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The cost effectiveness and optimal configuration of HIV self-test distribution in South Africa: a model analysis

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ABSTRACT

Background HIV self-testing (HIVST) has been shown to be acceptable, feasible and effective in increasing HIV testing uptake. Novel testing strategies are critical to achieving the UNAIDS target of 95% HIV-positive diagnosis by 2025 in South Africa and globally.

Methods We modelled the impact of six HIVST kit distribution modalities (community fixed-point, taxi ranks, workplace, partners of primary healthcare (PHC) antiretroviral therapy (ART) patients), partners of pregnant women, primary PHC distribution) in South Africa over 20 years (2020–2039), using data collected alongside the Self-Testing AfRica Initiative. We modelled two annual distribution scenarios: (A) 1 million HIVST kits (current) or (B) up to 6.7 million kits. Incremental economic costs (2019 US$) were estimated from the provider perspective; assumptions on uptake and screening positivity were based on surveys of a subset of kit recipients and modelled using the Thembisa model. Cost-effectiveness of each distribution modality compared with the status-quo distribution configuration was estimated as cost per life year saved (estimated from life years lost due to AIDS) and optimised using a fractional factorial design.

Results The largest impact resulted from secondary HIVST distribution to partners of ART patients at PHC (life years saved (LYS): 119 000 (scenario A); 393 000 (scenario B)). However, it was one of the least cost-effective modalities (A: $1394/LYS; B: $4162/LYS). Workplace distribution was cost-saving ($52–$76 million) and predicted to have a moderate epidemic impact (A: 40 000 LYS; B: 156 000 LYS). An optimised scale-up to 6.7 million tests would result in an almost threefold increase in LYS compared with a scale-up of status-quo distribution (216 000 vs 75 000 LYS).

Conclusion Optimisation-informed distribution has the potential to vastly improve the impact of HIVST. Using this approach, HIVST can play a key role in improving the long-term health impact of investment in HIVST.

WHAT IS ALREADY KNOWN?

⇒ HIV self-testing (HIVST) is an acceptable and feasible testing strategy that is also effective in increasing HIV testing uptake.

⇒ Testing strategies which focus on high yield populations (eg, female sex workers) and high-volume distribution modalities (eg, taxi ranks and workplaces) have been found to be more cost-effective than some community-based or any facility-based testing strategies.

WHAT ARE THE NEW FINDINGS?

⇒ Secondary distribution to partners of antiretroviral therapy patients has the largest impact in terms of saving life years lost due to AIDS; however, it is one of the least cost-effective strategies.

⇒ Taxi rank and workplace distribution is the most cost-effective, even cost-saving of strategies.

⇒ An optimisation-informed distribution of scaling up HIVST can greatly improve the impact of HIVST and result in a more cost-effective strategy compared with a status quo distribution of scaling up HIVST.

WHAT DO THE NEW FINDINGS IMPLY?

⇒ Determining the optimal mix of HIVST kit distribution is crucial in ensuring the most effective and cost-effective strategy for national roll-out of HIVST.

INTRODUCTION

South Africa has the highest number of HIV infections worldwide, with an estimated 7.8 million people living with HIV (PLHIV) and 5.0 million on antiretroviral therapy (ART) in 2019.[1] Despite having the largest ART programme in the world, over 23% of all deaths in South Africa in 2019 were AIDS-related.[2] HIV transmission and AIDS-related deaths can be greatly reduced by identifying PLHIV who are unaware of their HIV status early, linking all PLHIV to ART and retaining them in care.[3] The South African government is dedicated to meeting the UNAIDS 95-95-95 fast-track targets by 2025,[4] which aim to have 95% of PLHIV diagnosed, 95%

of those diagnosed on ART and 95% of those on ART virally suppressed by 2025. In 2017, a HIV household survey showed that 85% of South African PLHIV aged 15–64 years had been diagnosed, although men had a lower rate of diagnosis compared with women (80% vs 89%, respectively).[5] Increasing the uptake of HIV testing services (HTS) by introducing novel testing strategies is critical to achieving the UNAIDS target to diagnose 95% of PLHIV in the coming years.

In order to expand HIV testing coverage, the South African National Department of Health (NDoH) has implemented community-based testing to accompany existing conventional HTS, which is most frequently conducted at primary healthcare (PHC) clinics. Recently, HIV self-testing (HIVST) technology has been introduced to give people the opportunity to self-diagnose their HIV status. HIVST involves a person being able to privately collect their own specimen (most often oral fluid), performing the rapid diagnostic test and interpreting the result themselves, either assisted by HIVST distribution staff or unassisted.[6] Recent studies in sub-Saharan Africa, including South Africa, have shown that HIVST is acceptable, feasible and effective in increasing HIV testing uptake,[7–9] providing an alternative testing strategy that can overcome sociostructural barriers associated with conventional HTS in a clinic setting, including the stigma associated with accessing testing and limited hours of clinic availability.[10]

Furthermore, many health services have been disrupted due to COVID-19 as governments across high HIV prevalence countries instituted lockdowns and other forms of restrictions to curb the spread of COVID-19.[11] Though many of the restrictions have since been lifted, there remains a concern that with the pandemic still ongoing, people might be reluctant to attend PHC clinics for HIV testing. For this reason, US President's Emergency Plan for AIDS Relief (PEPFAR) and PEPFAR-supported partners have recently recommended scaling up decentralised access to HIVST.[12] Since 2016, the Unitaid-funded Self-Testing AfRica (STAR) Initiative started distributing HIVST kits through a variety of approaches/modalities in Malawi, Zambia and Zimbabwe, and later expanded to eSwatini, Lesotho and South Africa. Coordinated economic analyses alongside this roll-out found that the cost per kit distributed (in 2019 US$) was $8.91 in Malawi, $14.70 in Lesotho, $14.90 in Zimbabwe and $17.70 in Zambia using community-based distribution strategies,[13 14] $12.82 in circumcision clinics in Zambia[14] and $8.66 in Malawi, $9.15 in Zimbabwe, $5.37 in Zambia and $13.40 in South Africa when kit distribution was integrated into public primary care facilities.[15] A cost-effectiveness analysis of an array of community-based distribution approaches and settings in Sub-Saharan Africa showed these can be cost-effective if implementation is targeted based on HIV prevalence and health benefits, and if costs are considered over a relatively long time horizon.[16] In our analysis of South Africa's distribution programme, we found that facility-based distribution modalities had on average higher cost per kit distributed than community-based distribution approaches, which was unlike observations in Zambia and Zimbabwe.[17 18]

Previous modelling work by our team in 2019 using preliminary cost and effectiveness data on HIVST from other settings, showed that out of ten testing modalities analysed, HIVST combined with home-based testing would have the greatest impact on the proportion of PLHIV who are diagnosed, increasing the fraction of diagnosed PLHIV to 96.5% by 2030 and would be highly cost-effective compared with currently funded HIV interventions.[19] More recently, using data on intermediate outcomes such as person screened positive, tested positive in confirmatory testing and initiated on ART from the STAR-supported HIVST roll-out in South Africa, we established that testing strategies which focus on high yield populations such as female sex workers and high-volume distribution modalities such as taxi rank and workplace distribution were more cost-effective than other community-based or any of the facility-based testing strategies.[18]

This work is an update to our previous work, using data collected under the STAR Initiative to inform both effectiveness and cost parameters in the Thembisa model,[1] in order to model the impact and cost-effectiveness of different HIVST distribution modalities over a 20-year time horizon (2020–2039) and, based on these outcomes, determine the highest impact and most cost-effective combination of HIVST distribution modalities in a mathematical optimisation.

METHODS

Outcomes

To assess the epidemiological impact of different testing strategies, we used the Thembisa model, a deterministic compartmental model set up to simulate HIV testing in South Africa.[20] The model stratifies the population by sex and individual age and further divides the population into a number of sexual behaviour risk groups. Previously, the model simulated three HIV testing modalities: testing through antenatal clinics, testing of patients with opportunistic infections and 'general' HIV testing. For each modality, rates of testing uptake are specified by age and sex, based on routine testing data and survey data on the proportions of adults who had ever been tested for HIV.[20 21] All individuals are stratified according to their HIV testing history, into one of three compartments: never tested for HIV, previously tested but not diagnosed positive and diagnosed positive. Newly diagnosed individuals are assigned a probability of starting ART in the month of diagnosis, and a lower monthly rate of ART initiation is assumed for those who do not start ART in the month of diagnosis. The model allows for rediagnosis of previously diagnosed individuals, with relative rates of testing in previously diagnosed and treated individuals being set in such a way

that the model matches historic trends in HIV testing yields (declining from 25.8% in 2004–2005 to 6.25% in 2018–2019[22]). A more complete description of the model is provided elsewhere.[1]

For this analysis, we modelled the impact of six HIVST distribution modalities (fixed-point, taxi ranks, workplace, secondary distribution to partners of ART patients at PHC, secondary distribution to partners of pregnant women at PHC, primary PHC distribution using Thembisa). A more detailed description of each modality is provided in the online supplemental appendix table S1, but briefly-fixed-point distribution involves testing tents set up near busy, preselected locations within communities. Taxi rank distribution involves distributing HIVST kits in densely populated public taxi ranks and train stations. Facility-based modalities such as secondary distribution through pregnant women and ART patients focused on the individuals taking the HIVST kits to their partners, while primary PHC is focused on the individual using the HIVST kit for themselves. Workplace distribution involved primary and secondary distribution in large male-dominated workplaces in industries such as manufacturing, mining, construction and so on.

The impact of HIVST in Thembisa was parameterised using data from the STAR initiative for each of the six modalities that were incorporated into the model, with the exception of primary distribution to PHC (which was conducted by implementing partners and not PHC staff in STAR). Surveys of a subset of 4% of HIVST recipients (n=40 834), conducted telephonically at 2-week, 4-week and 6-week intervals postdistribution, provided information on the numbers of tests used, the age and sex profile of recipients, the self-reported test results (for those test kits that were used) and the proportions of those diagnosed positive who subsequently started ART, for each of the first five HIVST models. For each of these five models, the Thembisa assumptions about the age and sex profile of testers was set to match (approximately) that observed in the STAR data, but because the STAR data are not nationally representative and because HIV prevalence in South Africa is highly heterogeneous, we did not attempt to match the self-reported fraction of HIVST results that were positive (more detailed information is supplied in the online supplemental appendix). Model assumptions about test wastage (distributed HIVST kits which were reportedly not used) were also set to match those observed in the STAR data, although these could not be reliably determined in the case of the secondary distribution models, as many of the interviewed individuals did not know if their partner had actually used the test. A more detailed description of each modality and the self-testing extensions to the model is provided in the online supplemental appendix.

Data for the sixth model, primary distribution to PHC clients, were not based on STAR data as the only models supported by STAR in South Africa were non-integrated (ie, using stand-alone distribution staff rather than clinic staff) and as such not representative of likely routine roll-out. Because we lacked data on the uptake of HIVST in primary PHC, we assumed that the patterns of uptake would be the same as for conventional facility-based HTS, with primary PHC distribution of HIVST effectively replacing a proportion of the HIV testing in PHC. To ensure this distribution modality was representative of how it would be conducted within the PHC, we assumed the same screening positivity as conventional HTS and used the results of previous cost analyses work of conventional HTS at PHC level.[19]

Model outcomes reported are life years lost due to AIDS, HIV infections averted and AIDS deaths over 20 years (2020–2039). HIV infections are averted both as a result of reduced infectiousness of individuals on ART and an assumed 56% reduction in unprotected sex after HIV diagnosis.[1] No specific linkage to prevention services (or change in sexual behaviour) is assumed for people who test negative. Life years lost are calculated with reference to the life expectancies obtained from the West Level 26 lifetable.[23]

Cost analysis

To aid comparability across countries, the methods for the analysis of cost and outcomes of HIVST distribution through the six modalities were similar to the other economic analyses under STAR and are described in detail in Matsimela *et al*.[18] Briefly, costs were estimated from the provider perspective using a detailed expenditure analysis complemented by activity-based observations (time in motion analysis) and micro-costing and included capital cost items such as start-up training, sensitisation and equipment, as well as recurrent cost items such as personnel, test kits, other supplies, transportation, building operation and maintenance. Research costs and other costs that were only relevant to STAR and not related to routine implementation were excluded. To align the cost of primary HIVST distribution at PHC more closely with services offered within PHC, the cost per test kit distributed through this modality was estimated based on ingredients and prices adapted from previous work.[19] Capital costs were annualised over the 2 years' duration of the project using a 3% discount rate, in keeping with the methods used in other countries.

