199 HRHA per year for NSSA (190% coverage in steady state) and 494 HRHA per year for SA in steady state (99% coverage in steady state). With feedback however, as shown in Figure 2, universal ART coverage beyond year 10 is not sustainable for SSA with an inflow of 1,931 HRHA per year. Indeed, steady-state universal coverage would require an inflow of 3,028 HRHA per year for SSA (469 for NSSA and 2,294 for SA).

< Figure 2 >

Result 2: HRHA ART coverage does not appreciably affect total population ART coverage in steady state. The reasons for this vary for the different regions (Table 2 and Figure 3).

< Figure 3 >

In NSSA, the total HRHA population (675) is small enough and the incidence of HIV among HRHA is low enough (0.024% per year) that almost no infected HRHA enter the pool of HIV-positive HRHA needing treatment every year. Therefore the need for ART among HRHA is essentially zero. In SA, the incidence of HIV among HRHA is higher (2.4% per year) but HRHA emigration is so high (28% per year, compared with 9% per year for SSA and 2% per year for NSSA) that only a negligible number of HRHA enter the pool of HIV-positive HRHA needing treatment every year. In SSA, HRH HIV incidence is considerable (0.421% per year), but the number of HRHA needing treatment in steady state is small (4 out of a total of 1,334), so that population ART coverage in SSA is insensitive to changes in HRHA ART coverage.

Result 3: HRHA inflow and emigration have the most significant effects on population ART coverage (Table 2 and Figure 3).

A 25% increase in HRHA inflow increases ART coverage among the overall population by 9-21% (16% in SSA; 9% in NSSA; 21% in SA). A 25% decrease in HRHA emigration increases ART coverage by 11% in SSA, by 22% in SA, and by 3% in NSSA. Setting emigration to zero has a drastic effect on population ART coverage, increasing coverage in year 10 by 54% in SSA, by 157% in SA, and by 14% in NSSA.

Result 4: Sustainable universal population ART coverage in SSA and SA can be achieved beyond year 10 with much lower increases in HRHA inflow if HRHA *emigration is reduced. The alternative to reducing emigration is a several-fold increase in HRHA inflow (Table 3 and Figure 2).*

In order to achieve universal population ART coverage in SSA in year 10, we can increase the HRHA inflow to 1,931 HRHA per year. However, at this level of HRHA inflow and the base-case emigration level, universal ART coverage is not sustainable and drops to 89% in steady state (Figure 2). If, by contrast, HRHA emigration is set to zero, we need a substantially smaller HRHA inflow rate (1,262 HRHA per year) to both achieve universal ART coverage in year 10 and sustain it in steady state. In SA, universal coverage is obtained in year 10 with an HRHA inflow rate of 1,085 per year, but – because of high base-case HRHA emigration (28% per year) – ART coverage falls to 80% in steady state. In contrast, if emigration from SA is reduced to 0, universal coverage can be maintained by an inflow rate of 399 per year. In NSSA, the HRHA inflow rate required to achieve universal coverage by year 10 (532 HRHA per year) will be sufficient to sustain universal coverage in steady state *without* decreasing the level of HRHA emigration below its base-case value (because at 2% per year base-case emigration is already low).

Analytical results

Although the findings in the Results section are compelling, the results are numerical, that is, they reflect particular choices of model parameters (from Table 1). Similarly, the sensitivity analysis in the previous section is for limited variation of a few key parameters. Deeper insight into the model's behavior and wider sensitivity analysis are possible by analyzing the model's steady-state behavior. To do that, we first present the mathematical formulation of our model.

Notation

t = time period, $t = 0, \ldots, \infty$.

L = latency period from start of infection to needing treatment (for both HRHA and patients in the general population).

ϕ = number of HIV/AIDS patients treatable by one HRHA.

H_t^H = number of healthy HRHA at the beginning of period t.

$H_t^{I_k}$ = number of HIV-infected HRHA who do not yet need antiretroviral treatment (ART) at the beginning of period t, who were infected k periods ago, $k = 0,\ldots,L-1$.

H_t^N = number of HRHA needing ART at the beginning of period t.

H_t^T = number of HRHA needing and receiving ART at the beginning of period t.

H_t^U = number of HRHA needing but not receiving ART at the beginning of period t.

H_t = total number of HRHA at the beginning of period t.

P_t^T = population receiving ART at the beginning of period t.

P_t^U = population needing but not receiving ART at the beginning of period t.

P_t = total population needing ART at the beginning of period t.

The term 'rate', below, always means a fraction of the existing population and is always per period. It stands for the annual probability of an individual in the population experiencing an event (for instance, the annual probability of death, HIV infection, or emigration). Events are assumed to be independent over time.

m^H, m^I, m^T, m^U = mortality rates for healthy, infected, treated, and untreated HRHA.

e^H, e^I, e^T, e^U = emigration rates for healthy, infected, treated, and untreated HRHA.

m^{TP}, m^{UP} = mortality rates for people needing and receiving ART, and for people needing but not receiving ART.

m^G = mortality rate for the general population.

i^H = HRHA HIV incidence rate.

a^H = Number of new HRHA per period.

a^P = Number of people newly infected with HIV per period.

c_t^H = HRHA ART coverage in period t.

c = population ART coverage in period t.

We assume regularity conditions on the parameters of the form
$m^H + e^H \leq 1$, $m^I + e^I \leq 1$, $m^T + e^T \leq 1$, $m^U + e^U \leq 1$.

Formulation

The following formulation assumes that all quantities are continuous. Initial values at $t = 0$ for all quantities indexed by t are given. Then for $t = 1, 2, \ldots, \infty$, the HRHA population evolves as follows:

$$H_t^H = a^H + (1 - i^H)(1 - m^H - e^H)H_{t-1}^H,$$

$$H_t^{I_0} = i^H(1 - m^H - e^H)H_{t-1}^H,$$

$$H_t^{I_1} = (1 - m^I - e^I)H_{t-1}^{I_0},$$

$$\vdots$$

$$H_t^{I_{L-1}} = (1 - m^I - e^I)H_{t-1}^{I_{L-2}},$$

$$H_t^N = (1 - m^I - e^I)H_{t-1}^{I_{L-1}} + (1 - m^T - e^T)H_{t-1}^T + (1 - m^U - e^U)H_{t-1}^U,$$

$$H_t^T = c_t^H H_t^N,$$

$$H_t^U = (1 - c_t^H)H_t^N,$$

$$H_t = H_t^H + H_t^{I_0} + \cdots + H_t^{I_{L-1}} + H_t^N.$$

If HRHA coverage is exogenous and time independent, c_t^H is some constant c^H. Therefore the foregoing equations completely describe the evolution of HRHA over time. If HRHA ART coverage is endogenous but the same as population ART coverage, then the evolution of HRHA is completely specified by using $c_t^H = \min(\phi H_t / P_t, 1.0)$, where P_t is obtained from the following population evolution equations for $t = 1, 2, \dots, \infty$:

$$P_t = a^P (1 - m^G)^L + (1 - m^{TP}) P_{t-1}^T + (1 - m^{UP}) P_{t-1}^U,$$
$$P_t^T = \min(\phi H_t, P_t),$$
$$P_t^U = P_t - \min(\phi H_t, P_t).$$

Analysis

HRHA needed for universal population ART coverage in the steady state: At universal coverage $\phi H_\infty = P_\infty$ (where ∞ denotes steady state). In steady state, patient inflow must equal patient outflow, that is, $a^P (1 - m^G)^L = P_\infty m^{TP}$, which gives the following equation for universal coverage:

$$H_\infty = \frac{a^P (1 - m^G)^L}{\phi m^{TP}}.$$

The expression above allows us to compare HRHA requirements for universal population ART coverage in a model with feedback (caused by a lower mortality rate among those receiving versus those not receiving ART) with a model without feedback. Given the mortality rates from Table 1, $m^{TP} = 0.05$, and $m^{UP} = 0.23$, the model without feedback would use $m^{UP} = 0.23$ in the above expression in place of m^{TP}. The model with feedback therefore requires 4.6 times more HRHA for universal coverage in steady state than the model without feedback.

HRHA requirement as a function of a pre-specified steady-state population ART coverage $0 \le c \le 1$: In steady state, we must have $a^P(1-m^G)^L = P_\infty\left(cm^{TP} + (1-c)m^{UP}\right)$. With $c = \phi H_\infty / P_\infty$, this gives

$$H_\infty = \frac{ca^P(1-m^G)^L}{\phi\left(cm^{TP} + \left(1-c\right)m^{UP}\right)}.$$

Figure 4 shows how the annual inflow of HRHA required to reach steady state for a model with feedback increases nonlinearly with desired population coverage, compared with a linear increase for a model without feedback. The magnitude of the difference indicates the impact of feedback. The required number of HRHA for the model with feedback is 1.6 times that for a model without feedback at 50 percent coverage, 2.4 times at 75 percent coverage, 3.4 times at 90 percent coverage, and 4.6 times at 100 percent coverage.

