

# Examining the promise of HIV elimination by 'test and treat' in hyperendemic settings

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**Background:** It has been suggested that a new strategy for HIV prevention, 'Universal Test and Treat', whereby everyone is tested for HIV once a year and treated immediately with antiretroviral therapy (ART) if they are infected, could 'eliminate' the epidemic and reduce ART costs in the long term.

**Methods:** We investigated the impact of test-and-treat interventions under a variety of assumptions about the epidemic using a deterministic mathematical model.

**Results:** Our model shows that such an intervention can substantially reduce HIV transmission, but that impact depends crucially on the epidemiological context; in some situations, less aggressive interventions achieve the same results, whereas in others, the proposed intervention reduces HIV by much less. It follows that testing every year and treating immediately is not necessarily the most cost-efficient strategy. We also show that a test-and-treat intervention that does not reach full implementation or coverage could, perversely, increase long-term ART costs.

**Conclusion:** Interventions that prevent new infections through ART scale-up may hold substantial promise. However, as plans move forward, careful consideration should be given to the nature of the epidemic and the potential for perverse outcomes.

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## Introduction

The rate of new HIV infections has stabilized in recent years (2.7 million infections in 2007 [1]), and concomitantly, the global number of those infected on antiretroviral therapy (ART) has increased dramatically [2]. Despite this, the rate of new infections in developing countries still outpaces the rate at which individuals are started on treatment [2], and there is growing concern that this situation is unsustainable [3,4]. Incidence must be further reduced, but disappointingly, few HIV interventions have been shown to be effective in randomized controlled trials in developing countries: behaviour changes following counselling and testing are likely to have a minimal effect or even increase incidence [5,6]; two models of peer education for promoting reductions in risk behaviour have failed [7,8]; risk compensation and low adherence potentially contributed to no effect being found in trials to prevent HIV infection through

diaphragm use [9] and herpes treatment [10]; and, in the last year, another trial of herpes treatment showed no effect on the rate of HIV transmission from coinfecting individuals [11]. These results bring the tally of trials showing no efficacy in reducing HIV incidence to more than 30 [12]. Male circumcision has been shown to reduce the risk of men acquiring infection [13–15], although it is understood that this will not be enough to eliminate HIV, even under the most optimistic conditions [16,17].

In contrast, scale-up of ART has substantially reduced mortality [2,17–19]. As the availability of treatment expanded, Montaner *et al.* [20] proposed using treatment as an intervention to prevent infection, and Granich *et al.* [21] recently used a mathematical model to evaluate that argument. The model suggested that in a high prevalence setting, with an incidence of two per 100 person-years at risk, an intervention that tested everyone annually and

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initiated treatment immediately if they were infected ('universal test-and-treat' intervention) could reduce incidence to below one per 1000 person-years at risk, that is, more than a 95% reduction (described by the authors as elimination). The model predicted that despite high costs during the rollout phase, long-term ART costs would be much lower than the current strategy of treating on the basis of clinical need.

This result has stimulated extensive comment and sparked interest in rolling-out 'test-and-treat' type interventions [22–28]. However, it is worth further exploring the findings, as the model provided a limited representation of some aspects of HIV epidemiology and investigated only one type of intervention in one type of epidemiological context. In this article, we investigate the potential of alternate test-and-treat interventions under a range of contexts, and using a different mathematical model that incorporates updated information on the course of HIV infection and transmission rates on treatment along with a more explicit exploration of the potential role of heterogeneity in sexual risk behaviour [29,30].

## Methods

An HIV transmission model was developed that was defined by a set of partial differential equations incorporating variation in sexual risk behaviour [31]: changes in HIV transmissibility over the course of infection [29] and observed HIV survival rates from an African setting [32] (full technical details in online appendix). In the model, there are two subpopulations, with key parameters being the relative degree of risk behaviour for acquiring/transmitting infection between the two ( $\pi$ ), the relative size of the lower risk subpopulation ( $\theta$ ), the value of basic reproductive number in that subpopulation ( $R_0^L$ ) and the degree of sexual contact between individuals in the two subpopulations ( $\varepsilon$ ). It was assumed that the relative size of the two risk groups remained constant over time [33].

We modelled different 'test-and-treat' interventions by altering the time since infection that treatment is started and assuming that individuals on treatment are, on an average, 13-fold less infectious than untreated individuals [30,34]. As patients tend to live longer on ART if they start treatment earlier [18,35], survival on treatment was related to the timing of initiation, with a maximum of 28 years overall survival if treatment is started within 1 year of infection (sensitivity analyses showed that the results could be reproduced assuming no relationship between survival and timing of ART initiation). The timing of treatment initiation was related to the interval between HIV tests and the expected average CD4 cell count at initiation. The trend in CD4 cell count over time since infection was calculated using information from a recent

meta-analysis [36], showing mean time from infection to a level of 200 cells/ $\mu$ l of 7.6 years, and other observational data of the rate of CD4 cell count decline during earlier HIV infection among African populations [37].