In order to capture downstream programmatic effects, we modelled the impact of HIVST distribution on the cost and impact of the entire South African HIV programme over a 20-year time horizon; we included, among others, the cost of ART, medical male circumcision, condom distribution, prevention of mother-to-child transmission and conventional HTS with rapid tests through both facility-based and mobile testing modalities.[24] Additional information of costs of other interventions included in the HIV programme are shown in online supplemental appendix table S2. Costs are presented undiscounted and converted to 2019 US dollars (US$) using the period average of 14.45 South Africa Rand (ZAR)=1 US$.[25]

SCENARIOS

We consulted with a stakeholder panel of experts from the National Department of Health and from research organisations focused on HIVST regarding their expected outlook for HIVST distribution for South Africa beyond the STAR initiative, specifically for distribution through the six different modalities under analysis. The result constitutes our baseline scenario, a status-quo distribution, with 60% of HIVST kits assigned to primary PHC distribution, 20% to workplace distribution, 7% to secondary distribution to partners of women attending antenatal care (ANC) at PHC, 5% through fixed point distribution in communities, 5% to taxi rank distribution and 3% to secondary distribution to partners of ART patients at PHC. For our main analysis, we included two overarching coverage scenarios, defined by the number of HIVST distributed annually. Scenario A assumes that 1 million HIVST kits will be distributed annually, in keeping with the current volumes of programme implementation, while Scenario B represents a target volume, scaling up to a maximum of 6.7 million HIVST kits distributed annually by 2030 (equivalent to replacing 40% of conventional HTS). The consultation also resulted in choosing a target population for each of the six HIVST distribution modalities as well as a 'feasible maximum', that is, a maximum number of people in each target population who can feasibly be screened for HIV with HIVST (see online supplemental appendix table S1).

Cost effectiveness analysis

To calculate the incremental cost-effectiveness of each HIVST distribution modality in turn, we assumed that 100% of available HIVST kits would be distributed through one of the six distribution modalities in turn, for both coverage scenarios A and B. We estimated the incremental cost of HIVST as the change in the cost of the entire HIV programme and calculated the incremental cost per HIV infection averted, cost per life year saved and cost per AIDS death averted over the 20-year time period, incremental to the status quo distribution of 1 million HIVST.

Optimisation

We used a fractional factorial design to determine the optimal set of configurations between the different HIVST distribution modalities, resulting in the largest epidemiological impact and the most cost-effective configuration. This analysis was performed under both coverage scenarios A (1 million HIVST kits annually) and B (6.7 million HIVST kits annually), where we modelled all possible combinations of modalities at set increments, constrained only by the feasible maximum number of target population members reached in each modality. We compared all model runs to the status quo distribution of 1 million HIVST annually. We present different distributions across the different HIVST modalities and the impact on life years saved (LYS) and corresponding cost-effectiveness. Additional results regarding the impact on HIV infections averted are presented in the online supplemental appendix figures S1 and S2. We additionally compared the optimal distribution of HIVST in Scenario B to a scenario where the current status quo distribution of test kits was scaled up to meet the 6.7 million HIVST target. Additional analyses for both scenarios A and B were conducted in which the baseline scenarios containing no HIVST are given in the online supplemental appendix figures S3 and S4.

Patient and public involvement

Patients were not directly involved in this study; this analysis was conducted using data derived from a previous study.[18]

RESULTS

Outcomes

Scenario A

After accounting for uptake, the number of HIVST kits used ranges between 0.5 and 1.0 million kits across the six modalities (table 1). Compared with the status quo distribution of HIVST (table 1), primary distribution of all 1 million HIVST kits annually through PHC was dominated, due to the lower positivity yields compared with the HIVST modalities included in the status quo distribution, increasing new HIV infections and life years lost due to AIDS over 20 years (depicted as negative infections averted or LYS) (table 2). The distribution strategy with the highest epidemiological impact with respect to saving life years, compared with the status quo, was distributing all HIVST kits to partners of PHC ART patients, which saved 119 000 (0.3%) life years. All remaining distribution modalities (fixed point, taxi ranks, secondary distribution to partners of ANC clients, workplaces) were more effective than the status quo distribution and were estimated to save between 40 000 and 63 000 (0.1%–0.2%) life years and averted 9000–28 000 (0.4%–1.1%) HIV infections over 20 years.

Scenario B

When scaling up the number of HIVST to 6.7 million kits distributed annually by 2030, exclusive primary distribution to PHC clients was dominated (table 2). Secondary distribution through PHC ART patients had the highest impact, saving 393 000 (1.1%) life years and averting 112 000 (4.3%) new HIV infections over 20 years (table 2), while fixed point and workplace distribution modalities had a moderate impact (205 000; 0.6% and 156 000; 0.4% LYS, respectively). Distributing all kits through taxi ranks and partners of ANC clients had the least impact of all distribution modalities (98 000; 0.3% and 66 000; 0.2% LYS, respectively).

Costs

Scenario A

Due to the lower cost per test kit distributed, workplace distribution was estimated to be cost-saving compared with the status quo, saving an estimated $76 million over

Table 1 Description of modelled HIVST distribution modalities

		HIVST					
	Status quo distribution	Fixed point	Taxi ranks	Secondary PHC (ANC)	Secondary PHC (ART patients)	Workplace	Primary PHC
% of kit recipients screened positive		5.7%	5.2%	3.9%	19.9%	6.4%	4.0%
% of screened positive initiating ART		27%	27%	27%	27%	27%	40%
Cost per test kit distributed (2019 US$)	–	5.70	4.74	13.04	12.31	5.44	8.24
Distribution of HIVST into different modalities							
Fixed point	5%	100%	–	–	–	–	–
Taxi ranks	5%	–	100%	–	–	–	–
Secondary PHC (ANC)	7%	–	–	100%	–	–	–
Secondary PHC (ART patients)	3%	–	–	–	100%	–	–
Workplace	20%	–	–	–	–	100%	–
Primary PHC	60%	–	–	–	–	–	100%
Scenario A: Distributing 1 million HIVST per year							
Total HIV tests performed per year (millions)	15.4	15.5	15.5	15.6	15.4	15.5	15.3
HTS	14.5	14.6	14.7	14.8	14.9	14.6	14.3
HIVST	0.9	0.9	0.9	0.8	0.5	0.9	1.0
% of tests that are HIVST	6%	6%	5%	5%	4%	6%	7%
Scenario B: Distributing up to 6.7 million HIVST per year (to replace 40% of conventional HTS)							
Total HIV tests performed per year (millions)	15.4	15.9	15.7	15.6	15.9	15.8	15.3
HTS	14.5	9.6	12.4	14.4	10.5	9.5	9.0
HIVST	0.9	6.3	3.3	1.2	5.4	6.3	6.3
% of tests that are HIVST	6%	40%	21%	8%	34%	40%	41%

ANC, antenatal care; ART, antiretroviral therapy; HIVST, HIV self-testing; HTS, HIV testing services; PHC, primary healthcare.

20 years (table 2). HIVST distribution to partners of PHC ART patients and ANC clients were the most costly of the distribution strategies ($166 million each over 20 years), while distribution through taxi ranks and fixed point distribution had an incremental cost to the HIV programme of $9 million and $44 million, respectively.

Scenario B

Compared with the status quo, distribution of 6.7 million HIVST kits through workplaces was cost-saving ($52 million over 20 years) (table 2). Distributing all HIVST kits through other modalities was more costly compared with the status quo, having an estimated incremental cost ranging between $198 million (for taxi ranks) and $1.6 billion (for distribution to partners of ART patients) over 20 years.

Cost-effectiveness

Scenario A

With the exception of workplace distribution, which was cost-saving, the HIVST distribution modality with the lowest incremental cost effectiveness ratio (ICER) over 20 years was distribution through taxi ranks ($194/life year saved and $438/HIV infection averted) (figure 1, table 2). Fixed point distribution was the second most cost-effective ($705/life year saved and $3092/HIV infection averted), while secondary distribution through ART patients and ANC clients were the least cost-effective distribution modalities ($1394 and $2899/life year saved, respectively) (table 2).

Scenario B

Increasing distribution of HIVST kits up to 6.7 million and directing it all to taxi ranks had the lowest ICER relative to the other distribution modalities, compared with the status quo ($2030/life year saved and $4019/HIV infection averted), whereas secondary distribution to partners of ANC clients and ART patients at PHC were the least cost effective ($4162/life year saved and $14 688/HIV infection averted) (figure 1, table 2). The relative cost-effectiveness of secondary distribution to partners of ANC clients differed from scenario A as these clients were limited to a feasible maximum limit of 1.2 million people who could receive HIVST, thereby curtailing the incremental cost and impact overall.

Optimisation

Scenario A

Distributing the majority (IQR 38%–63%) of the 1 million HIVST kits through workplaces led to cost savings over 20 years, compared with the status quo distribution; LYS was estimated to range between 100 and 24 000 (figure 2A). Beyond the cost-saving configurations, ICER/LYS was lowest when a large portion of HIVST kits were

Table 2 Impact of HIVST distribution modalities on HIV infections, life years lost due to AIDS and incremental cost (2019 US$) on the HIV programme, over 2020–2039, compared with a baseline status quo distribution of 1 million HIVST annually

		HIVST					
	Status quo distribution	Fixed point	Taxi ranks	Secondary PHC (ANC)	Secondary PHC (ART patients)	Workplace	Primary PHC
Scenario A: Distributing 1 million HIVST per year							
New HIV infections, millions	2.57	2.55	2.55	2.54	2.54	2.56	2.58
HIV infections averted, thousands (%)		14 (0.6%)	20 (0.8%)	28 (1.1%)	27 (1.1%)	9 (0.4%)	−14 (−0.6%)
Life years lost due to AIDS, millions	36.50	36.44	36.45	36.44	36.38	36.46	36.55
Life years saved, thousands (%)		63 (0.2%)	46 (0.1%)	57 (0.2%)	119 (0.3%)	40 (0.1%)	−48 (−0.1%)
AIDS deaths, thousands	1011	1010	1011	1010	1008	1010	1012
Deaths averted, thousands (%)		1.4 (0.1%)	0.70 (0.1%)	0.8 (0.1%)	3.6 (0.4%)	0.9 (0.1%)	−1.0 (−0.1%)
Total cost of the HIV programme	28.77	28.81	28.77	28.93	28.93	28.69	28.76
Incremental cost, millions		44	9	166	166	−76	−5
Incremental cost-effectiveness ratio							
Cost/infection averted		3092	438	5988	6087	Cost-saving	Dominated
Cost/life years saved		705	194	2899	1394	Cost-saving	Dominated
Cost/AIDS death averted		31 696	12 676	200 097	46 541	Cost-saving	Dominated
Scenario B: Distributing up to 6.7 million HIVST per year (to replace 40% of conventional HTS)							
New HIV infections, millions	2.54	2.51	2.52	2.53	2.46	2.52	2.58
HIV infections averted, thousands (%)		63 (2.5%)	49 (1.9%)	34 (1.3%)	112 (4.3%)	51 (2.0%)	−14 (−0.6%)
Life years lost due to AIDS, millions	36.43	36.29	36.40	36.43	36.11	36.34	36.55
Life years saved, thousands (%)		205 (0.6%)	98 (0.3%)	66 (0.2%)	393 (1.1%)	156 (0.4%)	−48 (−0.1%)
AIDS deaths, thousands	1010	1007	1010	1010	1000	1008	1012
Deaths averted, thousands (%)		4.6 (0.5%)	1.5 (0.2%)	1.0 (0.1%)	11.1 (1.1%)	3.2 (0.3%)	−1.0 (−0.1%)
Total cost of the HIV programme, billions	29.10	29.31	28.96	29.01	30.40	28.71	29.02
Incremental cost, millions		544	198	240	1638	−52	250
Incremental cost-effectiveness ratio							
Cost/infection averted		8636	4019	7151	14 688	Cost-saving	Dominated
Cost/life years saved		2651	2030	3639	4162	Cost-saving	Dominated
Cost/AIDS death averted		119 315	129 359	251 141	147 396	Cost-saving	Dominated

ANC, antenatal care; ART, antiretroviral therapy; HIVST, HIV self-testing; HTS, HIV testing services; PHC, primary healthcare.