< Figure 4 >

Computing steady-state population ART coverage for given model parameters: To compute the steady-state coverage for a given a set of model parameters, we can obtain the steady-state versions of HRHA subpopulations in the exogenous HRHA coverage case as follows:

$$H_\infty^H = \frac{a^H}{m^H + e^H + i^H(1-m^H-e^H)},$$

$$H_\infty^{I_0} = i^H(1-m^H-e^H)H_\infty^H,$$

$$H_\infty^{I_1} = i^H(1-m^H-e^H)(1-m^I-e^I)H_\infty^H,$$

$$\vdots$$

$$H_\infty^{I_{L-1}} = i^H(1-m^H-e^H)(1-m^I-e^I)^{L-1}H_\infty^H.$$

For exogenous HRHA coverage, $H_\infty^T = c^H H_\infty^N$, $H_\infty^U = (1-c^H)H_\infty^N$, which gives

$$H_\infty^N = \frac{i^H(1-m^H-e^H)(1-m^I-e^I)^L H_\infty^H}{1-c^H(1-m^T-e^T)-(1-c^H)(1-m^U-e^U)},$$

$$H_\infty = H_\infty^H\left[1+i^H(1-m^H-e^H)\left(\begin{array}{c}1+(1-m^I-e^I)+\cdots+(1-m^I-e^I)^{L-1}+ \\ \dfrac{(1-m^I-e^I)^L}{1-c^H(1-m^T-e^T)-(1-c^H)(1-m^U-e^U)}\end{array}\right)\right].$$

The foregoing formulae readily allow the steady-state HRHA pool size to be computed. Its sensitivity to changes in various parameters – such as HRHA coverage, emigration, and HIV incidence rates – can then be plotted over their full range. Figures 5-7 show plots of steady-state HRHA pools size for SSA by HRHA ART coverage, HRHA emigration rate, and HRHA ART coverage, respectively. Figure 8 shows the plot of HRHA pool size for SSA when all three parameters (HRH ART coverage, HRHA emigration rate and HRHA ART) coverage are simultaneously increased from 0% to 100%.

< Figures 5-8 >

Figure 5 shows that HRHA emigration rate for SSA has the most pronounced effect on decreasing the steady-state HRHA pool size in the 0-40% emigration range. If fewer HRHA are available, fewer emigrate. Therefore at lower HRHA pool sizes the effects of emigration in reducing the HRHA pool size become smaller. However, emigration rates affect healthy and infected HRHA equally, so the proportion of healthy to infected HRHA remains unaltered by emigration rates.

Figure 6 shows that the steady-state HRHA pool size for SSA is relatively insensitive to changes in the HRHA HIV incidence rate, but that the number of infected HRHA is quite sensitive to such changes. This peculiarity is due to the high emigration rate for SSA (0.09), a rate that is higher than the mortality rate of healthy HRHA (0.06). Most infected

HRHA therefore emigrate or die within their 10-year latency period, at a level comparable to their combined emigration and mortality rate if they had not been infected. This makes the total HRHA pool size insensitive to the HRHA HIV incidence rate, even though at any given time high HRHA HIV incidence means more HRHA are infected as shown in Fig. 6.

Figure 7 shows the above phenomenon from another view. Because few infected HRHA survive emigration or mortality through the 10-year latency period, HRHA ART coverage does not have an appreciable effect on the total HRHA pool size. The number of healthy HRHA is of course independent of the HRHA ART coverage and is shown in Fig. 7 only for comparison.

In the exogenous HRHA coverage case, H_∞ evolves independently of the patient population. The steady-state patient population can then be computed from the expression $a^P(1-m^G)^L = \min(\phi H_{\infty,} P_\infty)m^{TP} + \left(P_\infty - \min(\phi H_{\infty,} P_\infty)\right)m^{UP}$. This gives

$$\begin{cases} P_\infty = \dfrac{a^P(1-m^G)^L + \phi H_\infty (m^{UP} - m^{TP})}{m^{UP}}, \quad if\ H_\infty \le \dfrac{a^P(1-m^G)^L}{\phi m^{TP}}, \\ P_\infty = \dfrac{a^P(1-m^G)^L}{m^{TP}}, \quad o/w. \end{cases}$$

In summary, the steady-state HRHA pool size, and thus population ART coverage, is very sensitive to changes in the HRHA emigration rate and is insensitive to changes in HRHA HIV incidence and HRHA ART coverage (Figures 5-8). Figure 5 shows that the sensitivity of the steady-state HRH pool size to changes in HRHA emigration rates increases with decreasing emigration rates. Figures 6 and 7 show that the steady-state HRH pool size is insensitive to changes in HRHA HIV incidence and HRHA ART coverage over the entire range of the two parameters.

Discussion

A number of policy implications flow from our model results.

Policy implication 1: Strategies to achieve universal ART coverage in developing countries are bound to fail if they do not take into account that higher current HRHA numbers will lead to higher future HRHA need.

One of the motivations for our study was to investigate the feedback effect from HRHA numbers on HRHA need. We find that even at low initial ART coverage, say 30%, ignoring feedback may result in substantial overestimation of the population ART coverage that can be achieved in the long run. Moreover, as ART coverage increases, the feedback effect becomes increasingly important. For instance, without feedback, an annual inflow of at least 788 HRHA would be required to achieve universal ART coverage in SSA 10 years from now, while with feedback that number would rise to 1,931 HRHA (Table 3). If no feedback occurred, the number of HRHA needed to achieve universal ART coverage 10 years from now would be sufficient to maintain near-universal coverage beyond year 10, while with feedback universal coverage could not be sustained at the inflow rate needed to achieve universal coverage in year 10. As ART programs in developing countries continue to scale up treatment in the coming years, they will increasingly fall victim to their own success, constantly needing to increase the number of HRHA simply to maintain ART coverage levels.

Our model assumes that the number of HRHA needed to treat 1,000 patients is constant over time. Changes in the mix of patients, the need for treatment, treatment technology, or experience may make an adjustment to the HRHA-to-patient ratio necessary. On the one hand, a plausible expectation is that more health workers will be needed to treat a fixed number of patients as ART programs mature. Patients in initial treatment cohorts may, on average, require less HRHA time because they are healthier, better educated, or have more effective social support than patients who access ART in later stages of ART roll-out. In addition, as the average time on ART increases, adherence failure (Mannheimer et al. 2006), ART failure due to viral resistance, and adverse events associated with ART (Orrell et al. 2007) will become more common, thereby increasing the amount of time that HRHA need to spend per patient. On the other hand, technological advances, such as combination pills, better patient management systems, or increasing experience in providing ART among HRHA, could reduce the HRHA-to-patient ratio over time. Furthermore, as patients gain treatment experience, knowledge about how to take antiretroviral medicines and how to deal with the side effects of ART may spread through the population, replacing time-consuming interactions between patients and HRHA with interaction between patients.

Policy implication 2: Even to maintain the current level of ART coverage in developing countries, health policies must be put into place to either increase the number of HRHA, reduce HIV incidence, or both.

While the feedback effect from the current level of HRHA to future HRHA need is moderately large at current levels of population ART coverage, we find that current levels of coverage will not be maintained in SAA and SA under base-case assumptions because of the continued high inflow of people needing ART into the population. If inflows into the pool of HRHA and outflows caused by emigration or death remain at their current levels, in the next five years, ART coverage will decline in SSA from 28% to 25% and in SA from 33% to 19%. The current level of ART coverage has been achieved as a result of immense efforts by national governments in developing countries and international initiatives, including WHO's 3 by 5 Program; the Global Fund to Fight AIDS, Tuberculosis and Malaria; and PEPFAR (Bärnighausen 2007). Even if these efforts are further intensified, universal coverage is unlikely to be achieved without substantial success in reducing the continued high incidence of HIV in developing countries, especially in SSA.

This conclusion from our model rests on the assumption that the estimate of the inflow of people into the pool of those needing treatment is valid and that HIV incidence in the three base-case regions has been approximately constant over the last 10 years. The rate of inflow of people needing ART is a function of HIV incidence and mortality during the latency period between HIV infection and treatment, two parameters that are uncertain. For instance, UNAIDS and WHO provide a range of 1.4 million to 2.4 million people around their estimate of 1.7 million people newly infected with HIV in SSA during 2007 as the “boundaries within which the actual numbers lie, based on the best available information” (UNAIDS and WHO 2007). However, while the precise parameter values are uncertain, our conclusion that current levels of ART coverage will not be maintained under base-case assumptions is robust to substantial changes in the base-case patient inflow rate.