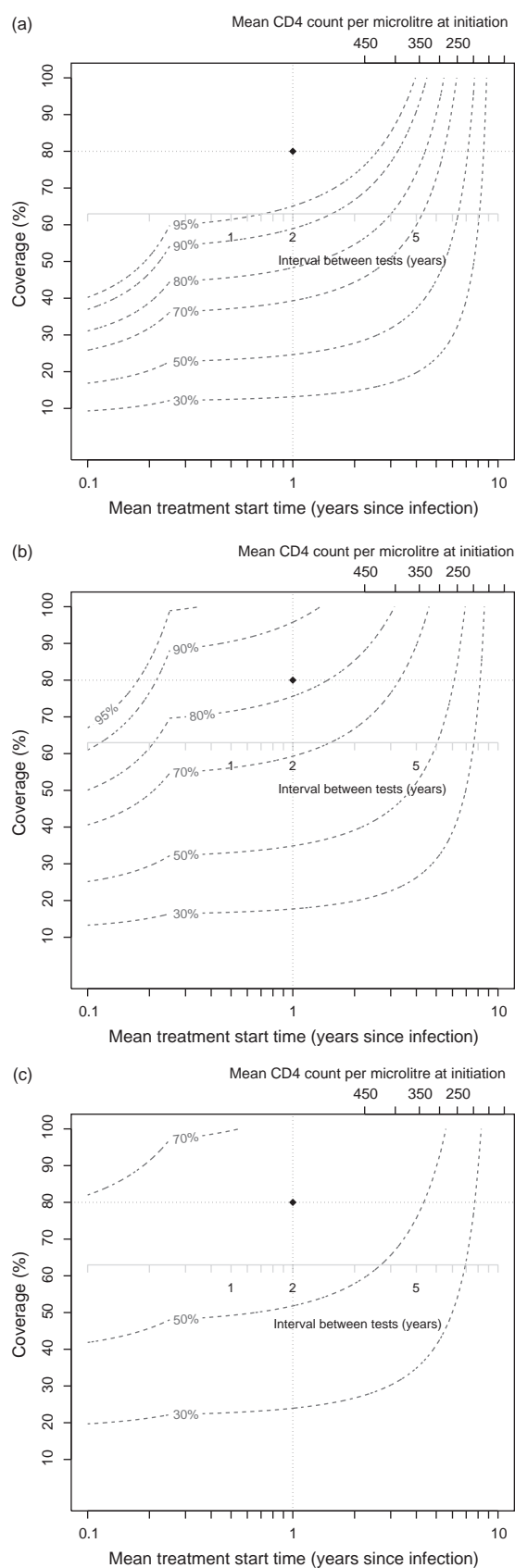
The impact of the intervention was evaluated in different types of populations in which the epidemic was sustained in both groups or only the higher risk group ( $R_0^L = 1.1$  or  $R_0^L = 0.7$ ), and in which mixing between the two groups was extensive or limited ( $\varepsilon = 0.1$  or  $\varepsilon = 0.9$ ). In each case, we assumed that most of the population was at a lower risk and a small minority was at a higher risk, in accord with observational studies [31]. The  $\pi$  parameter was then adjusted, so that the HIV incidence rate was exactly the same in each scenario: 1.5 per 100 person-years at risk before the intervention, which is typical of many countries in Eastern and Southern Africa currently [1]. Thus, the three scenarios were more homogenous distribution of risk ( $\pi = 1.6$ ,  $\theta = 0.9$ ,  $R_0^L = 1.1$ ,  $\varepsilon = 0.5$ ); heterogeneous risk distribution with random mixing ( $\pi = 4.3$ ,  $\theta = 0.9$ ,  $R_0^L = 0.7$ ,  $\varepsilon = 0.1$ ); and heterogeneous risk distribution with assortative mixing (i.e. most sex contacts are between individuals in the same subpopulation) ( $\pi = 13.1$ ,  $\theta = 0.9$ ,  $R_0^L = 0.7$ ,  $\varepsilon = 0.9$ ).

It was assumed that the sensitivity and specificity of the HIV test was 100%.

We quantify the impact of the intervention as the reduction in incidence at equilibrium following its introduction compared with the preintervention incidence rate. Treatment load was calculated as the fraction of individuals in the population who are on treatment at equilibrium. Annual costs per capita of the intervention are approximated by summing the product of the number of individuals on treatment and \$800, and the product of the annual number of HIV tests and \$10 (J.G. Kahn, personal communication), assuming a fixed population size. A cost-efficiency measure was calculated as the reduction in equilibrium incidence divided by annual costs per capita.

## Results

Our results broadly confirm the main findings of Montaner *et al.* [20] and Granich *et al.* [21]: treatment has the potential to substantially reduce HIV transmission. Figure 1 shows the eventual predicted impact of test-and-treat interventions under three different epidemiological contexts. The contour lines indicate the reduction in incidence for an assumed level of coverage (vertical axis) and treatment start time (horizontal axis). Two other horizontal axes show how this treatment start time corresponds to the average interval between tests required to initiate treatment at that time and the average CD4 cell