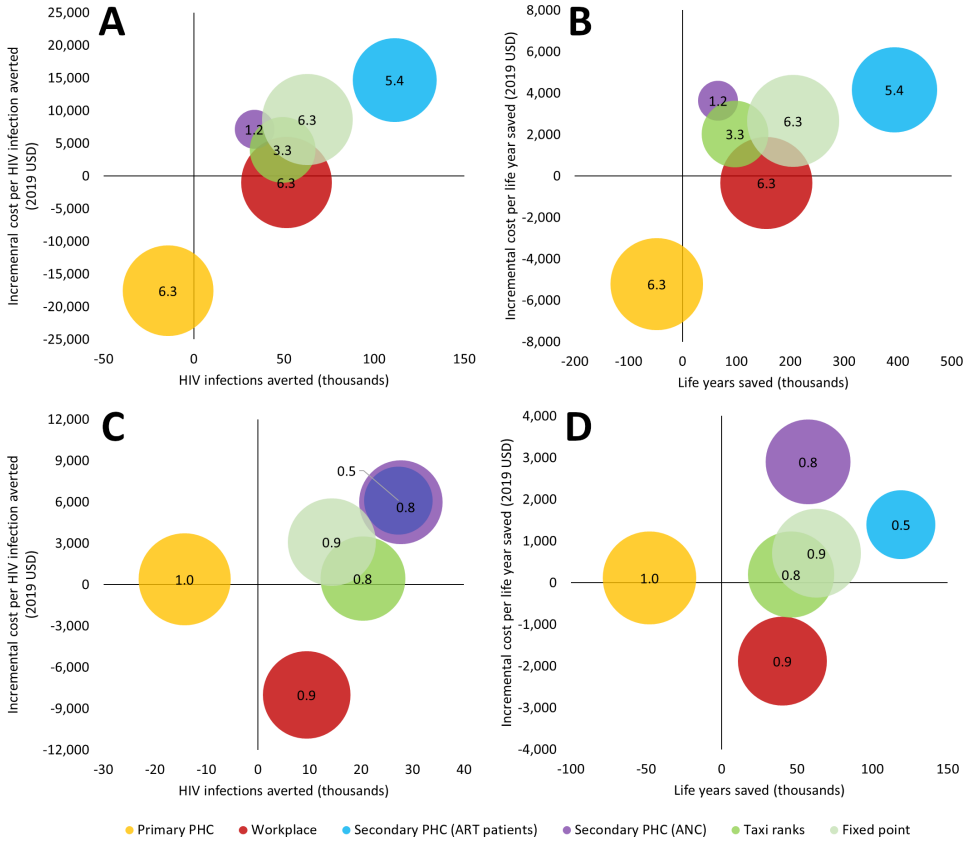

Figure 1 Impact and cost-effectiveness of redistribution all HIVST to different testing strategies, 2020–2039. For distributing 1 million HIVST annually, impact on HIV infections averted (A) and life years saved (B); for distributing up to 6.7 million HIVST annually, impact on HIV infections averted (C) and life years saved (D). Bubble size represents the number of HIVST distributed to each population annually. HIVST, HIV self-testing.

distributed to workplaces (IQR 13%–38%), while there was a mixed distribution for the other modalities: IQR 0%–38% each for fixed point and taxi rank distribution, IQR 0%–25% each for secondary distribution to partners of ART patients and primary distribution to PHC clients, while secondary distribution to partners of ANC clients

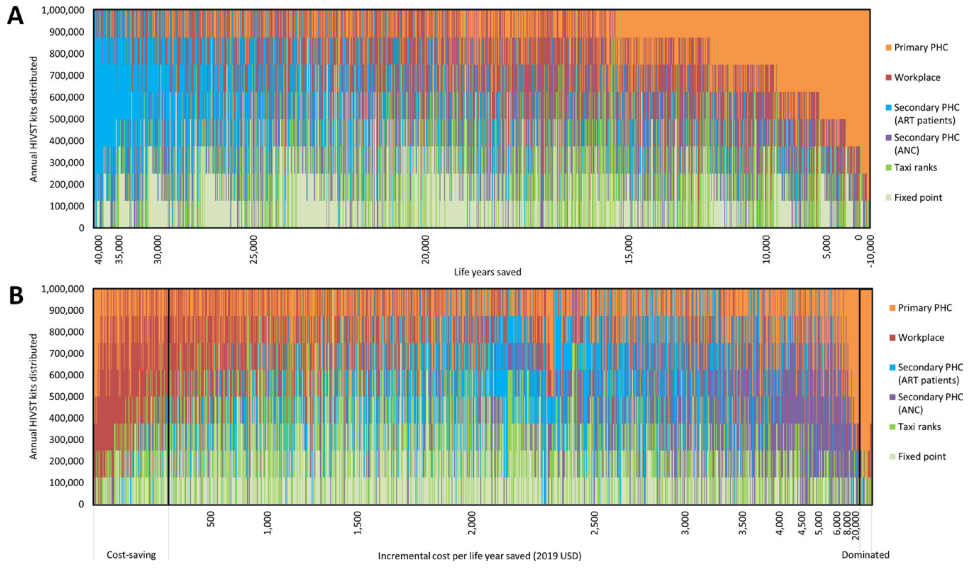

Figure 2 (A) Number of life years saved over the status quo and (B) incremental cost-effectiveness ratio, incremental cost per life year saved (2019 US$), distributing up to 1 million HIVST distributed per year. Status quo: 1 million HIVST distributed to fixed point (5% of HIVST), taxi ranks (5%), secondary PHC (ANC) (7%), secondary PHC (ART patients) (3%), workplace (20%) and primary PHC distribution (60%). ANC, antenatal care; ART, antiretroviral therapy; HIVST, HIV self-testing; PHC, primary healthcare.

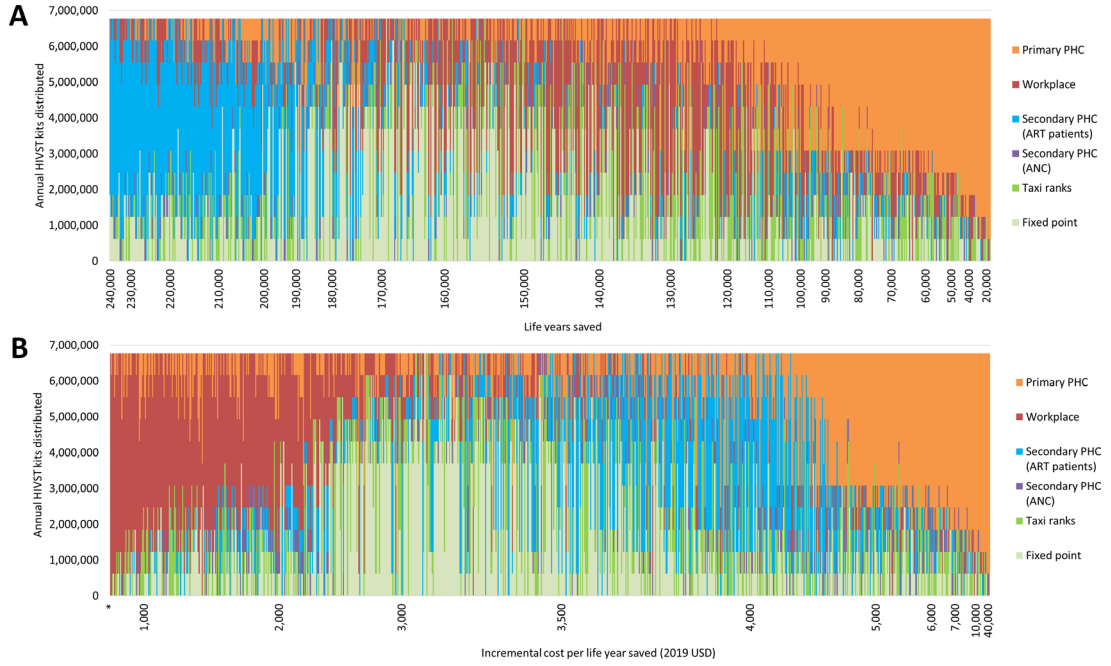

Figure 3 (A) Number of life years saved over the status quo and B) incremental cost-effectiveness ratio, incremental cost per life year saved (2019 US$), distributing up to ~6.7 million HIVST per year by 2030. Status quo: 1 million HIVST distributed to fixed point (5% of HIVST), taxi ranks (5%), secondary PHC (ANC) (7%), secondary PHC (ART patients) (3%), workplace (20%) and primary PHC distribution (60%). *Indicates single configuration where results are cost-savings (ie, 100% distribution to workplaces). ANC, antenatal care; ART, antiretroviral therapy; HIVST, HIV self-testing; PHC, primary healthcare.

had the lowest allocation (IQR 0%–13%) (figure 2B). The biggest epidemiological impact resulted from distributing the majority of HIVST (IQR 50%–75%) to partners of ART patients (ranging between 32 000 and 46 000 LYS), and these configurations were in the higher range of ICERs with an IQR of $2100–$2600 per life year saved (figure 2B). Configurations of HIVST distribution relying mainly on secondary distribution to partners of ANC clients (IQR 25%–63%) or primary PHC distribution (13%–50%) were the least cost-effective, with ICERs upwards of $4000 per life year saved, and even dominated (if 60% or more of HIVST was distributed to primary PHC) (figure 2B). Similar patterns were obtained when using HIV infections averted as an outcome (online supplemental appendix figure S1).

Scenario B

In comparison to the status quo distribution of 1 million HIVST kits distributed annually, if scaled up to 6.7 million HIVST annually, the largest impact was achieved when most HIVST kits (IQR 55%–64%) were distributed to partners of ART patients, saving between 200 000 and 241 000 life years over 20 years, while ICERs for these configurations ranged between $2400 to $4300 per life year saved (figure 3A,B). Using the set of configurations that result in the median impact as the optimal distribution strategy, the optimal HIVST kit distribution would look as follows: 64% to partners of ART patients, 9% each epidemiological fixed point, taxi ranks and workplaces and none to partners of PHC ANC clients and primary PHC clients. Compared with the status quo distribution of 1 million HIVST annually, an optimised scale-up of distribution to 6.7 million tests annually would result in an almost threefold increase in LYS compared with the same volume scale-up at the current status-quo distribution (table 2) (216 000 vs 75 000 LYS), and it would have a lower ICER ($3990 vs $4493 per LYS). Distribution to workplaces was cost-saving only when 100% of all HIVST were distributed through this modality, and it had a moderate impact: saving 137 000 life years over 20 years (figure 3). The distribution strategies with the lowest ICER/LYS were those where majority of HIVST kits were distributed to workplaces. Distributing more than 50% of HIVST kits to primary PHC showed the least impact relative to other configurations (<100 000 LYS), and it was the least cost-effective strategy, with ICERs upwards of $4000 per LYS (figure 3A,B). We see similar patterns when analysing the impact on HIV infections averted (online supplemental appendix figure S2).

Comparing against a baseline of no HIVST

In scenario A, when comparing against a baseline with no HIVST, we see similar patterns of distribution configurations where HIVST distributed mainly to partners of ART patients produced the largest epidemiological impact (ranging 75 000–93 000 LYS), while ICERs are upwards of $2000 per LYS (online supplemental appendix figure S3). HIVST distributed mostly (>50%) through secondary distribution to partners of ANC clients was the least cost-effective strategy with the highest ICERs among all configurations. Distributing most HIVST (>40%) to workplaces is the most cost-effective strategy, with ICERs falling below

$1100 per life year saved (online supplemental appendix figure S3). When scaling up to 6.7 million HIVST kits distributed annually, compared with a baseline with no HIVST, distribution to partners of ART patients was the strategy that yielded the largest impact (>235 000 LYS), although it had high ICERs relative to the other configurations (>$3200/life year saved) (online supplemental appendix figure S4). Primary PHC distribution was the least cost-effective (>$4000/life year saved) and least impactful strategy (<165 000 life year saved). Workplace distribution was the most cost-effective strategy (ICER <$2000/life year saved) but had a moderate epidemiological impact, ranging between 170 000 and 200 000 LYS (online supplemental appendix figure S4).

DISCUSSION

The distribution of HIVST kits is expected to have a large impact on averting new HIV infections and AIDS deaths over 20 years, compared with a baseline status quo where HIVST kits were already distributed through different modalities with a set distribution pattern (60% to primary PHC, 20% to workplaces, 7% to secondary distribution to partners of ANC clients in PHC, 5% to taxi ranks, 5% to fixed point and 3% to secondary distribution to partners of ART patients). Importantly, we have shown the importance in determining the optimal configuration of testing modalities as HIVST scales up. An optimisation-informed scale-up—instead of proportionally scaling-up the current distribution of HIVST testing modalities—is expected to nearly triple the number of LYS. Redirecting all HIVST towards any distribution strategy other than primary PHC performs better in terms of saving life years and averting HIV infections over 20 years than the planned status quo; however, results vary in terms of costs and cost effectiveness. We showed that secondary distribution to partners of ART patients will have the biggest epidemiological impact but will be the least cost-effective strategy due to its high cost, while distribution of HIVST to workplaces will be cost-saving but have only a moderate impact on averting HIV infections. Distribution to primary PHC is not cost-effective due to the lower HIV positivity yielded and may even be dominated compared with other distribution strategies.