Our model does not take into account other effects of increased HRHA that may affect future need for HRHA, such as reductions in the probability of HIV transmission per risky sex act (because ART reduces viral load) (Quinn, et al. 2000) and changes in risk behavior because of the availability of ART (Kennedy, O'Reilly, Medley, and Sweat 2007). Future models need to investigate whether such effects could alter the main results of our study.

Policy implication 3: To achieve universal ART coverage, the inflow of HRHA into ART programs in developing countries will need to increase substantially. In SSA and SA, policies that increase this inflow will be much more effective if accompanied by interventions to decrease HRHA emigration rates.

Even at current coverage levels of around 30%, ART programs in many developing countries struggle to find sufficient HRHA to further scale up ART (Médecins Sans Frontières 2007b; Ooms et al. 2007). We find that under a wide range of assumptions, the workforce required to treat HIV/AIDS patients will need to be increased dramatically if universal ART coverage is to be achieved. Such an increase may be especially difficult to achieve in SSA.

The capacity for providing health care education is currently very limited in SSA (WHO 2006). For instance, Eckhert (2002) estimates that 5,100 students graduate each year from medical school in SSA. A simple comparison to an estimate of the number of doctors that are currently lacking in SSA to ensure the delivery of “essential health interventions” helps to put this number into perspective (Joint Learning Initiative on Human Resources for Health (JLI) 2004, p. 23). JLI estimates that “a density of 2.5 workers per 1,000 may be considered a threshold of worker density necessary to attain adequate coverage of some essential health interventions and core MDG-related [Millennium Development Goal-related] health services” (JLI 2004, p.23) and derives from this density threshold that “sub-Saharan countries would immediately require an additional 1 million doctors, nurses, and midwives” (JLI 2004, p. 72). Using recent data on absolute numbers of doctors, nurses, and midwives available in the period 2002-2004 from the WHO *Global Atlas on the Health Workforce* (WHO 2007), we calculate an average ratio of 6 nurses and midwives to 1 doctor in SSA.[1] According to this ratio 143,000 of the 1 million health workers estimated to be needed in SSA are doctors. Assuming that none of the existing doctors and none of the doctors newly added to the workforce emigrated or died, at existing education capacity it would take 28 years to add 143,000 doctors to the current health workforce in SSA.

We estimate that 1,931 HRHA would need to be added annually to the HRHA workforce in SSA in order to achieve universal ART coverage. According to the health worker-to-patient ratios measured by Hirschhorn and colleagues (2006), the 1,931 HRHA represent 1,931 to 3,862 doctors (see Methods, p. 4). The annual need for additional doctors to achieve universal ART coverage in SSA estimated at the upper bound could not be met given the current education capacity in the region, even if all graduating doctors started working in ART programs. While the annual need for additional doctors estimated at the lower bound could theoretically be met, allocating 1,931 (or 38%) of the 5,100 doctors who are estimated to graduate from medical school in SSA each year to ART programs would very likely worsen the already severe shortage of doctors delivering non-ART health services.

[1] Data was available for 45 of the 48 countries in SSA. We compare the total number of doctors in all 45 countries to the total number of nurses and midwives.

Another option to increase the number of HRHA in developing countries is to attract international graduates to work in ART programs. SA, for instance, is actively recruiting international doctors and nurses to work in rural health centers (Rural Health Initiative 2007). However, the pool of physicians from developed countries who are willing to work in developing-country ART programs is probably quite limited, and international health workers may perform less well than locally educated workers, for example, because of language difficulties or lack of familiarity with the local health care system.

It seems unlikely that countries in SSA will be able to meet the HRHA need to achieve universal coverage, unless health care education capacity is increased. An increase in the capacity to train health workers, however, may itself be constrained by human resources shortages (Bossert et al. 2007). In many developing countries, not only are health care teachers scarce (WHO 2006), but so are secondary school graduates sufficiently qualified to undertake an education in health care (Kingsley and Juliet 2001).

We find that the increases in HRHA inflow required to achieve universal ART coverage are substantially reduced if HRHA emigration rates are decreased. A number of policy options exist to stem the current high levels of emigration from SSA to developed countries. These options include awarding “conditional scholarships” for health care education, whereby qualified candidates receive scholarships if they enter into a contract to work on delivering ART in the country where they were educated for a specific number of years following their graduation (Bärnighausen and Bloom 2007; Bärnighausen and Bloom 2008); training health workers to deliver ART who are not internationally mobile, because their health care profession is not recognized in developed countries (such as health officers), but who can (partially) replace internationally mobile workers (such as doctors and nurses) (Dovlo 2004); and requiring developed countries to adopt so-called ethical recruiting practices, which limit the admission of health workers from developing countries (Stilwell et al. 2003).

Various options are available to increase the inflow of HRHA. First, health workers who currently work in the general health care system can leave their positions and become part of the workforce treating HIV/AIDS patients. In countries with generalized HIV epidemics, large proportions of inpatient and outpatient admissions are related to HIV (Bardgett, Dixon, and Beeching 2006; Dedicoat, Grimwade, Newton, and Gilks 2003; Floyd, Reid, Wilkinson, and Gilks 1999). Since ART decreases health care utilization among HIV-positive people (Harling, Orrell, and Wood 2007), expansion of ART coverage may free up health care capacity to treat other patients. Thus in the short run, health systems in some developing countries may be able to sustain a shift of health workers into ART programs without detrimental effects on access to care that is not related to HIV/AIDS. However, these health systems are unlikely to be able to sustain large flows of health workers into ART programs over many years without an adverse impact on performance, especially if the integration of ART programs into the overall system is not well managed (Schneider, Blaauw, Gilson, Chabikuli, and Goudge 2006).

One of our aims was to examine the extent to which a reduction of HIV incidence among HRHA and an increase in HRHA ART coverage are effective interventions to increase the number of HRHA in the long run. Health policy makers and researchers have called for an increased focus on HIV prevention and AIDS treatment among the health workforce (Shisana 2007). We find that neither HIV prevention among health workers nor HRHA ART coverage are important determinants of long-term population ART coverage. However, these findings are certainly not arguments against ensuring that health workers have access to HIV prevention services and ART, which can be supported on a number of grounds (Macklin 2004). In addition, if – as Dovlo (2007) asserts – the provision of effective HIV prevention and free ART in the workplace reduce health worker emigration, our results provide an indirect argument for such service provision.

Conclusion

If efforts to achieve universal ART coverage in the developing world are to succeed, large numbers of health workers must enter the workforce to provide ART on an ongoing basis. Projections of the numbers of health workers required must take into account positive feedback phenomena. At high coverage levels, the effectiveness of ART in reducing mortality among HIV-positive people becomes the main determinant of HRHA need. HIV prevention that is effective in reducing HIV incidence and interventions to decrease health worker emigration from developing to developed countries could be effective means of reducing the extremely large shortfall of HRHA in developing countries.

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References

Badri, M., S. D. Lawn, and R. Wood. 2006. “Short-Term Risk of AIDS or Death in People Infected with HIV-1 before Antiretroviral Therapy in South Africa: A Longitudinal Study.” *Lancet* 368 (9543):1254–59.

Bardgett, H. P., M. Dixon, and N. J. Beeching. 2006. “Increase in Hospital Mortality from Non-Communicable Disease and HIV-Related Conditions in Bulawayo, Zimbabwe, Between 1992 and 2000.” *Tropical Doctor* 36 (3): 129–31.

Bärnighausen, T. 2007. Access to antiretroviral treatment in the developing world: a framework, review and health systems research agenda. *Therapy* 4(6): 753-766.

Bärnighausen, T., and D. E. Bloom. 2007. "’Conditional Scholarships’ for HIV/AIDS Health Workers: Educating and Retaining the Workforce to Provide Antiretroviral Treatment in Sub-Saharan Africa.” Working Paper 13396. National Bureau of Economic Research, Cambridge, MA.

Bärnighausen, T., and D. E. Bloom. 2008. *Financial incentives for return of service in underserved areas: a systematic review* (submitted).

Blower, S., E. Bodine, J. Kahn, and W. McFarland. 2005. “The Antiretroviral Rollout and Drug-Resistant HIV in Africa: Insights from Empirical Data and Theoretical Models.” *AIDS* 19 (1): 1–14.

Boerma, J. T., K. A. Stanecki, M. L. Newell, C. Luo, M. Beusenberg, G. P. Garnett, K. Little, J. G. Calleja, S. Crowley, J. Y. Kim, E. Zaniewski, N. Walker, J. P. Stover, and P. D. Ghys. 2006. “Monitoring the Scale-Up of Antiretroviral Therapy Programmes: Methods to Estimate Coverage. *Bulletin of the World Health Organization* 84 (2):145–50.