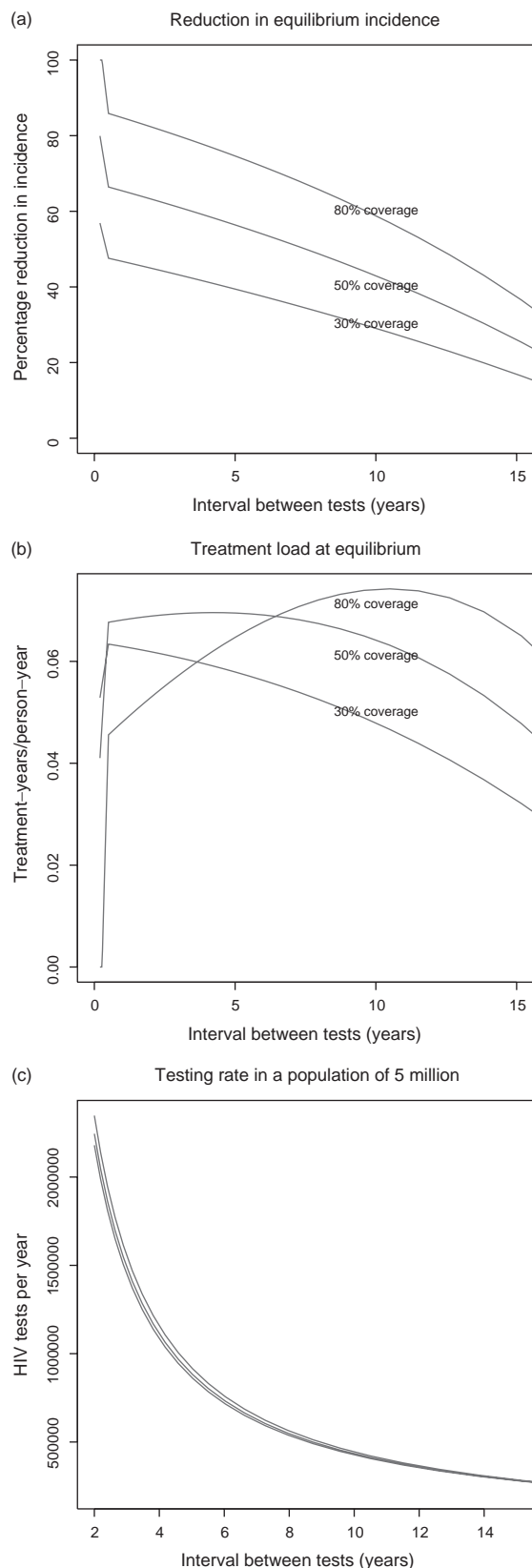
count (cells/ $\mu\text{l}$ ) among patients starting treatment. As expected, the impact is greater with higher coverage levels and earlier initiation of treatment (top-left corner of each panel). However, we also find that the expected impact varies depending on the epidemiological context assumed. In a population with a more even risk distribution ('scenario A'), testing 80% of the population every 2 years and treating immediately is expected to reduce incidence by more than 95% (Fig. 1a). The same intervention in a population with greater variation in risk ('scenario B') generates a smaller impact, reducing incidence by approximately 85% and fails to reduce the epidemic to the level termed 'elimination' [21] (Fig. 1b). In this scenario, all individuals would need to be treated within 1 month of infection for incidence to be reduced by 95%. If more partnerships are formed between individuals in the same subpopulation ('scenario C'), incidence is reduced by approximately 60% if individuals start treatment 1 year after infection (Fig. 1c). The reason is that in scenarios B and C, transmission is more dependent on a few individuals who spread infection rapidly once infected.

Our analysis shows that, depending on the epidemiological context, similar reductions in HIV incidence could be generated by less ambitious interventions. For instance, in a population with little variation in risk behaviour and random mixing ('scenario A'), incidence is still reduced by 95% if 80% of the population is tested only every 3–4 years, corresponding to a mean CD4 cell count at initiation of 400 cells/ $\mu\text{l}$ .

In each case, it would take approximately 30 years for these reductions in incidence to be fully realized, and there is the potential for incidence rates to rebound, as the first cohorts starting treatment progress to AIDS (see Figure 2 in the technical appendix).

We investigated the impact and approximate costs of implementing the test-and-treat intervention, in which the intervals between HIV tests ranged between 1 and 20 years (Fig. 2). Although shorter intervals between tests lead to greater reductions in incidence, the convex shape of the curves indicates a 'diminishing returns' relationship

**Fig. 1. The impact of test-and-treat interventions depends on epidemiological context.** Panels show impact of ART on incidence (percentage reduction) as contour lines, with respect to coverage of the intervention (vertical axis), the mean years after infection that treatment is begun (horizontal axis) and the corresponding mean CD4 cell count at initiation (horizontal axis) and required interval between tests (horizontal axis). Panels show three types of epidemiological context: scenario A – even risk distribution; scenario B – heterogeneous risk distribution with random mixing; and scenario C – heterogeneous risk distribution with assortative mixing. ART, antiretroviral therapy.



**Fig. 2. Test-and-treat impact and costs.** (a) Reduction in incidence (%) versus mean interval between HIV tests (years). (b) Person-years on ART required at equilibrium (as fraction of

(Fig. 2a). The sharp upturn in the impact if individuals are tested more frequently than every 6 months reflects treatment interrupting the period of primary infection when individuals are highly infectious.