There are several limitations to this work. First, cost data for the different distribution strategies were based on an initiative that was managed and implemented by non-governmental organisations, and therefore both cost and screening positivity could change once introduced and managed in the public sector. Second, for primary PHC testing, we assumed the same screening positivity as conventional HTS. It is plausible that screening positivity could be higher if implemented in the real world as PHC clients concerned about their HIV status might prefer self-screening over conventional HTS within the clinic setting to avoid stigma or have more control over the testing procedure. However, we do posit the screening positivity of primary PHC to remain lower than those of the higher performing distribution strategies, and indeed this was shown to be the case in the vertical, non-integrated PHC testing strategy included in Matsimela *et al*.[18] Third, the model estimates of HIV testing yields were in some cases inconsistent with those reported in the STAR data, suggesting that matching the age and sex profile of HIV test recipients may be insufficient to reasonably capture the different HIV risk profiles associated with different testing modalities. However, the STAR data are not nationally representative, and implementation has not been uniform, with different HIVST modalities being piloted in different areas by different implementers. Some divergence between observed testing yields and yields estimated in a national model is therefore to be expected, and it will be important to continue to monitor testing yields as different HIVST modalities are scaled up nationally.

Future work on HIVST should include the evaluation of the different testing strategies once scaled up in the public health system to understand the real cost and screening positivity. The positivity rate may decline differentially between testing modality as demand saturates, and therefore understanding the optimal timing and frequency of testing by modality will need to continue in order to help guide effective implementation.

CONCLUSION

In evaluating the impact and cost-effectiveness of different HIVST distribution modalities using a HIV transmission model and data collected alongside large-scale routine implementation under the STAR initiative, we were able to generate findings that could help inform policy makers making decisions on the most effective strategy to prioritise for national roll-out: the secondary distribution of HIVST to partners of ART patients. However, this will be a costly approach. The optimal distribution of HIVST is estimated to be a mix between secondary distribution of HIVST kits to partners of ART patients and pregnant women in care at PHC, workplace testing and fixed point HIVST distribution. Further, in the face of the global COVID-19 pandemic affecting all health services, including HIV testing, scaling up HIVST in order to limit patient contact with health services and providing an option of self-screening to those reluctant to attend a PHC clinic, would assist greatly in maintaining or increasing progress towards testing targets.

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Contributors LJ and GM-R conceptualised the study. LFJ developed the epidemiological model. LJ did the analysis and drafted the manuscript. LJ, GM-R and LFJ contributed to the interpretation of the results. All authors contributed to the interpretation of the results, revision and approval of the manuscript.

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Correction: *The cost effectiveness and optimal configuration of HIV self-test distribution in South Africa: a model analysis*

Jamieson L, Johnson LF, Matsimela K, *et al*. The cost effectiveness and optimal configuration of HIV self-test distribution in South Africa: a model analysis. *BMJ Global Health* 2021;6:e005598. DOI: http://dx.doi.org/10.1136/bmjgh-2021-005598

An error in applying the average cost of one of the HIV self-test modalities, the distribution to workplaces modality, resulted in the cost of this modality to be less expensive than it should have been. As the cost is applied to both the baseline scenario and the workplace scenario, it affects several results throughout the paper. After corrections, workplace testing was not cost-saving in Scenario A, although it remained one of the more cost-effective distribution strategies with one of the lowest incremental cost effectiveness ratio. As a result of a change in the baseline, taxi rank distribution was cost-saving in Scenario A. Of note is that this error had minimal impact on the optimal configuration of HIVST distribution when scaling up HIVST distribution.

The following corrections are noted in the Results text:

1. Under the costs paragraph,
   a. "…workplace distribution was estimated to be cost-saving compared with the status quo, saving an estimated $76 million…" should read "…taxi rank distribution was estimated to be cost-saving compared with the status quo, saving an estimated $13 million…"
   b. "$166 million each over 20 years" should read "$144 million each over 20 years"
   c. "distribution through taxi ranks and fixed point distribution had an incremental cost to the HIV programme of $9 million and $44 million, respectively" should read "distribution through workplaces and fixed point distribution had an incremental cost to the HIV programme of $12 million and $22 million, respectively."
   d. "Compared with the status quo, distribution of 6.7 million HIVST kits through workplaces was cost-saving ($52 million over 20 years)" should be removed.
   e. "$198 million (for taxi ranks)" should read "$176 million (for taxi ranks)".
2. Under the cost-effectiveness paragraph,
   a. "With the exception of workplace distribution, which was cost-saving" should read "With the exception of taxi rank distribution, which was cost-saving".
   b. "taxi ranks ($194/life year saved and $438/HIV infection averted)" should read "workplaces ($302/life year saved and $1,286/HIV infection averted)".
   c. "$705/life year saved and $3,092/HIV infection averted" should read "$351/life year saved and $1,541/HIV infection averted".
   d. "$1,394 and $2,899/life year saved" should read "$1,207 and $2,510/life year saved".
   e. "$2,030/life year saved and $4,019/HIV infection averted" should read "$1,802/life year saved and $3,568/HIV infection averted".
   f. "$4,162/life year saved and $14,688/HIV infection averted" should read "$4,106/life year saved and $14,488/HIV infection averted".
3. Under the Optimisation paragraph,
   a. "Distributing the majority (IQR 38%–63%) of the 1 million HIVST kits through workplaces led to cost savings over 20 years, compared with the status quo distribution; LYS was estimated to range between 100 and 24,000" should read "Distributing the majority (IQR 38%–63%) of the 1 million HIVST kits through primary PHC led to cost savings over 20 years, compared with the status quo distribution, however this had a relatively small, even harmful, impact on LYS, ranging between −10,000 (ie, a harmful effect) and 16,000"

b. "large portion of HIVST kits were distributed to workplaces (IQR 13–38%)" should read "large portion of HIVST kits were distributed to taxi ranks (IQR 6–38%)"
c. "IQR 0%–38% each for fixed point and taxi rank distribution" should read "IQR 0%–38% each for fixed point and workplace distribution"
d. "IQR 0%–25% each for secondary distribution to partners of ART patients and primary distribution to PHC clients, while secondary distribution to partners of ANC clients had the lowest allocation (IQR 0%–13%)" should read "IQR 0%–25% for primary distribution to PHC clients, while secondary distribution to partners of ART patients and ANC clients had the lowest allocation (IQR 0%–13%)"
e. "IQR of $2,100 to $2,600 per life year saved" *should read* "IQR of $1,900 to $2,300 per life year saved"
f. "Configurations of HIVST distribution relying mainly on secondary distribution to partners of ANC clients (IQR 25%–63%) or primary PHC distribution (13%–50%) were the least cost-effective, with ICERs upwards of $4,000 per life year saved, and even dominated (if 60% or more of HIVST was distributed to primary PHC)" should read "Configurations of HIVST distribution relying mainly on secondary distribution to partners of ANC clients (IQR 13%–38%) and primary PHC distribution (0%–38%) were the least cost-effective, with ICERs upwards of $2,000 per life year saved, and even dominated (if 75% or more of HIVST was distributed to primary PHC)"
g. "$2,400 to $4,300 per life year saved" should read "$3,309 to $4,300 per life year saved"
h. "64% to partners of ART patients, 9% each epidemiological fixed point, taxi ranks and workplaces, and none to partners of PHC ANC clients and primary PHC clients" should read "55% to partners of ART patients, 18% each to fixed point and taxi ranks, 9% to partners of PHC ANC clients and none to workplaces or primary PHC clients"
i. "and it would have a lower ICER ($3,990 vs $4,493 per LYS)" should read "and it would have a lower ICER ($3,923 vs $5,373 per LYS)."
j. To be removed: "Distribution to workplaces was cost-saving only when 100% of all HIVST were distributed through this modality, and it had a moderate impact: saving 137,000 life years over 20 years"
k. "The distribution strategy with the lowest ICER/LYS were those where majority of HIVST kits were distributed to workplaces" should read "The distribution strategy with the lowest ICER/LYS were those where majority of HIVST kits were distributed to fixed point distribution points"

4. Under the "Comparing against a baseline of no HIVST" paragraph,
   a. "Distributing most HIVST (>40%) to workplaces is the most cost-effective strategy, with ICERs falling below $1,100 per life year saved" should read "Distributing a large portion HIVST (>25%) to taxi ranks is the most cost-effective strategy"
   b. "Workplace distribution was the most cost-effective strategy (ICER <$2,000/life year saved) but had a moderate epidemiological impact, ranging between 170,000 and 200,000 LYS" should read "Distributing majority of HIVST kits to fixed points was the most cost-effective strategy compared with other configurations (ICER <$3,000/life year saved) but had a moderate epidemiological impact, ranging between 164,000 and 238,000 LYS"
5. Under the Discussion, "workplaces will be cost-saving" should read "taxi ranks will be cost-saving"
6. Under the Conclusion, "a mix between secondary distribution of HIVST kits to partners of ART patients and pregnant women in care at PHC, workplace testing and fixed point HIVST distribution." should read "a mix between secondary distribution of HIVST kits to partners of ART patients and pregnant women in care at PHC, taxi ranks and fixed point HIVST distribution."

Corrected versions of Table 2, Figures 1-3, Figures S1-S4 are below.

Table 2 Impact of HIVST distribution modalities on HIV infections, life years lost due to AIDS and incremental cost (2019 USD) on the HIV programme, over 2020-39, compared to a baseline status quo distribution of 1 million HIVST annually

		HIVST					
	Status quo distribution	Fixed point	Taxi ranks	Secondary PHC (ANC)	Secondary PHC (ART patients)	Workplace	Primary PHC
Scenario A: Distributing 1 million HIVST per year							
New HIV infections, millions	2.57	2.55	2.55	2.54	2.54	2.56	2.58
HIV infections averted, thousands (%)		14 (0.6%)	20 (0.8%)	28 (1.1%)	27 (1.1%)	9 (0.4%)	-14 (-0.6%)
Life years lost due to AIDS, millions	36.5	36.44	36.45	36.44	36.38	36.46	36.55
life years saved, thousands (%)		63 (0.2%)	46 (0.1%)	57 (0.2%)	119 (0.3%)	40 (0.1%)	-48 (-0.1%)
AIDS deaths, thousands	1,011	1,010	1,011	1,010	1,008	1,010	1,012
deaths averted, thousands (%)		1.4 (0.1%)	0.70 (0.1%)	0.8 (0.1%)	3.6 (0.4%)	0.9 (0.1%)	-1.0 (-0.1%)
Total cost of the HIV programme	28.79	28.81	28.77	28.93	28.93	28.8	28.76
incremental cost, millions		22	-13	144	144	12	-28
Incremental cost-effectiveness ratio							
cost/infection averted		1,541	Cost-saving	5,186	5,270	1,286	Dominated
cost/life years saved		351	Cost-saving	2,510	1,207	302	Dominated
cost/AIDS death averted		15,797	Cost-saving	173,299	40,300	14,230	Dominated
Scenario B: Distributing up to 6.7 million HIVST per year (to replace 40% of conventional HTS)							
New HIV infections, millions	2.57	2.51	2.52	2.53	2.46	2.52	2.58
HIV infections averted, thousands (%)		63 (2.5%)	49 (1.9%)	34 (1.3%)	112 (4.3%)	51 (2.0%)	-14 (-0.6%)
Life years lost due to AIDS, millions	36.5	36.29	36.4	36.43	36.11	36.34	36.55
life years saved, thousands (%)		205 (0.6%)	98 (0.3%)	66 (0.2%)	393 (1.1%)	156 (0.4%)	-48 (-0.1%)
AIDS deaths, thousands	1,011	1,007	1,010	1,010	1,000	1,008	1,012
deaths averted, thousands (%)		4.6 (0.5%)	1.5 (0.2%)	1.0 (0.1%)	11.1 (1.1%)	3.2 (0.3%)	-1.0 (-0.1%)
Total cost of the HIV programme, billions	28.79	29.31	28.96	29.01	30.4	29.26	29.02
incremental cost, millions		522	176	218	1,615	475	228
Incremental cost-effectiveness ratio							
cost/infection averted		8,283	3,568	6,488	14,488	9,237	Dominated
cost/life years saved		2,543	1,802	3,302	4,106	3,045	Dominated
cost/AIDS death averted		114,438	114,850	227,875	145,395	148,111	Dominated