Bossert, T., T. Bärnighausen, D. Bowser, A. Mitchell,and G. Gedik 2007. *Assessing financing, education, management and policy context for strategic planning of human resources for health.* Geneva: World Health Organization.

Braitstein, P., M. W. Brinkhof, F. Dabis, M. Schechter, A. Boulle, P. Miotti, R. Wood, C. Laurent, E. Sprinz, C. Seyler, D. R. Bangsberg, E. Balestre, J. A. Sterne, M. May, and M. Egger 2006. “Mortality of HIV-1-Infected Patients in the First Year of

Antiretroviral Therapy: Comparison between Low-Income and High-Income Countries." *Lancet* 367 (9513): 817–24.

Chen, L., and P. Hanvoravongchai. 2005. "HIV/AIDS and Human Resources." *Bulletin of the World Health Organization* 83 (4):243–44.

Clark J. 2006. "HIV Programmes in Poor Countries Lack Health Workers." *British Medical Journal* 333 (7565): 412.

Clinton Foundation. 2007. "Clinton Foundation HIV/AIDS Initiative." http://www.clintonfoundation.org/cf-pgm-hs-ai-home.htm. Last accessed: September 1, 2007.

Connelly, D., Y. Veriava, S. Roberts, J. Tsotetsi, A. Jordan, E. DeSilva, S. Rosen, and M. B. DeSilva 2007. "Prevalence of HIV Infection and Median CD4 Counts among Health Care Workers in South Africa." *South African Medical Journal* 97 (2):115–20.

Dedicoat, M., K. Grimwade, R. Newton, and C. Gilks. 2003. "Changes in the Patient Population Attending a Primary Health Care Clinic in Rural South Africa Between 1991 and 2001." *South African Medical Journal* 93 (10): 777–78.

Docquier, F., and A. Bhargava. 2007a. "A New Panel Data Set on Physician's Emigration rates (1991-2004)." Report. Washington, D.C.: World Bank.

Docquier, F., and A. Bhargava. 2007b. "The Medical Brain Drain: Physicians' Emigration Rates 1991–2004." http://siteresources.worldbank.org/INTRES/Resources/DataSetDocquierBhargava_Medical_BD100306.xls. Last accessed: December 8, 2007.

Dovlo, D. 2004. "Using Mid-Level Cadres as Substitutes for Internationally Mobile Health Professionals in Africa: A Desk Review." *Human Resources for Health* 2 (1): 7.

_____. 2007. "Migration of Nurses from Sub-Saharan Africa: A Review of Issues and Challenges." *Health Services Research* 42 (3 Pt 2): 1373–88.

Eckhert, N. L. 2002. "The Global Pipeline: Too Narrow, too Wide or Just Right?" *Medical Education* 36 (7): 606–13.

Floyd, K., R. A. Reid, D. Wilkinson, and C. F. Gilks. 1999. "Admission Trends in a Rural South African Hospital During the Early Years of the HIV Epidemic." *Journal of the American Medical Association* 282 (11): 1087–91.

Global Fund to Fight AIDS, Tuberculosis and Malaria. 2007. "Fighting AIDS." http://www.theglobalfund.org/en/. Last accessed: September 1, 2007.

Hargreaves, J. R., and J. R. Glynn. 2002. "Educational Attainment and HIV-1 Infection in Developing Countries: A Systematic Review." *Tropical Medicine & International Health* 7 (6): 489–98.

Harling, G., C. Orrell, and R. Wood. 2007. "Healthcare Utilization of Patients Accessing an African National Treatment Program." *BMC Health Services Research* 7: 80.

Herbst, K., Cooke, G., Bärnighausen, T., Kany Kany, A., Tanser, F., and Newell, M.-L. (2008). Adult mortality and antiretroviral treatment roll-out in a rural population in KwaZulu-Natal (submitted).

Hirschhorn, L. R., L. Oguda, A. Fullem, N. Dreesch, and P. Wilson. 2006. "Estimating Health Workforce Needs for Antiretroviral Therapy in Resource-Limited Settings." *Human Resources for Health* 4: 1.

Hogg, R. S., B. Yip, C. Kully, K. J. Craib, M. V. O'Shaughnessy, M. T. Schechter, and J. S. Montaner. 1999. "Improved Survival among HIV-Infected Patients after Initiation of Triple-Drug Antiretroviral Regimens." *Canadian Medical Association Journal* 160 (5): 659–65.

Hosseinipour, M., P. Kazembe, I. Sanne, and C. van der Horst. 2002. "Challenges in Delivering Antiretroviral Treatment in Resource Poor Countries". *AIDS* 16 (Suppl 4 (16): 177–87.

Institute of Medicine. 2007. PEPFAR Implementation: Progress and Promise. Washington, DC: National Academies Press.

JLI (Joint Learning Initiative). 2004. *Human Resources for Health – Overcoming the Crisis*. Boston: Harvard University Press.

Kennedy, C., K. O'Reilly, A. Medley, and M. Sweat. 2007. "The Impact of HIV Treatment on Risk Behaviour in Developing Countries: A Systematic Review.: *AIDS Care* 19 (6): 707–20.

Kingsley, B., and E. Juliet. 2001. "The World Bank and Financing Higher Education in Sub-Saharan Africa." *Higher Education* 42 (1): 1–34.

Kober, K., and W. Van Damme. 2004. "Scaling-Up Access to Antiretroviral Treatment in Southern Africa: Who Will Do the Job?" *Lancet* 364 (9428):103–107.

Law, A. M., and W. D. Kelton. 2000. *Simulation Modeling and Analysis*. Boston: McGraw-Hill.

Macklin, R. 2004. *Ethics and Equity in Access to HIV Treatment: 3 by 5 Initiative*. Geneva: World Health.

Mannheimer, S. B., E. Morse, J. P. Matts , L. Andrews, C. Child, B. Schmetter, G. H. Friedland; Terry Beirn Community Programs for Clinical Research on AIDS. 2006. "Sustained Benefit from a Long-Term Antiretroviral Adherence Intervention: Results of a Large Randomized Clinical Trial." *Journal of Acquired Immune Deficiency Syndromes* 43 (Suppl 1): S41–S47.

Marchal, B., V. De Brouwere, and G. Kegels. 2005. "Viewpoint: HIV/AIDS and the Health Workforce Crisis: What Are the Next Steps?" *Tropical Medicine & International Health* 10 (4): 300–4.

Marchal, B., G. Kegels, and V. De Brouwere. 2004. "Human Resources in Scaling Up HIV/AIDS Programmes: Just a Killer Assumption or in Need of New Paradigms?" *AIDS* 18 (15): 2103–5.

Médecins Sans Frontières. 2007a. "HIV/AIDS." http://www.doctorswithoutborders.org/news/hiv-aids/. Last accessed: December 5, 2007.

_____. 2007b. *Help Wanted: Confronting the Health Care Worker Crisis to Expand Access to HIV/AIDS Treatment: MSF Experience in Southern Africa*. Johannesburg: Médecins Sans Frontières.

Merson, M. H., J. M. Dayton, and K. O'Reilly. 2000. "Effectiveness of HIV Prevention Interventions in Developing Countries." *AIDS* 14 (Suppl 2):S68–84.

Ncayiyana, D. J. 2004. “Doctors and Nurses with HIV and AIDS in Sub-Saharan Africa.” *British Medical Journal* 329 (7466): 584–85.

Ooms, G., W. Van Damme, and M. Temmerman. 2007. “Medicines without Doctors: Why the Global Fund Must Fund Salaries of Health Workers to Expand AIDS Treatment”. *PLoS Medicine* 4 (4): e128.

Orrell, C., G. Harling, S. D. Lawn, R. Kaplan, M. McNally, L. G. Bekker, and R. Wood. 2007. “Conservation of First-Line Antiretroviral Treatment Regimen Where Therapeutic Options Are Limited.” *Antiviral Therapy* 12 (1): 83–88.

PEPFAR (President’s Emergency Plan for AIDS Relief) 2007. “The United States President's Emergency Plan for AIDS Relief.” http://www.pepfar.gov/. Last accessed: September 1, 2007.

Quinn, T. C., M. J. Wawer, N. Sewankambo, D. Serwadda, C. Li, F. Wabwire-Mangen, M. O. Meehan, T. Lutalo, and R. H. Gray. 2000. “Viral Load and Heterosexual Transmission of Human Immunodeficiency Virus Type 1: Rakai Project Study Group.” *New England Journal of Medicine* 342 (13): 921–29.

Rehle, T., O. Shisana, V. Pillay, K. Zuma, A. Puren, and W. Parker. 2007. “National HIV Incidence Measures: New Insights into the South African Epidemic.” *South African Medical Journal* 97 (3): 194–99.