The numbers on treatment at equilibrium and the numbers of tests each year for alternative test-and-treat strategies are shown in Fig. 2b and c. For 80% coverage, the treatment load increases as the interval between testing is reduced from 15 to 10 years, as more treatment is provided to those in late-stage disease, without an associated large effect on HIV transmission. Further decreases in the interval between testing from every 10 to 1 years lead to lower treatment loads, as, in this phase, ART is directly reducing the endemic level of HIV and treatment needs. In contrast, if the test-and-treat intervention is scaled-up to only 30 or 50% of the population, more testing gives greater years of treatment per person without attracting large reductions in incidence, so the ART load only increases.

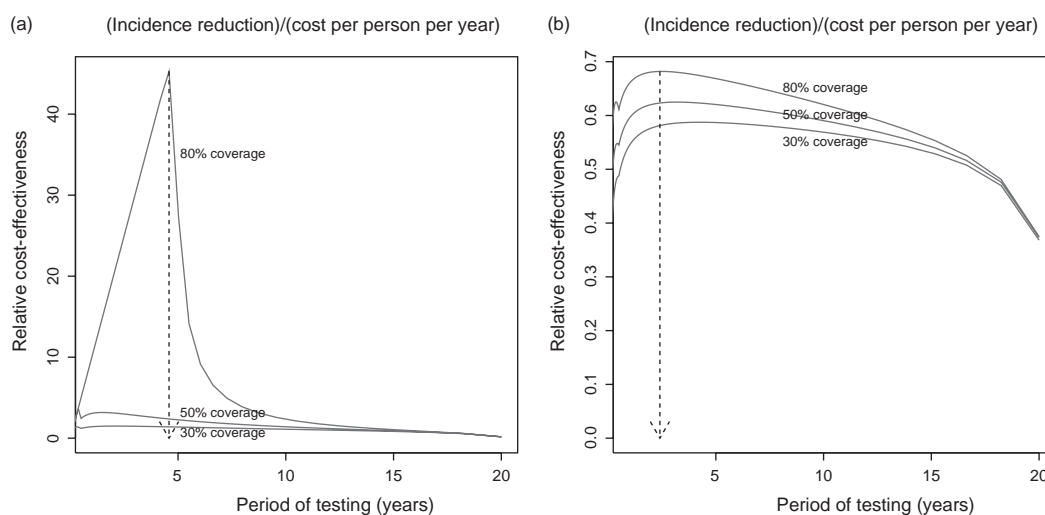
An approximate indication of cost-efficiency is presented in Fig. 3. The highest parts of the curves correspond to the test-and-treat strategy that generates the greatest reduction in incidence per unit cost. The optimal position varies according to the epidemiological context, the level of coverage achieved and the relative costs of treatment and testing. For more fragile epidemics ('scenario A', Fig. 3a), the optimal strategy is testing every 4–5 years or initiating treatment at a CD4 cell count of 350–400 cells/ $\mu$ l. Here, the position of the optimum at 80% coverage is determined largely by the frequency of testing that is necessary for HIV elimination.

For the most robust epidemic ('scenario C', (Fig. 3b), the optimal strategy (at 80% coverage) is testing every 2–3 years, corresponding to treatment at a CD4 cell count above 450 cells/ $\mu$ l. In this scenario, the optimum is determined by a balance between providing ART for longer duration and the greater reductions in incidence, as the testing interval decreases.

For scenario B, the optimum is 1–2 years, the suggested strategy of Granich *et al.* [21]. Here, equilibrium treatment loads do not change substantially with testing frequency, as the increased duration of treatment is almost exactly offset by concomitant reductions in incidence; so, the position of the optimum is mainly determined by the relative costs of treatment and testing.

**Fig. 2 (continued)**

population) versus mean interval between HIV tests (years). (c) Number of tests per year at equilibrium (assuming population of 5 million adults) versus mean interval between HIV tests (years). Parameters values are for 'scenario B' (described in the text). ART, antiretroviral therapy.



**Fig. 3. Test-and-treat cost-efficiency.** Cost-efficiency (reduction in incidence divided by ART and HIV testing costs) of the test-and-treat interventions reaching 30, 50 or 80% of the population in epidemiological context scenario A (a) and scenario C (b). Dashed vertical lines indicate optimal strategy for each level of coverage. ART, antiretroviral therapy.

## Discussion

It is important that our modelling approach (incorporating recent estimates of transmission in acute infection, transmission rates on treatment and heterogeneity in sexual risk behaviour) has partially confirmed the finding that earlier initiation of ART can lead to substantial reductions in HIV transmission [20,21]. However, our analysis has highlighted three important aspects of 'test-and-treat' interventions that should be carefully considered as plans for implementing such an intervention move forward. First, the impact of the intervention depends crucially on the epidemiological context: under some circumstances, we find the effect to be as large as estimated by Granich *et al.* [21], but in others, the effect is much less. The context is proximally determined by many properties of the sex partner network (such as heterogeneity, concurrency and mixing [38,39]), and it is not easy to determine which of the modelled contexts (A, B or C) is most similar to a particular population. Thus, earlier model assumptions [21] accurately represent a particular population, even if the prevalence/incidence level appears similar (i.e. the fit of a model to data does not imply that the model is validated). The uncertainty in the specification of the epidemiological context can be reduced by incorporating local behavioural data into more detailed models of HIV transmission [40], but the remaining variance in projections should be fully reflected in cost-effectiveness calculations. It is likely that the 'test-and-treat' approach is much better suited to some populations and poorly suited to others.