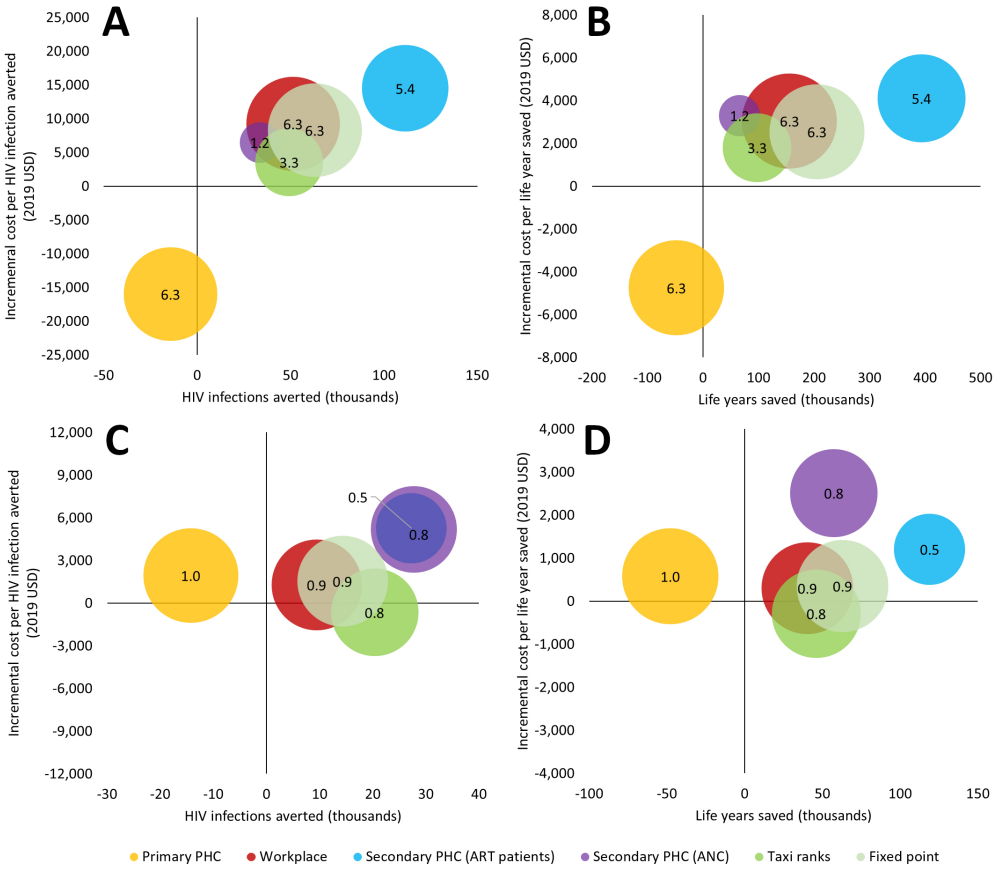

Figure 1

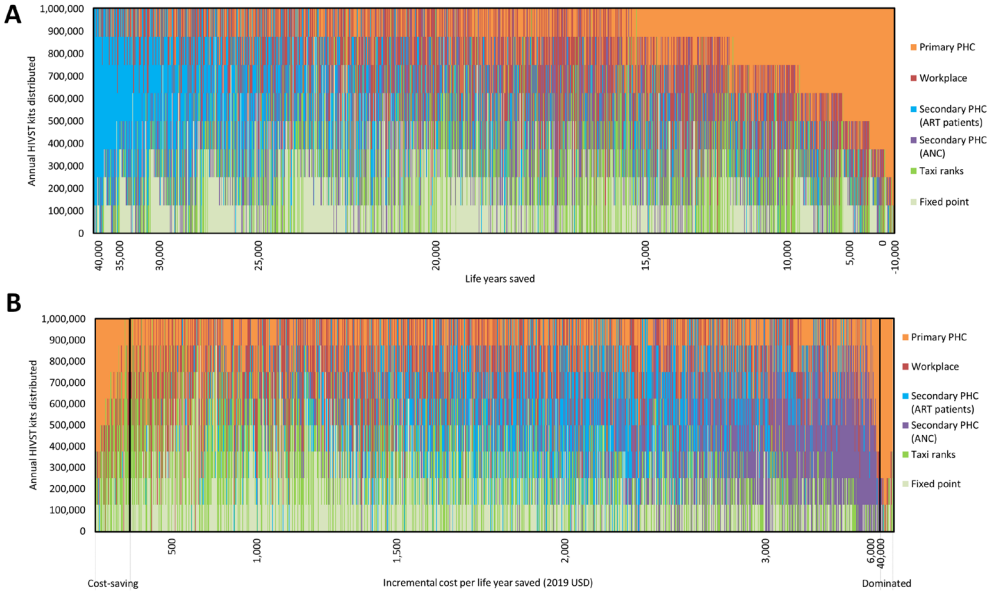

Figure 2

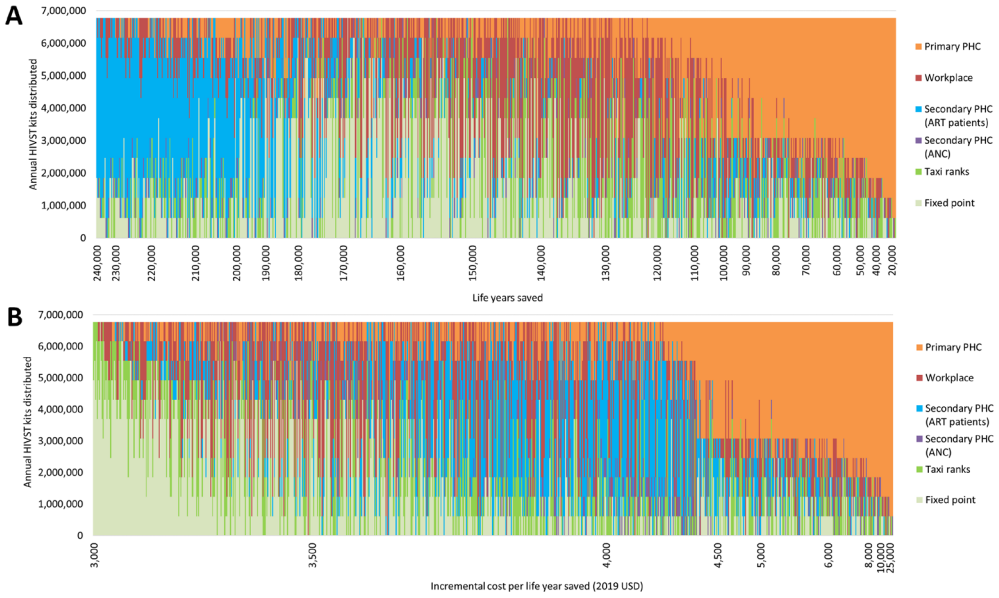

Figure 3

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Appendix to

The cost effectiveness and optimal configuration of HIV self-test distribution in South Africa: A model analysis

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Section 1: Modelling self-testing in Thembisa

Previous versions of Thembisa have not included self-testing. This supplementary material describes extensions made to the Thembisa model to include different forms of self-testing.

We define the following variables:

$\tau_{g,i,s}(x,t)$ is the rate of health worker-administered testing in sexually experienced individuals of age x and sex g, in HIV stage s and with HIV testing history i, in year t;
$\tau'_{g,i,s}(x,t)$ is the rate of health worker-administered testing in virgins of age x and sex g, in HIV stage s and with HIV testing history i;
$S_{g,i,s}(x,t)$ is the rate of self-testing in sexually experienced individuals of age x and sex g, in HIV stage s and with HIV testing history i;
$Z_{g,i,s}(x,t)$ is the rate of any HIV testing (health worker-administered or self-administered) in sexually experienced individuals of age x and sex g, in HIV stage s and with HIV testing history i, in year t.

In HIV-negative individuals ($s = 0$) and acutely-infected individuals ($s = 1$), the total rate of testing is simply

$$Z_{g,i,s}(x,t) = \tau_{g,i,s}(x,t) + S_{g,i,s}(x,t).$$

However, in HIV-seropositive individuals it is necessary to take into account that some of the HIV-positive self-testers seek confirmatory testing, i.e. there could be double-counting of the individuals diagnosed by self-testing and by health worker-administered testing. The total rate of testing is therefore calculated as

$$Z_{g,i,s}(x,t) = \tau_{g,i,s}(x,t) + S_{g,i,s}(x,t)(1 - \gamma \mathrm{I}(s > 1))$$

for $s > 0$, where γ is the fraction of individuals diagnosed through self-testing who seek confirmatory testing by health workers, and $\mathrm{I}(s > 1)$ is an indicator of whether the individual has detectable HIV antibodies (0 if HIV-seronegative, 1 if HIV-seropositive). We set γ to 68%, based in part on the STAR study, in which the proportion of individuals testing positive on self-testing who reported going for confirmatory testing varied between 48% and 74% across modalities. The assumption is also consistent with our previous assumption that the relative rate of linkage to ART services in people who self-test positive, when compared to that in people who test positive in a health facility, is 0.68 [1].

We consider five types of self-testing:

1. Self-testing through fixed point distribution (a form of community-based distribution)
2. Self-testing kits distributed at taxi ranks
3. Self-testing kits distributed to partners of pregnant women
4. Self-testing kits distributed to partners of ART patients
5. Self-testing kits distributed to employees in workplace settings

The symbol $c_j(t)$ represents the coverage/uptake of self-testing method j (indexed as 1 for fixed point distribution, 2 for taxi ranks, 3 for pregnant women's partners, 4 for partners of ART patients and 5 for employees).

Fixed point distribution

In the case of self-testing through fixed point distribution, our analyses of initial programme data suggest that the age and sex profile of individuals receiving self-testing roughly matches the age and sex profile of people who receive 'general' HIV testing in the Thembisa model (i.e. after excluding testing in antenatal clinics and people with HIV-related symptoms). We therefore set the self-testing rate to

$$\lambda^1_{g,i,s}(x,t) = c_1(t)\, A_g(x,t)\, r^*_i(t),$$

where $A_g(x,t)$ is the same age and sex adjustments that applies in the case of 'general' testing, and $r^*_i(t)$ is the relative rate of testing in individuals with HIV testing history i (1 for individuals who have never been tested or who have only tested negative, 0.5 for untreated HIV-diagnosed individuals and 0.15 for individuals on ART).[1] Figure S1 shows that with the standard age and sex adjustments for 'general' testing the model estimates of patterns of test uptake by age and sex are roughly consistent with the STAR data – although the STAR data suggest lower rates of HIV testing than predicted by the model in the 15-19 and 50+ age groups.

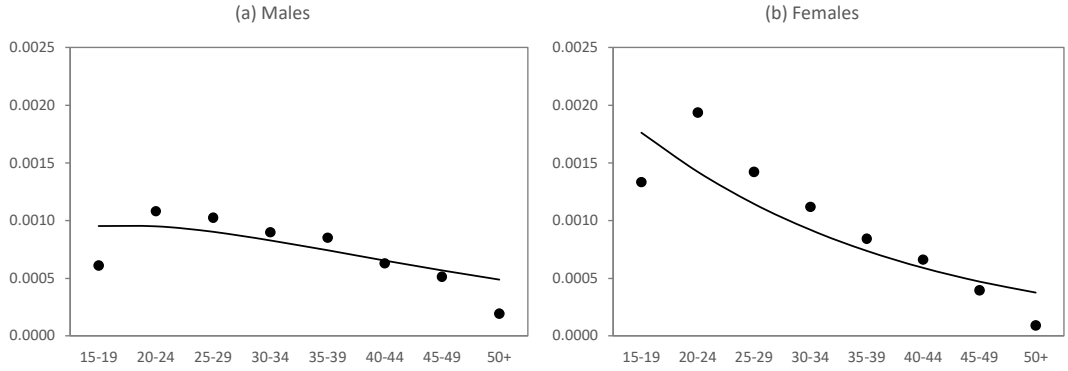

Figure S1: Rates of self-testing through fixed point distribution in Gauteng, 2017-2019
Programme data from the STAR project have been divided by the Thembisa estimates of the size of the sexually experienced population at each age in Gauteng, where most of the distribution through fixed points occurred (dots). Solid lines represent the estimates from the previous equation, scaled by an arbitrary factor to match the relative levels of testing by age and sex.