Rural Health Initiative. 2007. “Welcome to Rural Health Initiative South Africa.” http://www.rhi.org.za/. Last accessed: June 25, 2007.

Schneider, H., D. Blaauw, L. Gilson, N. Chabikuli, and J. Goudge. 2006. “Health Systems and Access to Antiretroviral Drugs for HIV in Southern Africa: Service Delivery and Human Resources Challenges.” *Reproductive Health Matters* 14 (27): 12–23.

Shisana, O. 2007. “High HIV/AIDS Prevalence among Health Workers Requires Urgent Action.” *South African Medical Journal* 97 (2):108–9.

Shisana, O., E. J. Hall, R. Maluleke, J. Chauveau, and C. Schwabe. 2004. “HIV/AIDS Prevalence among South African Health Workers.” *South African Medical Journal* 94 (10): 846–50.

Shisana, O., T. Rehle, L. C. Simbayi, W. Parker, K. Zuma, A. Bhana, C. Connolly, S.Jooste, and V. Pillay. 2005. South African National HIV Prevalence, HIV Incidence, Behaviour, and Communication Survey. Cape Town, South Africa: HSRC Press.

Stilwell, B., K. Diallo, P. Zurn, M. R. Dal Poz, O. Adams, and J. Buchan. 2003. "Developing Evidence-Based Ethical Policies on the Migration of Health Workers: Conceptual and Practical Challenges." *Human Resources for Health* 1 (1): 8.

Tawfik, L., and S. Kinoti. 2003. *The Impact of HIV/AIDS on Health Systems and the Health Workforce in Sub-Saharan Africa*. Washington, DC: U.S. Agency for International Development, Bureau for Africa.

UNAIDS (Joint United Nations Programme on HIV/AIDS) and WHO (World Health Organization). 2007. *AIDS Epidemic Update: Special Report on HIV/AIDS: December 2007*. Geneva: UNAIDS.

United Nations 2007. "Political Declaration on HIV/AIDS." http://data.unaids.org/pub/Report/2006/20060615_HLM_PoliticalDeclaration_ARES60262_en.pdf. Last accessed: September 1, 2007.

Van Damme, W., K. Kober, and M. Laga. 2006. "The Real Challenges for Scaling Up ART in Sub-Saharan Africa." *AIDS* 20 (5): 653–56.

WHO (World Health Organization). 2004. *Scaling Up Antiretroviral Therapy in Resource-Limited Settings: Treatment Guidelines for a Public Health Approach*. Geneva: WHO.

_____. 2006. *World Health Report 2006: Working Together for Health*. Geneva: WHO.

_____. 2007. "Global Health Atlas." http://www.who.int/globalatlas/default.asp. Last accessed: December 9, 2007).

WHO (World Health Organization), UNAIDS (Joint United Nations Programme on HIV/AIDS), and UNICEF (United Nations Children's Fund). 2007. *Towards Universal Access*. Geneva: WHO.

Williams, B. G., E. L. Korenromp, E. Gouws, G. P. Schmid, B. Auvert, and C. Dye. 2006. "HIV Infection, Antiretroviral Therapy, and CD4+ Cell Count Distributions in African Populations." *Journal of Infectious Diseases* 194 (10): 1450–58.

World Bank. 2007. *World Development Indicators*. Washington, DC: World Bank.

Table 1: Parameter estimates for base cases

Parameters	Base-case values SSA	NSSA	SA	Sources
HRHA work lifetime (years)	17	30	18	World Bank 2007
HRHA emigration rate (%)	0.09	0.02	0.28	Docquier and Bhargava 2007b
Initial HRHA HIV prevalence (%)	5.00	0.30	18.80	UNAIDS/WHO 2007
HRHA HIV incidence rate (%)	0.421	0.024	2.400	UNAIDS/WHO 2006, Rehle et al. 2007
Initial total number of HRHA	1,340	675	325	Hirschhorn et al. 2006
Number of people newly infected with HIV (per year)	1,700,000	734,000	571,000	UNAIDS/WHO 2007
Initial size of total population needing ART	4,800,000	2,297,000	1,000,000	WHO/UNAIDS/UNICEF 2007
Initial size of population needing but not receiving ART	3,460,000	1,622,000	675,196	WHO/UNAIDS/UNICEF 2007
Initial size of population receiving ART	1,340,000	675,000	324,804	WHO/UNAIDS/UNICEF 2007

HRHA = human resources to treat HIV/AIDS, ART = antiretroviral treatment, SSA = sub-Saharan Africa, NSSA = non-sub Saharan African low- and middle-income countries, SA = South Africa. HRHA emigration rate is the annual probability of death in HRHA. HRHA HIV incidence is the annual probability of HIV infection in HIV-negative HRHA.

Table 2: Results of base-case scenarios and sensitivity analyses

[redacted]

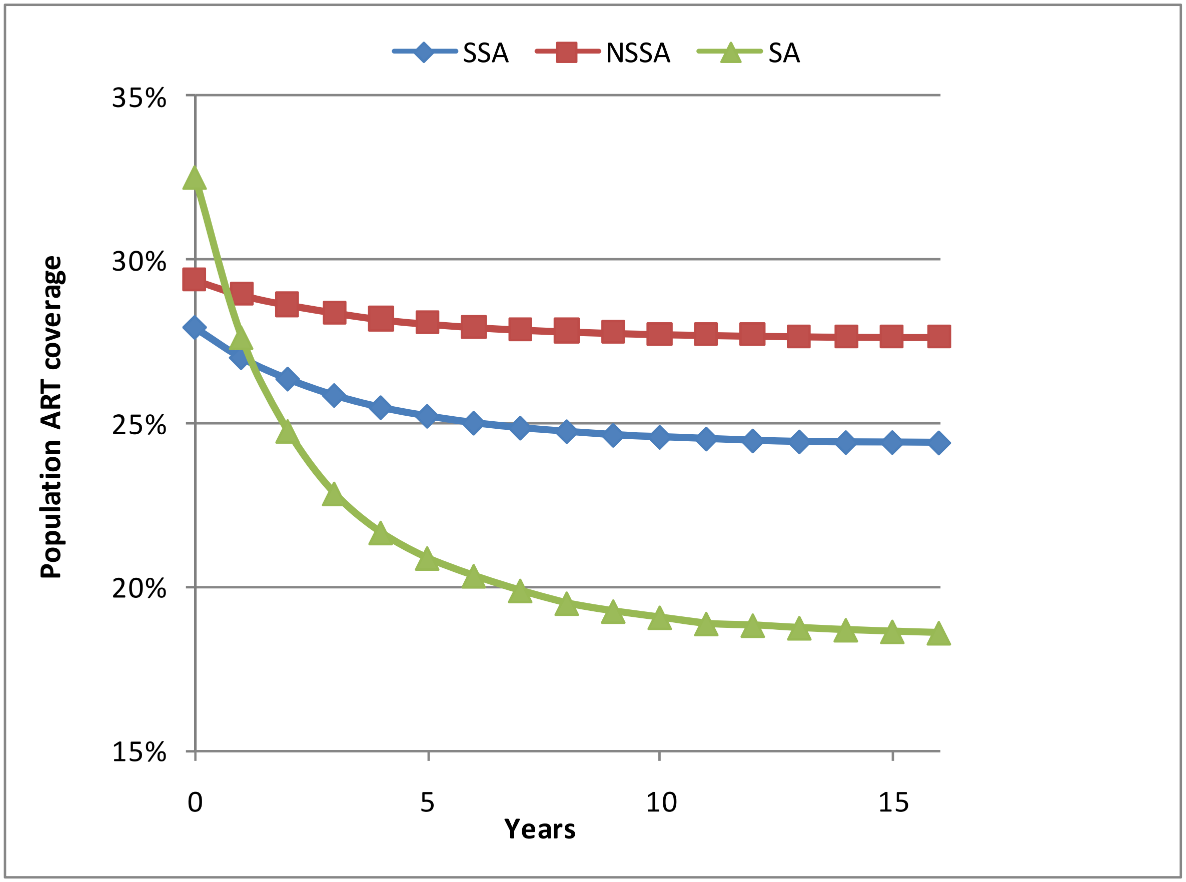
HRHA = human resources to treat HIV/AIDS, ART = antiretroviral treatment, SSA sub-Saharan Africa; NSSA non-sub Saharan African low- and middle-income countries, SA = South Africa, SS = steady state. HRHA emigration rate is the annual probability of death in HRHA. HRHA HIV incidence is the annual probability of HIV infection in HIV-negative HRHA.