The second main finding is that although increasing the frequency of testing does lead to a larger reduction in HIV transmission, there are diminishing returns for increasing testing frequency to the once-per-year levels proposed in the study by Granich *et al.* [21]. Under some situations,

much later initiation can still stall the epidemic. Granich *et al.* [21] suggest that testing every year and treating immediately was an effective and cost-saving strategy compared with later initiation, but, in our model, the most cost-efficient strategy could be testing everyone 3–5 years, depending on the epidemiological context and the coverage achieved (Fig. 3). However, the position of the optimum is highly sensitive to aspects of the epidemic context, life expectancy on treatment and relative costs of treatment and testing, especially when interventions do not reach universal coverage, making it difficult to formulate firm recommendations without further information and specification.

Our third main finding was that although a high coverage implementation of test and treat could lead to reductions in incidence and ART use, failing to achieve sufficiently high coverage levels or failing to test frequently enough could just lead to a dramatic spiralling of treatment costs. In this scenario, the intervention does not interrupt transmission, so the pool of those developing treatment needs continues to grow. It is essential that this eventuality is avoided, especially in many countries where healthcare systems already struggle to provide care for HIV-infected patients in clinical need. Losses to follow-up, imperfect adherence or the evolution of resistance [41,42] could all contribute to reducing the effective coverage of the programme.

Our analysis was intended to provide qualitative insights rather than precise quantitative predictions about the effect of test-and-treat interventions, and we have not considered the logistical challenges presented by implementing such an intervention. Thus, our estimates of cost and cost-effectiveness analysis are simplified, and our consideration of the epidemic is most focused on the equilibrium incidence level. The impact and costs of the rollout phase of interventions is, therefore, not fully

captured in all our analyses. Also, our modelled costs are not sensitive to scale, as they can be in practice [43] (e.g. through clinicians' time being occupied with testing rather than other activities), and we have not explicitly considered the increased chance of adverse events, toxicities and viral evolution and need for second-line therapies associated with long-term use of ART [42,44]. To reinforce our main findings in this analysis, we have not included how the chance of complying with repeat testing and treatment can vary according to how frequently tests are offered, nor how sexual behaviour can change as a result of learning one's serostatus where HIV is negative or positive [45,46]. This could mean that our estimates of costs for testing very frequently are underestimated, and if these were reflected in our analysis, the optimum test-and-treat strategy would be longer intervals between the tests. However, we have also not quantified the extra life-years saved associated with earlier treatment initiation nor how the chance of stopping treatment or developing resistance and moving to second-line therapies could depend on the timing of initiation [18,35], which may favour more frequent testing. All these factors interact with the generalizable issues we have highlighted in this study and will demand attention in further modelling work tailored to specific settings. The model does not explicitly capture the real variation in the risk of transmission between different sexual partnerships due to the frequency of sex, presence of sexually transmitted infections and condom use, and although this detail is not expected to affect the findings presented here, incorporating these factors in further models will improve the specification of the epidemiological context and precision of the projections.

The impact of many interventions, including test and treat, can be amplified by targeting those that are most at risk of acquiring and transmitting infections [47]. Therefore, in the generalized epidemics in southern Africa, testing women in beer halls [48] and truck drivers [49] most often might improve impact and cost-efficiency. The extent of that amplification also depends on the epidemiological context (especially extent of contact between higher and lower risk individuals [50]), so that the advantage of targeting would be modest in some situations (e.g. scenario A) but great in others (e.g. scenario C). Combining interventions can also lead to synergies, so that applying two interventions together leads to increases in effectiveness [47]. Therefore, the opportunity to counsel those testing HIV-negative, promoting behaviour change to reduce the risk of infection [5,46], should not be missed.

## Conclusion

Leveraging the infrastructure and capacity that have so rapidly grown-up to support the expansion of ART

programmes in Africa to also reduce HIV transmission is a promising strategy. However, by failing to capture some important features of HIV epidemiology, overoptimistic projections can be generated. It is also essential to recognize that testing every year is not necessarily the most cost-efficient strategy, and that failing to fully implement the test-and-treat strategy could perversely lead to overall increased long-term ART costs.

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We declare that no conflicts of interest exist.

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## Abstract

This document contains the details of the model used in the main paper.

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## Introduction

Throughout, we consider an entirely heterosexual population with a mixing matrix of the form:

$$K = \begin{pmatrix} 0 & M \\ W & 0 \end{pmatrix} \quad (1)$$

where  $M$  and  $W$  are  $2 \times 2$  matrices referring to high- and low-sexual activity men and women.

In each case, the stable endemic equilibria of the models were obtained directly by numerically solving algebraic equations derived from setting all  $t$ -derivatives equal to zero. The proportion of the population in each activity class at equilibrium was fixed.

In the following two sections we describe the model both with, and without antiretroviral therapy (ART). We then describe how we parametrized the mixing; and finally go on to state our assumptions mortality, infectiousness, and the effect of ART on these.

Note that a simplified notational scheme was used in the main text. The correspondence with the scheme used there is detailed in Table 1.