If we know the total number of self-testing kits distributed through fixed points in year t, $E_1(t)$, then we can approximate the self-testing uptake by the formula

$$c_1(t) = \frac{E_1(t)(1-W_1)}{\sum_g \sum_i \sum_s \sum_x N_{g,i,s}(x,t) A_g(x,t) r^*_i(t)},$$

where W_1 is the proportion of self-testing kits that are not used ('wastage'), and $N_{g,i,s}(x,t)$ is the size of the sexually experienced population aged x, of sex g, with HIV testing history i, at time t. In the routine data from the STAR programme, most of the self-testing kits distributed through fixed points were used 'on site' (at the point of distribution) and there was thus relatively little wastage; out of 9980 self-testing kits distributed to individuals who were interviewed, 8868 (89%) were used by the individual interviewed or (in a minority of cases) given to someone else. We therefore set W_1 to 11%.

Taxi rank distribution

We adopt a similar approach in modelling the effect of self-test kit distribution through taxi ranks. However, the STAR testing data suggest a different age and sex distribution of test recipients, with relatively high testing rates in males and in the 20-34 age group. We therefore represent the age and sex adjustment factor by the symbol $A_g'(x,t)$, which is parameterized as

$$A_g'(x,t) = B_g\, (x/25)^{\alpha - 1} \exp(-\sigma(x - 25))$$

where B_g is a scaling factor to represent the effect of sex ($B_1 = 7.5$ for men and $B_2 = 1$ for women), and α and σ are coefficients to represent the effect of age on the rate of testing. Setting α and σ to 14.1 and 0.469 respectively yields a reasonable model fit to the age-specific rates of self-testing through taxi ranks, as shown in Figure S2.

[1] This is consistent with the assumptions made about self-testing in the MicroCOSM model.

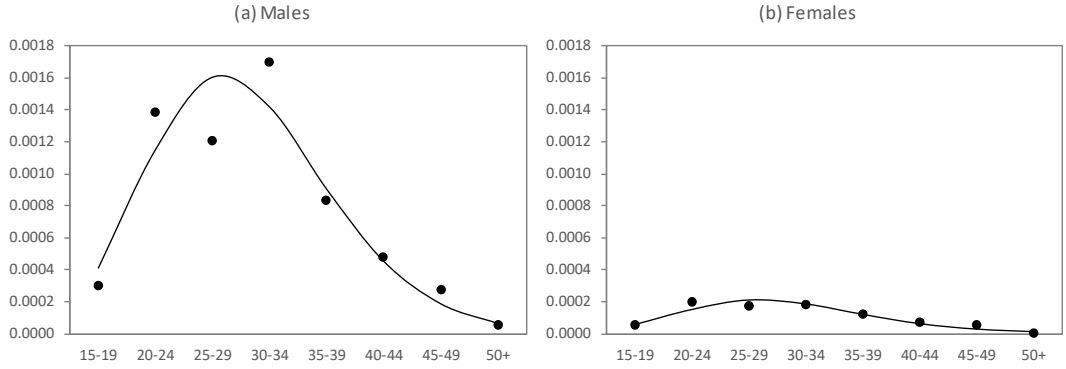

Figure S2: Monthly rates of self-testing through taxi rank distribution in Gauteng, 2018
Programme data from the STAR project have been divided by the Thembisa estimates of the size of the sexually experienced population at each age in Gauteng, where most of the distribution through taxi ranks occurred (dots). Solid lines represent the estimates from the previous equation, scaled by an arbitrary factor to match the relative levels of testing by age and sex.

We set $\lambda^2_{g,i,s}(x,t) = c_2(t)\ A_g'(x,t)\ r^*_i(t)$, where $c_2(t)$ represents the rate of self-testing through taxi ranks in females aged 25. This parameter is calculated in the same way as $c_1(t)$, using recorded numbers of tests distributed through taxi ranks ($E_2(t)$) and observed levels of wastage (W_2). Out of 5922 self-testing kits distributed to individuals who were interviewed after receiving self-testing kits through taxi ranks in the STAR project, 5028 (85%) were used by the individual interviewed or (in a small fraction of cases) given to someone else. We therefore set W_2 to 15%.

Secondary distribution to partners of pregnant women

We model the rate of self-testing in sexually experienced men, using tests distributed to them by pregnant female partners, as

$$\lambda^3_{g,i,s}(x,t) = c_3(t)\ F(x-3,\ t)\ r^*_i(t)\ (1 - W_3),$$

where $F(x,\ t)$ is the fertility rate in HIV-negative women aged x in year t. The $c_3(t)$ parameter is defined here as the proportion of HIV-positive pregnant women who are given self-testing kits to give to their partners. For the sake of simplicity, we do not incorporate effects of female HIV status and ART use on fertility, which would depend on the male's HIV status. We also assume, for the sake of simplifying the self-testing calculations, that men are on average three years older than their female partners, and that each sexually experienced male has one heterosexual partner (this assumption is made only for the purpose of approximating the effect of secondary distribution through antenatal clinics and does not apply to the rest of the Thembisa model). With these assumptions the modelled relative rates of HIV testing in men, by age, approximate those observed in the STAR data (Figure S3).

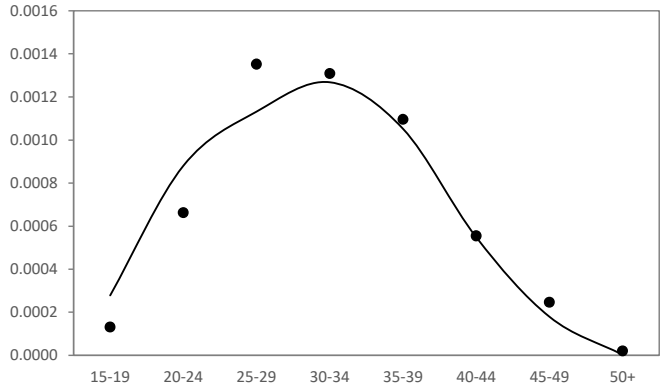

Figure S3: Male rates of self-testing through pregnant partners in Gauteng, 2017-2019
Programme data from the STAR project (numbers of men who were known to have used self-testing kits given to them by their pregnant partners) have been divided by the Thembisa estimates of the size of the sexually experienced male population at each age in Gauteng, where most of the distribution through pregnant women occurred (dots). Solid lines represent the estimates from the previous equation, scaled by an arbitrary factor to match the relative levels of testing by age.

In the STAR data, 9777 pregnant women who were given self-testing kits to give to their partners were interviewed; all reported that they gave the test(s) to at least one partner, but only 3783 (39%) reported knowing that the partner had actually used the test.

This is probably an under-estimate of actual test use, since some men may have used the test without informing their female partners, so we optimistically set W_3, the fraction of tests that are not used by HIV-negative male partners, to 0.12, consistent with the parameters estimated for the previous testing modalities. (It is worth noting that if the male partner is HIV-positive, the probability of the test not being used is $1 - r^*_i(t) \times (1 - 0.12)$.) If we know the total number of self-testing kits distributed through pregnant women in year t, $E_3(t)$, then we can estimate $c_3(t)$ by dividing $E_3(t)$ by the total number of pregnancies in year t.

Secondary distribution to partners of ART patients

We model the rate of self-testing in sexually experienced individuals, following secondary distribution of self-testing kits by sexual partners on ART, as

$$\lambda^4_{g,i,s}(x,t) = c_4(t)\, H_s(g \mid p_0, p_1)\, K_g(x, t)\, r^*_i(t)\, (1 - W_4),$$

where $H_s(g \mid p_0, p_1)$ is the probability that an individual of HIV status s and sex g has an HIV-positive partner (given HIV prevalence levels of p_0 in male partners and p_1 in female partners), and $K_g(x, t)$ is the ART coverage in year t in HIV-positive sexual partners of individuals aged x and of sex g. $H_s(g \mid p_0, p_1)$ is calculated using a formula given in the appendix, based on South African data on levels of seroconcordance in heterosexual relationships. The coverage parameter, $c_4(t)$, is defined as the proportion of ART patients who are given self-testing kits to give to their sexual partners, and W_4 is the proportion of self-test kits distributed that do not get used by sexual partners. Out of 4153 HIV-diagnosed individuals who were given self-testing kits to give to their sexual partners through the STAR project, all reported giving the test to sexual partners, but only 1871 (45%) reported knowing that the test was used. Again, this is likely to be an under-estimate of the fraction of tests actually used. We have therefore set W_4 to 0.12, the same value as assumed for secondary distribution of self-testing kits to partners of pregnant women. If we know the total number of self-testing kits distributed through index partners in year t, $E_4(t)$, then we can approximate the self-testing uptake by the formula

$$c_4(t) = \frac{E_4(t)}{\sum_i \sum_s \sum_x N_{g,i,s}(x,t) H_s(g \mid p_0, p_1) K_g(x,t)}$$

Note that in this equation (as in the equation for $c_3(t)$) we do not have a wastage term or a testing history adjustment, because the uptake parameter is inclusive of tests that are not used. In contrast, the uptake parameters for the fixed point and taxi rank distribution strategies were exclusive of wastage, and the associated formulas for $c_1(t)$ and $c_2(t)$ therefore excluded wastage.

Distribution through workplaces

Our approach to modelling distribution through workplaces is similar to that for taxi ranks, with a different age distribution from that for general HIV testing. As with fixed point and taxi rank self-test distribution, the STAR data suggest that almost all tests distributed are used by the individuals who receive the tests, and a relatively small fraction are given to others. We therefore ignore secondary distribution, in the interests of simplicity. We model the rate of self-testing in sexually-experienced individuals, through workplace distribution programmes, as

$$\lambda^5_{g,i,s}(x,t) = c_5(t)\, \mathrm{Q}(x, g)\, A^*_g(x,t)\, r^*_i(t),$$

where $\mathrm{Q}(x, g)$ is the rate of employment in individuals aged x, of sex g, and $A^*_g(x,t)$ determines the relative rates of testing uptake by age and sex among employed individuals. The $\mathrm{Q}(x, g)$ parameters are estimated from the 2015 Quarter 3 Labour Force Survey [2], and are shown in Table S1. (We assume rates of employment are zero below age 15 and at ages 65 and older.)

Table S1: Proportion of individuals employed, by age and sex

	15-19	20-24	25-29	30-34	35-39	40-44	45-49	50-54	55-59	60-64
Male	2.6%	26.7%	48.3%	54.3%	57.7%	60.3%	59.3%	51.1%	44.9%	24.1%
Female	1.5%	17.4%	35.6%	44.1%	49.0%	48.7%	47.0%	41.4%	35.4%	16.3%

Source: South African Labour Force Survey 2015, Quarter 3 (authors' own calculations).

Similar to the modelling of the age and sex pattern of testing uptake through taxi ranks, we use the following function to represent the age and sex pattern of self-testing in employed populations:

$$A^*_g(x,t) = B^*_g(x/25)^{\alpha^*_g - 1} \exp(-\sigma^*_g(x - 25))$$

where B^*_g is a scaling factor to represent the effect of sex ($B^*_1 = 0.95$ for men and $B_2 = 1$ for women), and α^*_g and σ^*_g are coefficients to represent the effect of age on the rate of testing. Setting α^*_1 and σ^*_1 to 4.59 and 0.153 respectively in men, and setting α^*_2 and σ^*_2 to 2.94 and 0.122 respectively in women, yields a reasonable model fit to the age-specific rates of self-testing through workplaces, as shown in Figure S4. The peak testing rates in males are higher than those in females, despite the B^*_g adjustment being slightly lower for men than for women, which is because of the higher rates of employment in men.

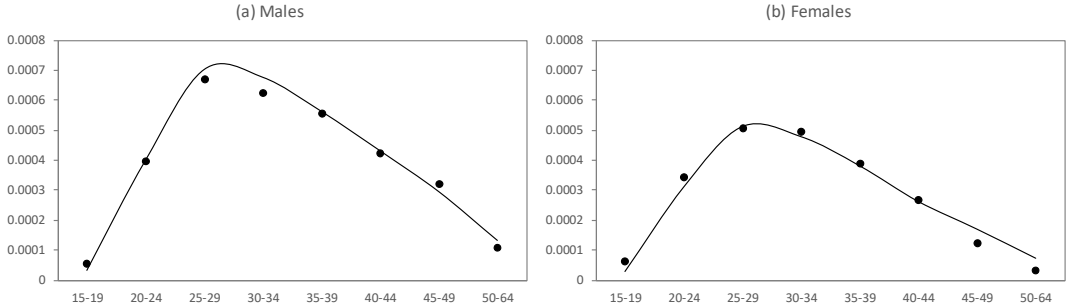

Figure S4: Rates of self-testing through workplaces
Programme data from the STAR project (2017-2020) have been divided by the Thembisa estimates of the size of the sexually experienced population at each age in South Africa (dots). Solid lines represent the estimates from the $\lambda^5_{g,i,s}(x,t)$ equation, scaled by an arbitrary factor to match the relative levels of testing by age and sex.