Table 3: Annual number of new HRHA needed to achieve universal ART coverage by year 10

	HRHA per year		
Scenario	SSA	NSSA	SA
Base case	1,931	532	1,085
HRHA emigration rate 0%	1,262	470	399
HRHA ART coverage 100%	1,931	532	1,085
HRHA emigration rate 0% and HRHA ART coverage 100%	1,262	470	399

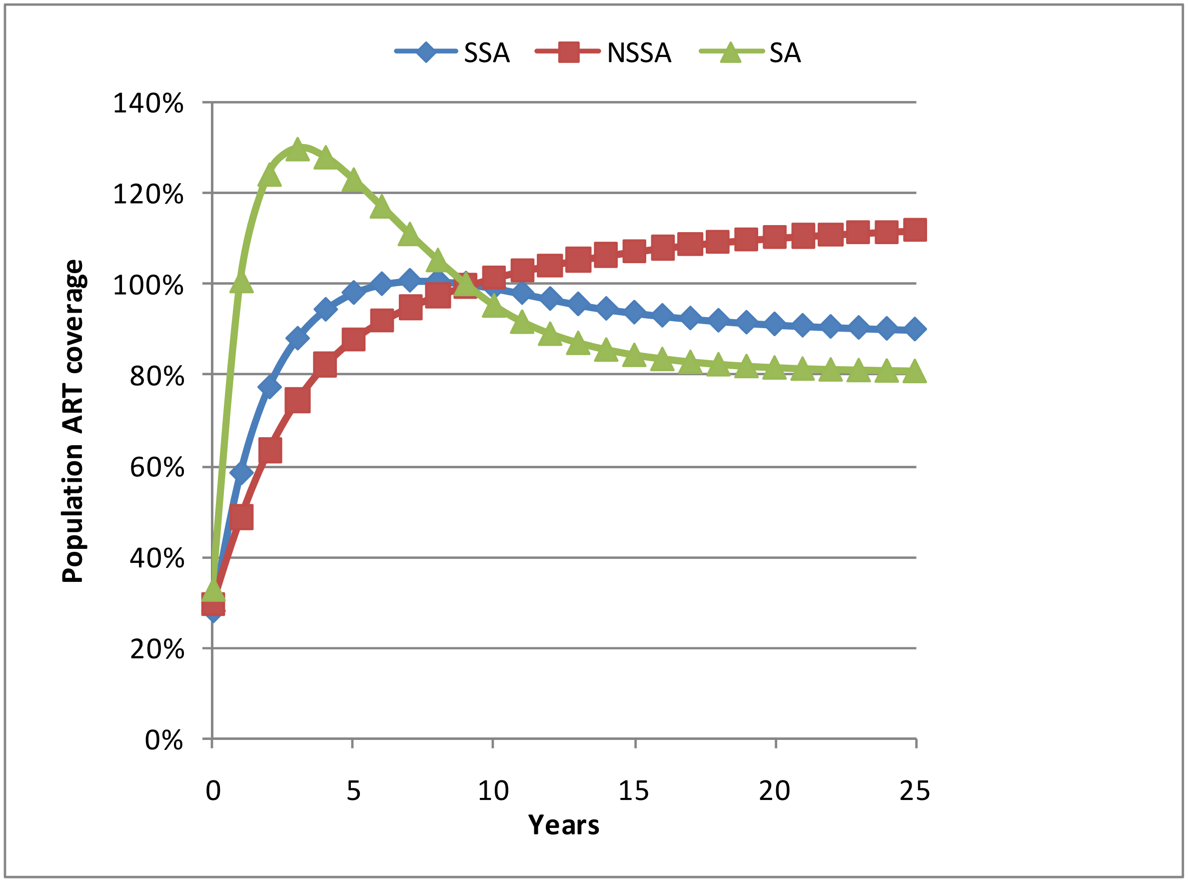
HRHA = human resources to treat HIVAIDS, ART = antiretroviral treatment, SSA = sub-Saharan Africa, NSSA = non-sub Saharan African low- and middle-income countries, SA = South Africa.

Figure 1: Population ART coverage under base-case assumptions



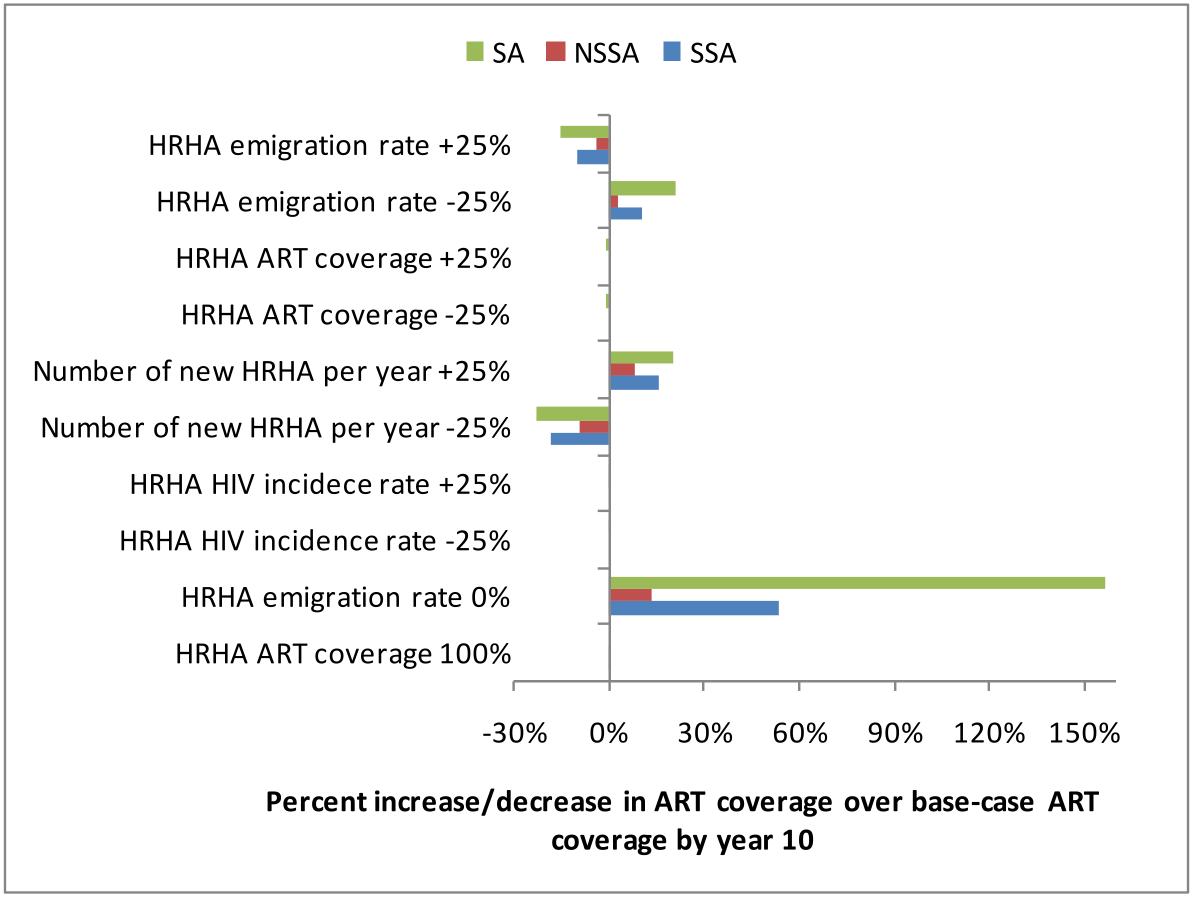
HRHA = human resources to treat HIVAIDS, ART = antiretroviral treatment, SSA = sub-Saharan Africa, NSSA = non-sub Saharan African low- and middle-income countries, SA = South Africa

Figure 2: Sustainability of universal ART coverage achieved by year 10 using a constant inflow rate of HRHA