## Model without ART

The model is specified by a set of partial differential equations (PDEs), where  $\tau$  denotes the time since an individual has been infected.  $I_j(t, \tau)$  denotes the density of infectious individuals in class  $j$  (the index specifying a gender, and a sexual activity group) who have been infected for a time in the interval  $[\tau, \tau + d\tau)$  at time  $t$ . An individual at this stage in their infection is assumed to have a relative infectiousness given by a function  $\phi(\tau)$  and an excess hazard of death described by a function  $\nu(\tau)$ . The background mortality rate for disease-free individuals is

denoted  $\mu$ , and the number of susceptible individuals in a class  $j$  is denoted  $S_j$ . These quantities obey the dynamics

$$\begin{aligned} \dot{S}_j(t) &= B_j(t) - \sum_k \int K_{jk} S_j(t) \phi(\tau) \frac{I_k(t, \tau)}{N_k(t)} d\tau - \mu S_j(t) \\ (\partial_t + \partial_\tau) I_k(t, \tau) &= -(\nu(\tau) + \mu) I_k(t, \tau) \\ I_j(t, 0) &= \sum_k \int K_{jk} S_j(t) \phi(\tau) \frac{I_k(t, \tau)}{N_k(t)} d\tau \end{aligned}$$

where  $B_j(t)$  is the recruitment rate into a given category  $j$ , and  $N_j$  is the total number of infected and susceptible individuals in category  $j$ . The first equation represents the arrival of new susceptibles in category  $j$ , and their removal due to infection or death; the second represents the progress of infected individuals through their infection, being removed at an enhanced mortality rate; and the last equation is the boundary condition which accounts for the arrivals of new infections at the point  $\tau = 0$ .

## Model with ART

We will assume that, upon infection, a proportion  $p_j$  of the  $S_j$  move onto an unbarred  $I_j$  time-course corresponding to no treatment, and a proportion  $\bar{p}_j = 1 - p_j$  (i.e. the coverage of the intervention) onto the  $\bar{I}_j$  time-course (with its treatment-modified  $\bar{\phi}$  and  $\bar{\nu}$ ). Thus we have

$$\begin{aligned} \dot{S}_j &= B_j(t) - S_j \sum_k \int \frac{(K_{jk} \phi(\tau) I_k(t, \tau) + K_{jk} \bar{\phi}(\tau) \bar{I}_k(t, \tau))}{N_k(t)} d\tau - \mu S_j(t) \\ (\partial_t + \partial_\tau) I_j(t, \tau) &= -(\mu + \nu(\tau)) I_j(t, \tau) \\ (\partial_t + \partial_\tau) \bar{I}_j(t, \tau) &= -(\mu + \bar{\nu}(\tau)) \bar{I}_j(t, \tau) \\ I_j(t, 0) &= p_j S_j \sum_k \int \frac{(K_{jk} \phi(\tau) I_k(t, \tau) + K_{jk} \bar{\phi}(\tau) \bar{I}_k(t, \tau))}{N_k(t)} d\tau \\ \bar{I}_j(t, 0) &= \bar{p}_j S_j \sum_k \int \frac{(K_{jk} \phi(\tau) I_k(t, \tau) + K_{jk} \bar{\phi}(\tau) \bar{I}_k(t, \tau))}{N_k(t)} d\tau \end{aligned}$$

It is assumed that  $\bar{\phi}(\tau)$  and  $\bar{\nu}(\tau)$  would only depart from the untreated values,  $\phi(\tau)$  and  $\nu(\tau)$ , once  $\tau$  reaches the average time at which treatment begins.

## Equilibria

Asymptotically, it follows from the continuity equation for  $I_j$  above that

$$I_j(\infty, \tau) = I_j(\infty, 0) e^{-H(\tau)} \quad (2)$$

where  $H$  is the cumulative hazard  $H(\tau) = \int_0^\tau (\nu(\tau) + \mu) d\tau$ . Writing the next generation matrix  $\bar{K}$

$$\bar{K} = \int_0^\infty \phi(\tau) e^{-H(\tau)} K d\tau \quad (3)$$

and the equilibrium prevalences in each group as  $x_j$ , the boundary condition above yields the algebraic system

$$x_i = (1 - x_i) \sum_k \bar{K}_{ik} x_k \quad (4)$$

which can be solved numerically. The incidences at equilibrium are given by

$$I_i(\infty, 0)_{x_i} / \left( \int e^{-H(\tau)} d\tau \right) \quad (5)$$

Notice that although the asymptotic recruitment rates,  $B_i$ , are necessary to determine the sizes of populations, they do not affect the per-capita prevalences. The reproduction number  $R_0$  is defined as the largest eigenvalue of  $\bar{K}$ ; the working for the case with ART follows very similarly.