The coverage parameter $c_5(t)$ is defined as the rate of self-testing through workplace programmes, in employed women aged 25 in year t. We estimate this parameter from the total number of self-tests distributed through campaigns in workplaces in year t, $E_5(t)$, and the assumed fraction of test kits that are not used, W_5:

$$c_5(t) = \frac{E_5(t)(1-W_5)}{\sum_g \sum_i \sum_s \sum_x N_{g,i,s}(x,t) \mathrm{Q}(x,g) A^*_g(x,t) r^*_i(t)}.$$

In the STAR programme, out of 13 308 tests distributed to interviewed individuals, 12 321 (93%) were reported to have been used or given to someone else. We therefore set $W_5 = 0.07$.

Total testing rates and index testing

Table S2 summarizes the data from the STAR programme for the 2017-2020 period, on total numbers of self-testing kits distributed. We assume that this represents the total number of self-test kits distributed, although the STAR programme has also distributed kits through other distribution channels (data forthcoming), and some self-testing kits may be distributed through other providers, or sold through pharmacies.

Table S2: Total self-testing kits distributed in South Africa

Year	Fixed point distribution	Taxi rank distribution	ANC client distribution	Index testing	Workplace testing
2017-18	57701	155643	1107	859	84713
2018-19	117215	225107	9847	3798	165624
2019-2020*	68720	74531	10183	4923	128951

ANC = antenatal clinic. * Results for 2020 are only available up to the end of March so are an under-estimate of the true total.

The total rate of self-testing is calculated as

$$S_{g,i,s}(x,t) = \sum_j \lambda^j_{g,i,s}(x,t).$$

The annual rate at which sexually experienced individuals get tested by health workers is calculated as

$$\tau_{g,i,s}(x,t) = b(t)A_g(x,t)r_i(t) + \Omega_s d_i(t) + F_{g,s}(x,t)v_i(t) + S_{g,i,s}(x,t)\gamma \mathrm{I}(s>1)$$

where $b(t)$ is the base rate of 'general' HIV testing in year t, in individuals who do not have any HIV symptoms and are not pregnant; $A_g(x,t)$ is the adjustment factor to represent the effect of age and sex on the base rate of test uptake; $r_i(t)$ is the adjustment factor to represent the effect of testing history; Ω_s is the annual incidence of OIs in CD4 stage s; $d_i(t)$ is the fraction of OI patients who are tested for HIV in year t; $F_{g,s}(x,t)$ is the fertility rate in sexually experienced women aged x, in HIV stage s, during year t (set to zero for men); and $v_i(t)$ is the proportion of pregnant women who receive HIV testing in year t. The first three terms on the right-hand side of this equation correspond to the three HIV testing modalities previously modelled in Thembisa, and the associated symbols are the same as defined previously [3].

The rate of HIV testing in asymptomatic virgins is assumed to be a multiple φ of the rate of HIV testing in asymptomatic girls aged 15 who are sexually experienced and non-pregnant, i.e.

$$\tau'_{g,i,s}(x,t) = b(t)A_2(15,t)r_i(t)\varphi + \Omega_s d_i(t).$$

For virgins we are therefore excluding antenatal testing (since they would not be pregnant) and self-testing.

Suppose that $G(t)$ is the total number of HIV tests performed by health workers in adults aged 15 and older, in year t. If $V_{g,i,s}(x,t)$ is the number of virgins, at the start of year t, then

$$G(t) \approx \sum_g \sum_i \sum_s \sum_x N_{g,i,s}(x,t)\tau_{g,i,s}(x,t) + V_{g,i,s}(x,t)\tau'_{g,i,s}(x,t).$$

(The relation is not exact because the numbers of individuals in the different strata change over the course of the year, so relying only on the values at the start of the year may lead to some bias.) We use the above calculation to estimate the base rate of testing in year t:

$$\hat{b}(t) = \frac{G(t) - \sum_g \sum_i \sum_s \sum_x N_{g,i,s}(x,t)\{\Omega_s d_i(t) + F_{g,s}(x,t)v_i(t) + S_{g,i,s}(x,t)\gamma I(s>1)\} + V_{g,i,s}(x,t)\Omega_s d_i(t)}{\sum_g \sum_i \sum_s \sum_x N_{g,i,s}(x,t)A_g(x,t)r_i + V_{g,i,s}(x,t)A_2(15,t)r_i\varphi}$$

Sensitivity and specificity of self-testing

Based on a previous review, we assume that self-testing is 100% specific [4] [Figueroa]. We further assume that self-testing sensitivity depends on the recency of HIV infection: self-testing is assumed to have 0% sensitivity during the acute phase of HIV infection (approximately the first 3 months after HIV acquisition) and 100% sensitivity thereafter. With these assumptions the average sensitivity across all HIV testers is around 96% [5], roughly consistent with sensitivities reported in various studies [Figueroa]. These sensitivity and specificity assumptions are the same as for conventional HIV testing in Thembisa.

Linkage to ART after diagnosis

In the previous version of Thembisa we assumed that the probability of ART initiation soon after diagnosis depended on the setting in which diagnosis occurred, with the probability being highest in antenatal care settings (95% in the period after 2015), lower in people diagnosed when seeking treatment for HIV-related OIs (78%), and lowest for individuals diagnosed in other settings (40%).

In the new version of the model, we apply the same 40% probability of linkage to individuals who seek confirmatory testing after a positive self-testing result. This means that the actual proportion of all individuals diagnosed through self-testing who link to ART is 27% (40% × 68%, where 68% is the assumed proportion of positive self-testers who seek confirmatory testing). This is consistent with the assumption made in MicroCOSM (also 27%), which was based on rates of linkage observed in other models of community-based testing, prior to the availability of local data on linkage to care after self-testing [1]. However, rates of linkage to ART after diagnosis through self-testing are difficult to estimate reliably, and these estimates should be treated with caution [6].

Model results and calibration

Table S3 compares the model estimates of the yield on self-testing with the yields estimated from the STAR data. The model estimates of yield are based only on the tests that were used (i.e. the denominator does not include unused test kits). In the case of the secondary distribution testing modalities (index testing and testing of male partners of pregnant women), there is uncertainty regarding the true yield, because individuals only reported on whether they knew that their partner used the test and whether they knew their partner tested positive. In these cases, a conservative lower bound on the yield would be the total number of known positive results divided by the total numbers of tests distributed to sexual partners. An upper bound on the yield would be the total number of known positive tests divided by the numbers of tests that were known to have been used (although one might argue that this is not an upper bound if partners who test positive are less likely to tell their partners that they used the test, or if they are likely to misreport that they are negative). For both secondary testing modalities, the model estimate of the testing yield falls between the lower and upper bounds estimated from the STAR data, which is reassuring.

Table S3: HIV testing yields, averaged over the 2017-2020 period

	Fixed point distribution	Taxi rank distribution	ANC client distribution	Index testing	Workplace testing
Model estimate	5.73% (5.36-6.09%)	5.18% (4.86-5.45%)	3.91% (3.66-4.15%)	19.9% (19.3-20.4%)	6.44% (6.05-6.74%)
STAR data	3.05%	8.98%	-	-	4.23%
Lower bound	-	-	2.22%	11.0%	-
Upper bound	-	-	5.74%	24.4%	-

ANC = antenatal clinic.

In the case of the fixed point distribution, taxi rank distribution and workplace distribution modalities, however, the yields estimated by the model are very inconsistent with the STAR data. While the model estimates that the three modalities should have relatively similar testing yields (5.2-6.4%), the STAR data suggest that the testing yields on these three modalities are very different. Previous studies have identified taxi ranks as 'hotspots' or locations with high HIV prevalence [7, 8], but our model assumes HIV prevalence in taxi ranks is no different from that in the general population (after controlling for age and sex), which may be unrealistic.

Table S4 summarizes the estimates of the testing coverage in each year, for each modality, based on the numbers in Table S1. For all modalities, there was a substantial increase in coverage/uptake between 2017-18 and 2018-19. However, coverage either increased minimally or dropped substantially in the following year, which may be a reflection of the 2019-20 data being incomplete at the time of this analysis.

Table S4: Coverage/uptake of self-testing in South Africa

Year	Fixed point distribution $c_1(t)$	Taxi rank distribution $c_2(t)$	ANC client distribution $c_3(t)$	Index testing $c_4(t)$	Workplace testing $c_5(t)$
2017-18	0.00259	0.00185	0.00099	0.00022	0.01166
2018-19	0.00523	0.00265	0.00803	0.00088	0.02258
2019-20	0.00305	0.00087	0.00833	0.00106	0.01741
Average*	0.00362	0.00179	0.00578	0.00072	0.01722

ANC = antenatal clinic. * The average coverage is assumed to apply in the post-2020 period.

Limitations

The results shown in Tables S3 and S4 are the results obtained using the national version of the Thembisa model. However, almost all of the STAR data come from Gauteng province, and one could argue that it would be more meaningful to run the Gauteng version of the Thembisa model.

Another limitation is that there is substantial uncertainty regarding the relative rates of testing in previously diagnosed individuals, and these assumptions affect the estimated yield on self-testing (Table S3). We assume that individuals who retest positive are no more likely to initiate ART than individuals who were previously diagnosed and did not get tested, i.e. there are no modelled benefits to retesting individuals who have already been diagnosed. This assumption is unrealistic, as evidence suggests that previously-diagnosed individuals who retest positive are as likely to link to HIV care as individuals who are diagnosed positive for the first time [9, 10]. However, the assumption is consistent with the assumption made for health worker-administered testing. In future versions of Thembisa we plan to revise these assumptions about linkage to ART after re-diagnosis, to better reflect the benefits of repeat testing.

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Appendix A: Predicting HIV seroconcordance in South African couples

For the purpose of modelling index testing, it is necessary to be able to estimate the probability that an individual who tests positive has a positive partner. Suppose that we consider a population of n heterosexual couples. We further define a to be the number who are concordant positive, b the number who are serodiscordant with the female partner positive and the male negative, c the number who are serodiscordant with the male partner positive and d the number who are concordant negative (Figure A1).

		Male HIV status: Positive	Male HIV status: Negative
Female HIV status	Positive	a	b
	Negative	c	d

Figure A1: Numbers of couples by HIV status

We define θ to be the odds ratio relating the odds of HIV infection in the individual to the odds of HIV infection in their partner, i.e. $\theta = ad / bc$. We also define π_0 to be the HIV prevalence in male partners $((a + c) / n)$ and π_1 to be the HIV prevalence in female partners $((a + b) / n)$. These quantities can be estimated from various South African studies, as summarized in Table A1. Estimates of θ appear highly heterogeneous across studies, varying between 2.5 and 32, with the odds ratios generally being highest in the studies in which HIV prevalence is lowest. This is because as HIV prevalence increases in the general population, individuals are relatively more at risk of having acquired HIV from partners other than their current partner, and the strength of association between the individual's HIV status and their partner's status thus becomes weaker.

Table A1: South African studies of seroconcordance in heterosexual couples

Study	a	b	c	d	π_0	π_1	θ (95% CI)
Mbulawa *et al* [11]	112	158	44	155	33.3%	57.6%	2.50 (1.62-3.87)
de Bruyn *et al* [12]	302	126	326	671	44.1%	30.0%	4.93 (3.83-6.37)
Kilembe *et al* [13]	245	175	93	394	37.3%	46.3%	5.93 (4.36-8.08)
Lurie *et al* [14]	16	10	25	117	24.4%	15.5%	7.49 (2.78-20.53)
Doherty *et al* [15]	26	50	12	200	13.2%	26.4%	8.67 (3.87-20.06)
2016 DHS [16]	61	44	21	293	19.6%	25.1%	19.34 (10.35-36.55)
Simbayi *et al* [17]	124	134	57	1378	10.7%	15.2%	22.37 (15.37-32.64)
Naik *et al* [18]	11	7	10	201	9.2%	7.9%	31.59 (8.72-115.52)

For the sake of developing a predictive model, we performed a meta-regression on the data in Table A1, using the natural log of the female HIV prevalence as the explanatory variable. (The meta-regression was also done using the log of the male HIV prevalence as the explanatory variable, but this was found to not fit the data as well, so the results of this analysis are not presented here.) The best-fitting model was of the form $\theta(\pi_1) = \exp(0.536) \times \pi_1^{-1.218}$. Figure A2 shows the meta-regression model fit to the data in Table A1.