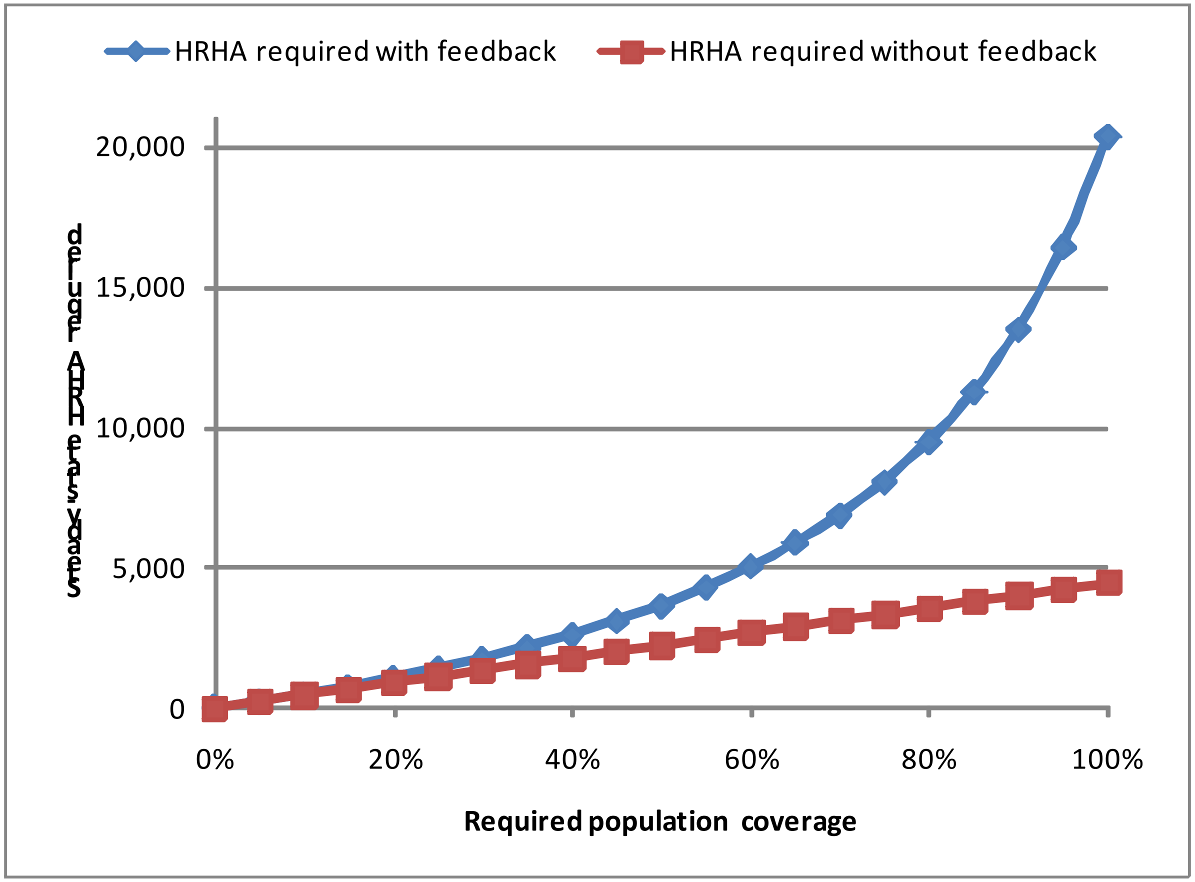
HRHA = human resources to treat HIVAIDS, ART = antiretroviral treatment, SSA = sub-Saharan Africa, NSSA = non-sub Saharan African low- and middle-income countries, SA = South Africa

Figure 3: Sensitivity of population ART coverage to model parameters



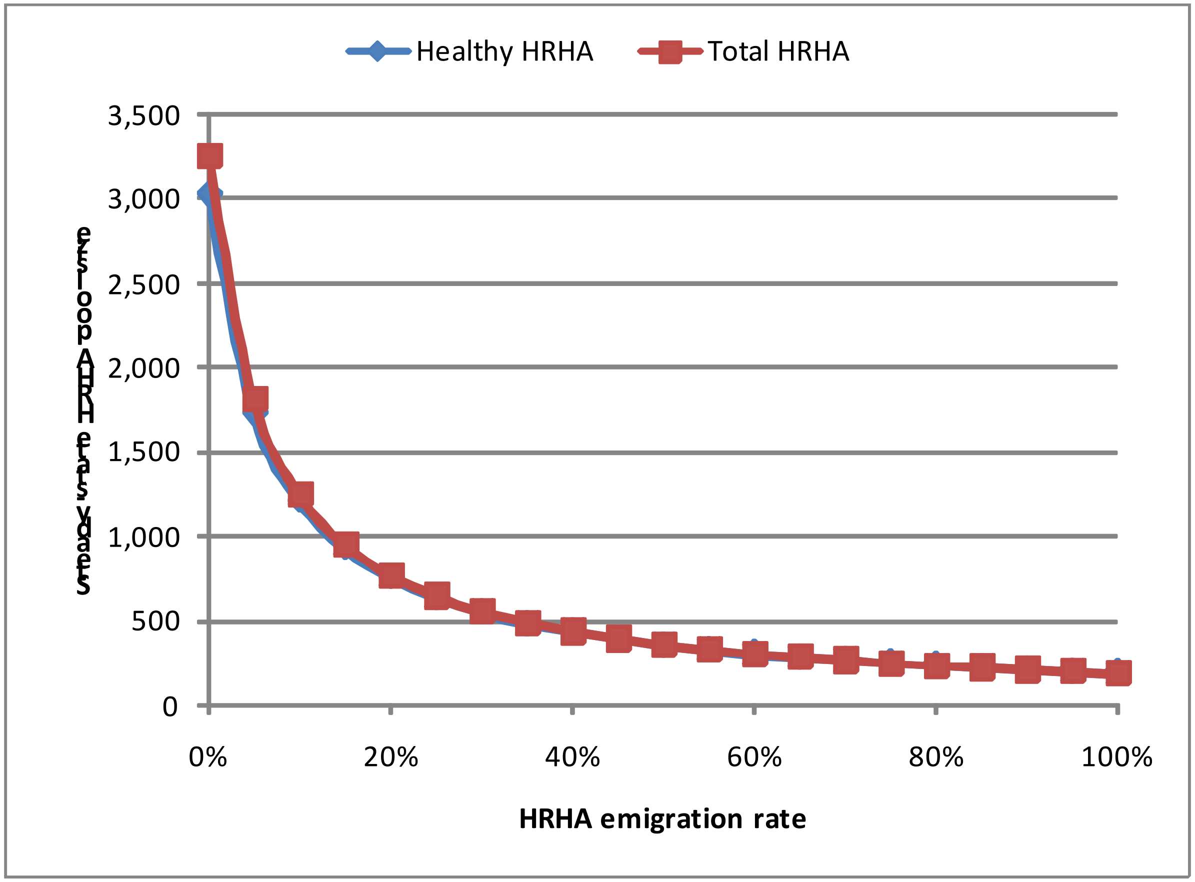
HRHA = human resources to treat HIVAIDS, ART = antiretroviral treatment, SSA = sub-Saharan Africa, NSSA = non-sub Saharan African low- and middle-income countries, SA = South Africa

Figure 4: Steady-state HRHA required for SSA as a function of population coverage



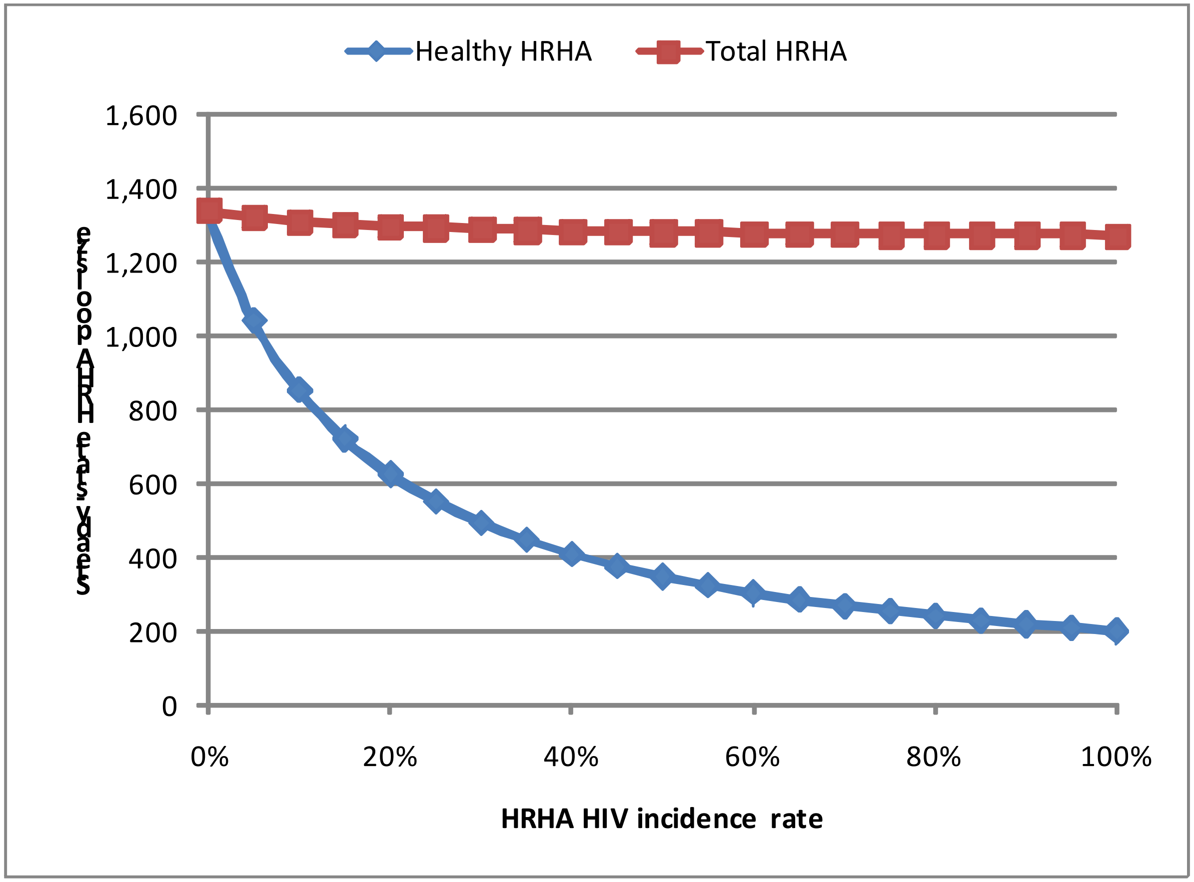
HRHA = human resources to treat HIVAIDS, SSA = sub-Saharan Africa