## Mixing

Let  $n_{Wj}^i$ , with  $j \in \{H, L\}$ , be the number of women in the population who are high- or low-class respectively, and similarly  $n_{Mj}^i$ , with  $j \in \{H, L\}$ , for the number of high- and low-class men. Let  $q_i^j$ , with  $j \in \{H, L\}$  and  $i \in \{M, W\}$ , be the respective average number of partnerships for a given type of individual during a certain time interval. Let  $Q$  be the total number of partnerships owned by men (or equivalently by women), i.e.

$$n_W^H q_W^H + n_W^L q_W^L = Q = n_M^H q_M^H + n_M^L q_M^L \quad (6)$$

Let

$$f_M^j = \frac{n_M^j q_M^j}{Q} \quad (7)$$

be the fraction of all partnerships with  $j$ -class men, and similarly. Let

$$\Pi_M = \begin{pmatrix} \Pi_M^{HH} & \Pi_M^{HL} \\ \Pi_M^{LH} & \Pi_M^{LL} \end{pmatrix} \quad (8)$$

be the mixing matrix, comprising of  $\Pi_M^{XY}$ : the proportion of all partnerships which involve an  $X$ -class man and an  $Y$ -class woman. Similarly,  $\Pi_W^{XY}$  is the proportion of all partnerships which involve an  $X$ -class woman and an  $Y$ -class man. Because partnerships are symmetrically owned, we have

$$\Pi_M = \Pi_W^T \quad (9)$$

If mixing between the two classes were at random, the mixing would be

$$\Pi_M \begin{pmatrix} f_M^H f_W^H & f_M^H f_W^L \\ f_M^L f_W^H & f_M^L f_W^L \end{pmatrix} \quad (10)$$

If mixing were completely assortative, we would have

$$\Pi_M = \begin{pmatrix} f_M^H & 0 \\ 0 & f_M^L \end{pmatrix} \quad (11)$$

Linearly interpolating between these two extremes so that  $\epsilon = 1$  corresponds to completely assortative mixing and  $\epsilon = 0$  to completely random, we get

$$\Pi_M(\epsilon) = \begin{pmatrix} f_M^H(\epsilon + (1 - \epsilon)f_W^H) & (1 - \epsilon)f_M^H f_W^L \\ (1 - \epsilon)f_M^L f_W^H & f_M^L(\epsilon + (1 - \epsilon)f_W^L) \end{pmatrix} \quad (12)$$

Note that the transpose condition forces any separate assortativity parameters for men and women to be the same.

The proportion of an  $X$ -man's partnerships which are with class- $Y$  women can be calculated as the

$$c_M^{XY}(\epsilon) = \frac{\Pi_M^{XY}(\epsilon)}{(\Pi_M^{XY}(\epsilon) + \Pi_M^{X\bar{Y}}(\epsilon))} \quad (13)$$

where  $\bar{Y}$  means "not- $Y$ ". Thus

$$c_M(\epsilon) = \begin{pmatrix} \frac{f_M^H(\epsilon + (1 - \epsilon)f_W^H)}{(1 - \epsilon)f_M^L f_W^H} & \frac{(1 - \epsilon)f_M^H f_W^L}{f_M^L(\epsilon + (1 - \epsilon)f_W^L)} \\ \frac{f_M^L}{f_M^H} & \frac{f_M^H}{f_M^L} \end{pmatrix} = \begin{pmatrix} (\epsilon + (1 - \epsilon)f_W^H) & (1 - \epsilon)f_W^L \\ (1 - \epsilon)f_W^H & (\epsilon + (1 - \epsilon)f_W^L) \end{pmatrix} \quad (14)$$

Thus, for a basis in the order  $(WH, WL, MH, ML)$ ,

$$M = \beta \begin{pmatrix} q_M^H(\epsilon + (1 - \epsilon)f_W^H) & q_M^H(1 - \epsilon)f_W^L \\ q_M^L(1 - \epsilon)f_W^H & q_M^L(\epsilon + (1 - \epsilon)f_W^L) \end{pmatrix} \\ W = \beta \begin{pmatrix} q_W^H(\epsilon + (1 - \epsilon)f_M^H) & q_W^H(1 - \epsilon)f_M^L \\ q_W^L(1 - \epsilon)f_M^H & q_W^L(\epsilon + (1 - \epsilon)f_M^L) \end{pmatrix} \quad (15)$$

We can therefore determine our choice of next generation by specifying, e.g.

- $q_M^H$ ,  $q_M^L$ ,  $q_W^H$ , and  $q_W^L$ , with the interpretation of relative partner-change
- rates in each class.
- $F_M^H$  and  $F_W^H$ : the fraction of men and women respectively who are in the 'H'-class.
- $R_0^L$ : the value of  $R_0$  if the whole population consisted of 'L'-class individuals.
- $\epsilon$ : the assortativity.

Other combinations would also be possible. From these we can calculate the  $f$ s by, e.g.

$$f_M^H = \frac{F_M^H q_M^H}{F_M^H q_M^H + (1 - F_M^H) q_M^L}, \quad f_M^L = \frac{(1 - F_M^H) q_M^L}{F_M^H q_M^H + (1 - F_M^H) q_M^L} \quad (16)$$

and by using the fact that

$$R_0^L \propto \sqrt{q_M^L q_W^L} \quad (17)$$

with the same constant of proportionality as the next generation matrix.

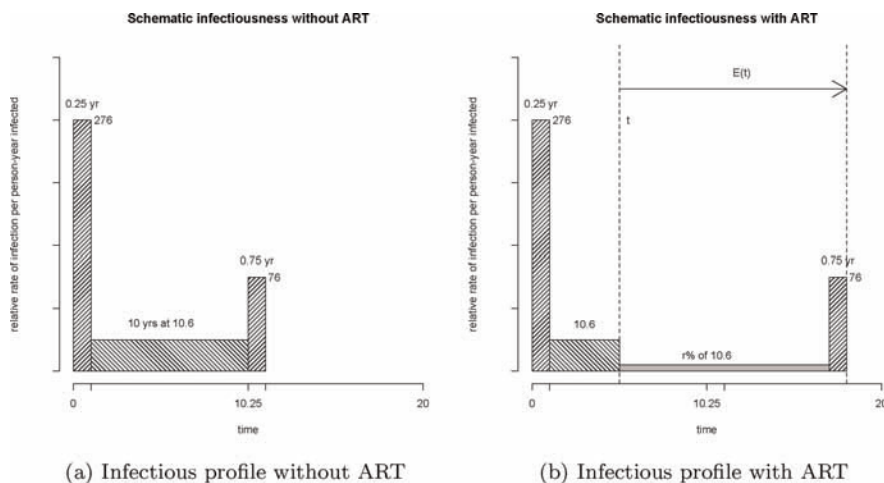
**Table 1. Parameter values for scenarios considered.**

Scenario	$q_M^L = q_W^L$	$q_M^H = q_W^H$	$R_0^L$	$F_M^H = F_W^H$	$\in$
Notation in main text	$\pi$	$\pi$	$R_0^L$	$(1-\theta)$	$\in$
A	1	1.613	1.1	0.1	0.5
B	1	4.348	0.7	0.1	0.1
C	1	13.111	0.7	0.1	0.9

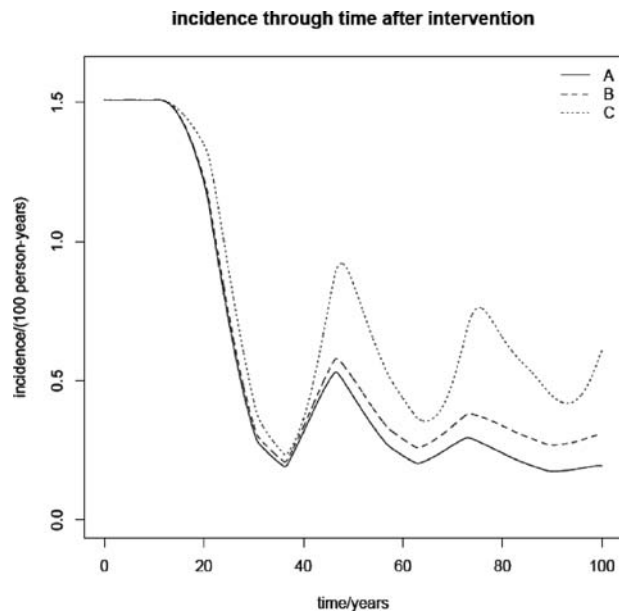
In practice we took  $F_M^H = F_W^H$  and  $q_M^j = q_W^j$  for  $j \in \{H, L\}$ , and (without loss of generality)  $q_M^L = q_W^L = 1$ . With these conventions, and with  $\phi$  normalized so that  $\int e^{-H} \phi.d\tau = 1$ , it is easy to see that  $R_0^L = \beta$ . We also adjusted the  $q$  so as to standardize the equilibrium incidence at 0.015 persons per person per year. The parameters used for the scenarios were therefore those given in Table 1.

### Infection profiles and the effect of treatment

Untreated individuals were assumed to live for 11 years after infection (i.e. a step-function survival distribution) and follow the infectious profiles as given in [1] as shown in Fig. 1(a). Individuals started on ART time  $t$  after their infection are assumed to live an extra  $E(t) = 2:5(11 - t)$  years (step-function survival distribution) : i.e. more than 25 years if treatment is started promptly, with a linearly decreasing return until 11 years when individuals are assumed to have died. The length of the acute and \_nal phases are assumed unchanged, and the extra life is achieved by a longer set-point phase. ART introduced at time  $t$  is assumed to bring the infectiousness down to  $r\%$  of the untreated level, until the last 0.75 years of life when



**Figure 1. Without ART, individuals are assumed to go through 3 phases of infectiousness before dying after 11 years. If ART is introduced at time  $t$ , individuals are assumed to live an extra  $E(t) = 2:5 * (11 - t)$  years from then, with an infectiousness of  $r\%$  of the untreated set-point level until the last 0:75 years of life.**



**Figure 2. Incidence rate (per 100 person-years at risk) over time following the start of a Test and Treat intervention (ART starting 1 year after infection). The intervention starts in year 10 and reaches 80% coverage by year 20, and the lines show the impact of the intervention on incidence in each of the three scenarios A (solid line), B (dashed line) and C (dotted line). The rebounds in incidence are due to the first cohorts on treatment failing simultaneously, which would be dampened in reality by variance in survival times on treatment (although this does not affect the eventual reduction in incidence).**

the infectiousness is the same as the last 0.75 years of life without treatment. The choice of value for  $r$  is discussed in the main paper. This is shown schematically in Fig. 2(b). In the small region of parameter space where

the extra period of life achieved is less than 0.75 years, the infectiousness in the final stage is assumed to be at a lower, so that it has the same total weight as the same (shorter) stage without treatment.

## References

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