Figure 5: Steady-state healthy and total HRHA pool size for SSA as a function of HRHA emigration rate



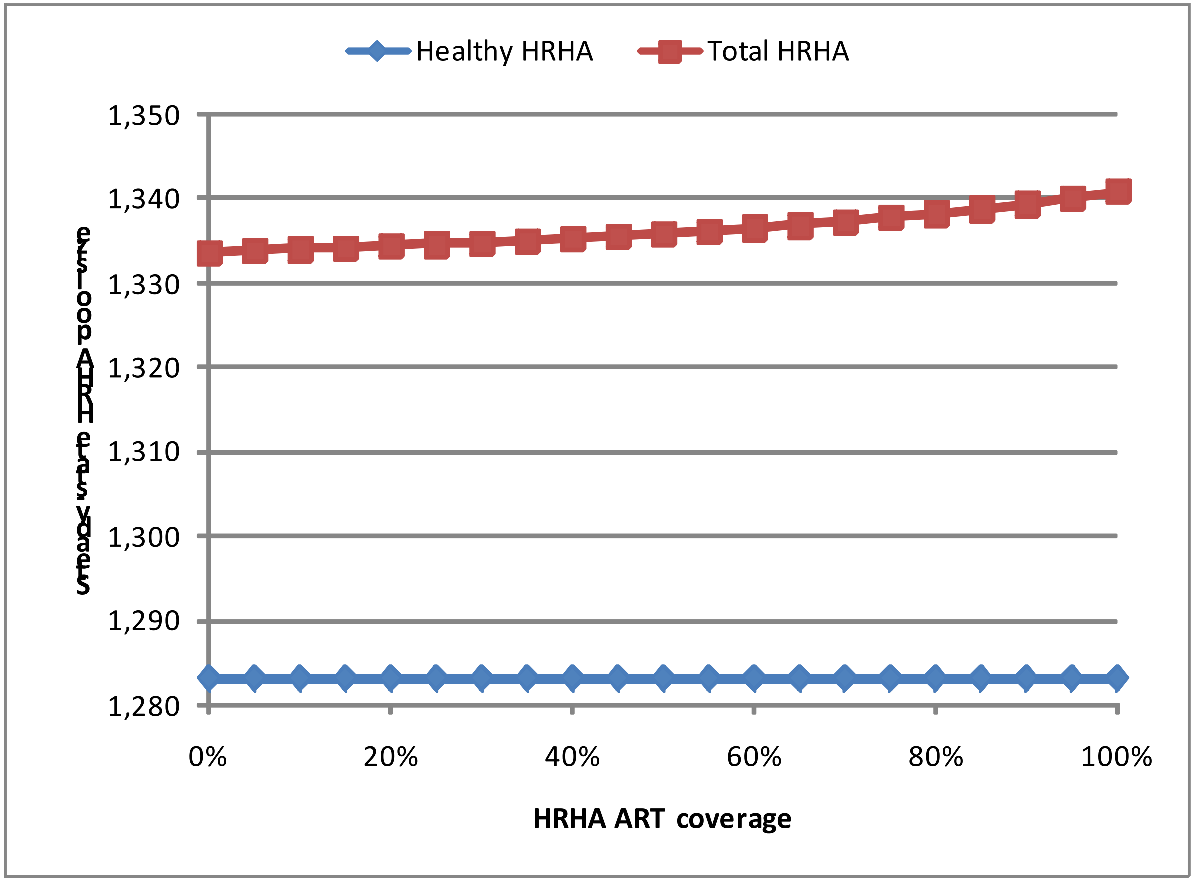
HRHA = human resources to treat HIVAIDS, SSA = sub-Saharan Africa

Figure 6: Steady-state healthy and total HRHA pool size for SSA as a function of HRHA HIV incidence rate



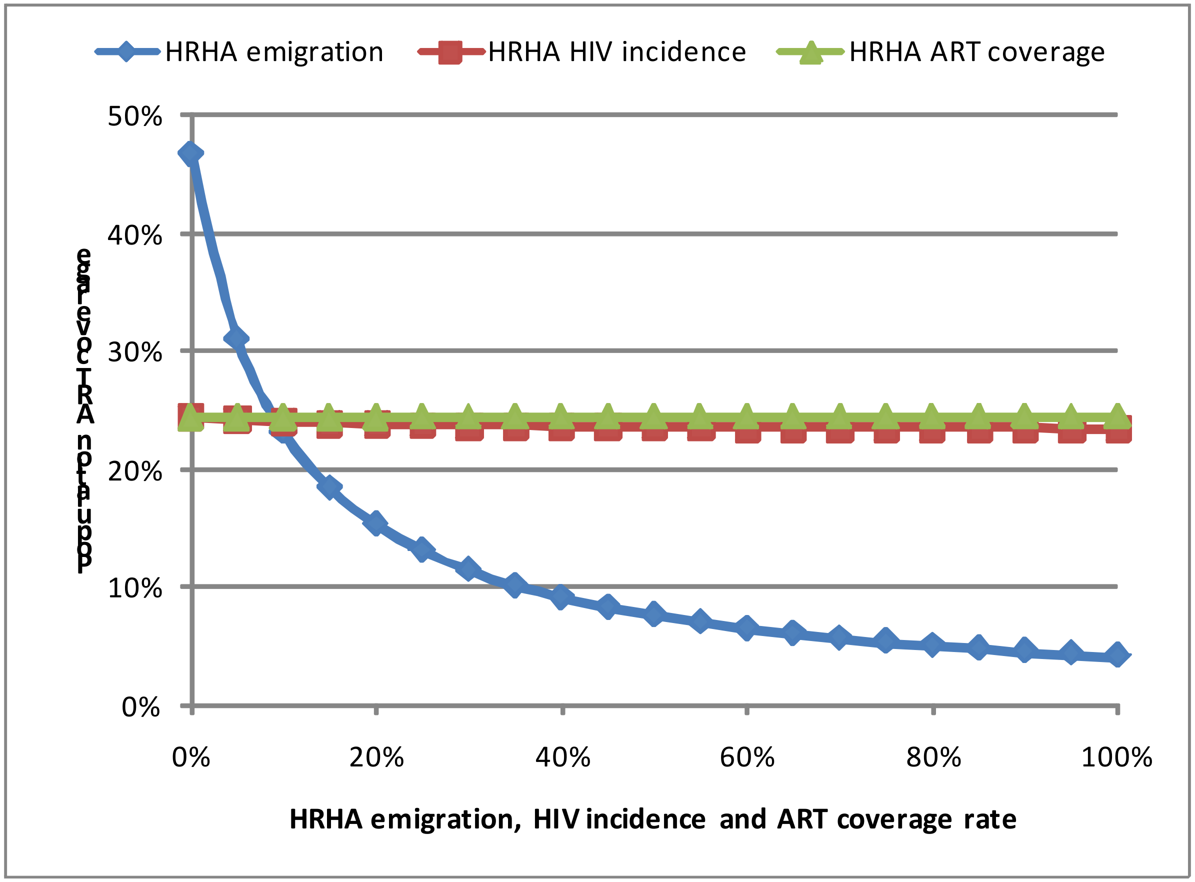
HRHA = human resources to treat HIVAIDS, SSA = sub-Saharan Africa

Figure 7: Steady-state healthy and total HRHA pool size for SSA as a function of HRHA ART coverage



HRHA = human resources to treat HIVAIDS, ART = antiretroviral treatment, SSA = sub-Saharan Africa

Figure 8: Steady-state population ART coverage for SSA as a function of HRHA emigration rate, HRHA HIV incidence rate, and HRHA ART coverage



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