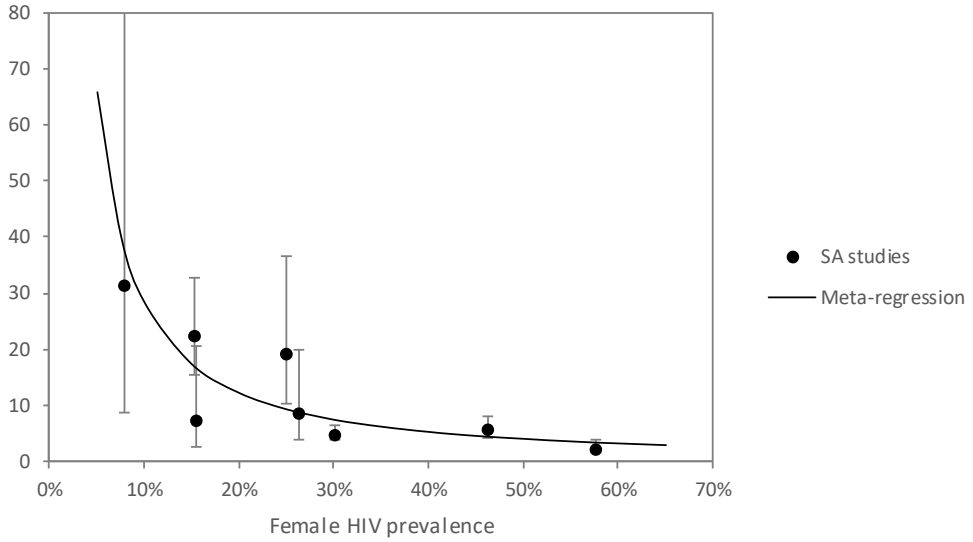

Figure A2: Odds of infection if partner is HIV-positive, relative to odds of infection if partner is HIV-negative

For the purpose of developing a predictive model, we need to be able to estimate a, b, c and d from the parameters $\theta(\pi_1)$, π_0 and π_1. For the sake of simplicity, we will re-express a, b, c and d as proportions that sum to 1, so that $n = 1$, $d = 1 - a - b - c$, $\pi_0 = a + c$, and $\pi_1 = a + b$. Substituting these equations into the odds ratio formula gives

$$\theta(\pi_1) = \frac{a(1-a-(\pi_0-a)-(\pi_1-a))}{(\pi_0-a)(\pi_1-a)}.$$

This can be expressed as a quadratic in a; solving for a gives

$$a = \frac{1+(\theta-1)(\pi_0+\pi_1)-\sqrt{(1+(\theta-1)(\pi_0+\pi_1))^2-4(\theta-1)\theta\pi_0\pi_1}}{2(\theta-1)}.$$

The probability that the female partner is positive, given that the male partner is positive, is then $a / (a + c) = a / \pi_0$. Similarly, the probability that the male partner is positive, given that the female partner is positive, is a / π_1. We thus have formulas for predicting partner concordance as a function of the HIV prevalence in males and females, in a population of heterosexual couples.

Section 2: Supplementary results

Table S1. Description of HIVST modalities and feasible maximum number of target populations

Fixed point	
Description	HIV self-test (HIVST) kits distributed at pre-selected locations within local communities. Testing tents are set up near areas of congregation (eg. hostels, taverns and brothels); demonstration of HIVST kit use provided, HIVST kits are distributed to consenting clients. Clients can choose option of self-testing in the tent or can take kit home for private use. For clients screening positive on site, confirmatory testing conducted by a professional provider was offered on site.
Target population description	HIV- adults and undiagnosed HIV+ adults (assuming fixed point distribution will be concentrated in 5 largest metropolitan municipalities)
Feasible maximum number of people	~14 million[1]
Taxi ranks	
Description	Distribution of HIVST kits to commuters, taxi drivers and street vendors in densely populated taxi ranks and train stations, with high foot traffic. Distribution agents provided a demonstration of HIVST kit use and offered kits to interested clients for private use off site.
Target population description	Adults accessing taxis who are HIV negative or undiagnosed PLHIV
Feasible maximum number of people	~3.9 million[2]
Secondary PHC (ANC)	
Description	Women attending their first antenatal care (ANC) visit at a primary healthcare (PHC) clinic were offered HIVST kits, to take home to their current male sexual partner(s) – defined as secondary distribution.
Target population description	Women attending ANC care
Feasible maximum number of people	~1.2 million[3]
Secondary PHC (ART patients)	
Description	HIVST kits offered by to ART patients and newly diagnosed HIV positive adults at a PHC clinic to share with their sexual partner(s) or family members who were unaware of their HIV status.
Target population description	Adults on antiretroviral treatment (ART) + newly diagnosed HIV-positive adults
Feasible maximum number of people	~5.4 million[4]
Workplace	
Description	Workplace distribution was predominantly conducted in a number of male-dominated sectors such as manufacturing, mining, construction, security, petroleum and agriculture. Two types of workplaces included: a) Larger companies without formalised HIV testing programmes or those with low HIV testing uptake were contacted before the distribution event for sensitisation; b) Distribution also took place more ad-hoc and without prior arrangement with management to employees of smaller workplaces such as petrol stations or construction sites.
Target population description	Employed population
Feasible maximum number of people	~10 million[5]
Primary PHC	
Description	This modality involved primary distribution of HIVST for on-site screening of clients attending the clinic for different services including family planning and treatment for sexually transmitted infections.
Target population description	Existing patient population seeking conventional HTS at PHC
Feasible maximum number of people	~15 million[6]

Footnotes:

1. Statistics South Africa Mid-year Population Estimates 2020 in the five largest metro municipalities (City of Cape Town, Ekurhuleni, Johannesburg, Tshwane, eThekwini), combined with provincial-level Thembisa 4.3 estimates of % diagnosed and district-level HIV prevalence statistics from the Naomi model (https://www.hivdata.org.za/)
2. Estimated from worker and higher education population using minibus taxis (Statistics South Africa National Household Travel Survey 2013), combined with HIV prevalence and known diagnosis estimates from Thembisa 4.3
3. Estimates of women attending antenatal care in 2020 from Thembisa 4.3
4. Estimates of adult population on antiretroviral treatment and newly diagnosed HIV+ adults in 2020 from Thembisa 4.3
5. Estimates of employed population from Statistics South Africa. Statistical Release P0277. Quarterly Employment Statistics. December 2019.

Table S2: Unit costs used in the costing of the HIV programme

Intervention	Cost unit	Unit cost (2019 USD)
ART provision per adult (first line regimen, first year)	per person	299.15
ART provision per adult (first line regimen, follow-up years)	per person	196.48
ART provision per adult (second line regimen, follow-up years)	per person	323.64
ART provision per child (first year)	per person	322.39
ART provision per child (follow-up year)	per person	229.20
Early infant male circumcision	per person	43.24
Medical male circumcision (MMC)	per person	86.47
Condom provision (per condom distributed)	per condom	0.05
Prevention of mother-to-child transmission	per person	21.03
Conventional HTS: general (negative)	per test	3.75
Conventional HTS: general (positive)	per test	5.52
Conventional HTS: antenatal care (negative)	per test	3.26
Conventional HTS: antenatal care (positive)	per test	5.01
Conventional HTS: provider-initiated testing and counselling (negative)	per test	3.75
Conventional HTS: provider-initiated testing and counselling (positive)	per test	5.52
Conventional HTS: Mobile testing (negative)	per test	5.76
Conventional HTS: Mobile testing (positive)	per test	6.66
Conventional HTS: Home based testing (negative)	per test	5.76
Conventional HTS: Home based testing (positive)	per test	6.28
Conventional HTS: Partner notification (negative)	per test	3.41
Conventional HTS: Partner notification (positive)	per test	5.32
HIVST: fixed point	per test	5.70
HIVST: taxi ranks	per test	4.74
HIVST: partners of pregnant women	per test	13.04
HIVST: partners of ART patients	per test	12.31
HIVST: primary PHC	per test	8.24

Figure S1. A) number of HIV infections averted over the status quo, and B) incremental cost (2019 USD) per HIV infection averted; distributing up to 1 million HIVST distributed per year. Status quo distribution of 1 million HIVST kits: fixed point (5% of HIVST), taxi ranks (5%), secondary PHC (ANC) (7%), secondary PHC (ART patients) (3%), workplace (20%) and primary PHC distribution (60%).

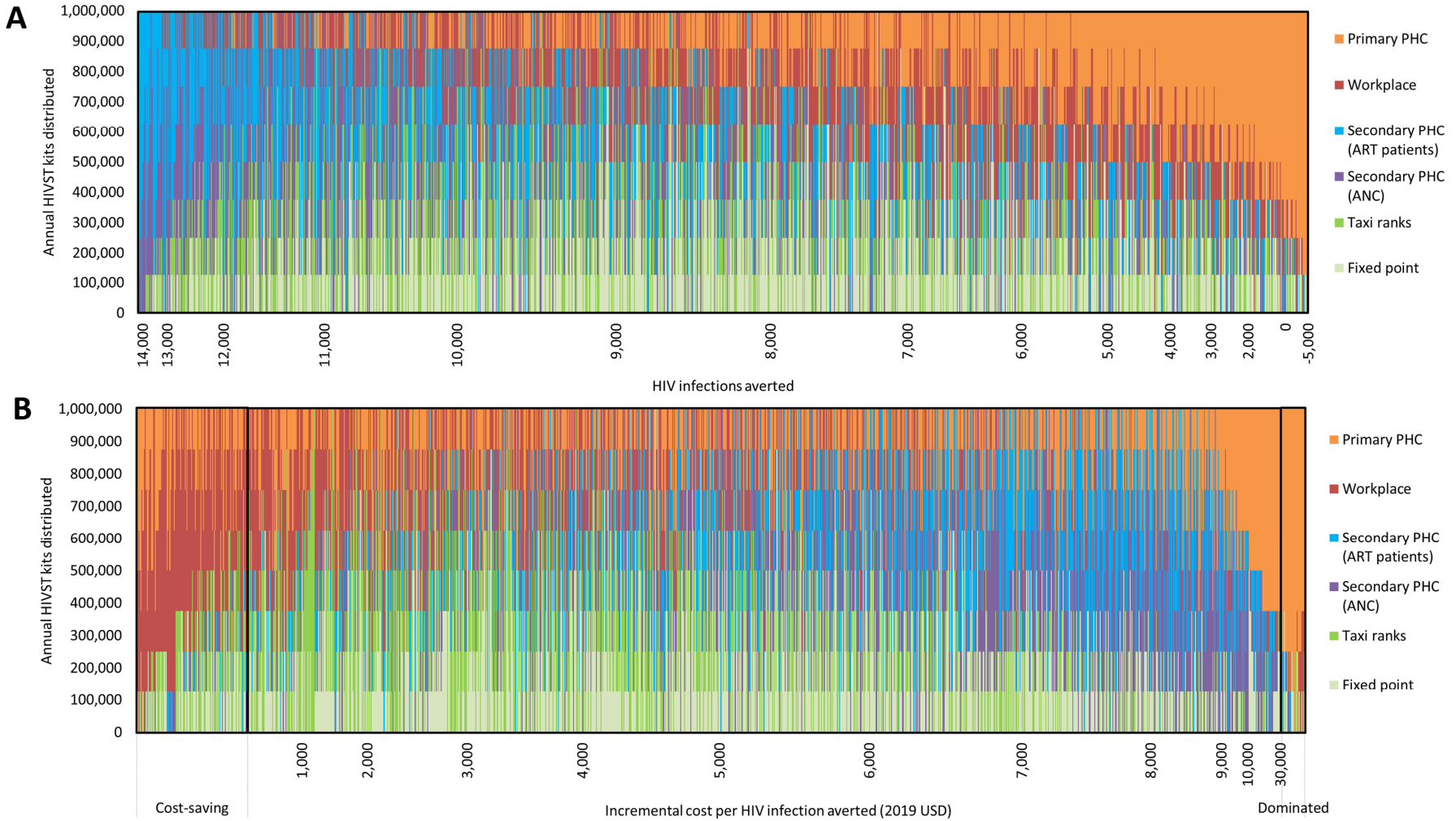

Figure S2. A) number of new HIV infections averted over the status quo, and B) incremental cost (2019 USD) per HIV averted; distributing up to ~6.7 million HIVST per year by 2030. Status quo distribution of 1 million HIVST kits: fixed point (5% of HIVST), taxi ranks (5%), secondary PHC (ANC) (7%), secondary PHC (ART patients) (3%), workplace (20%) and primary PHC distribution (60%)

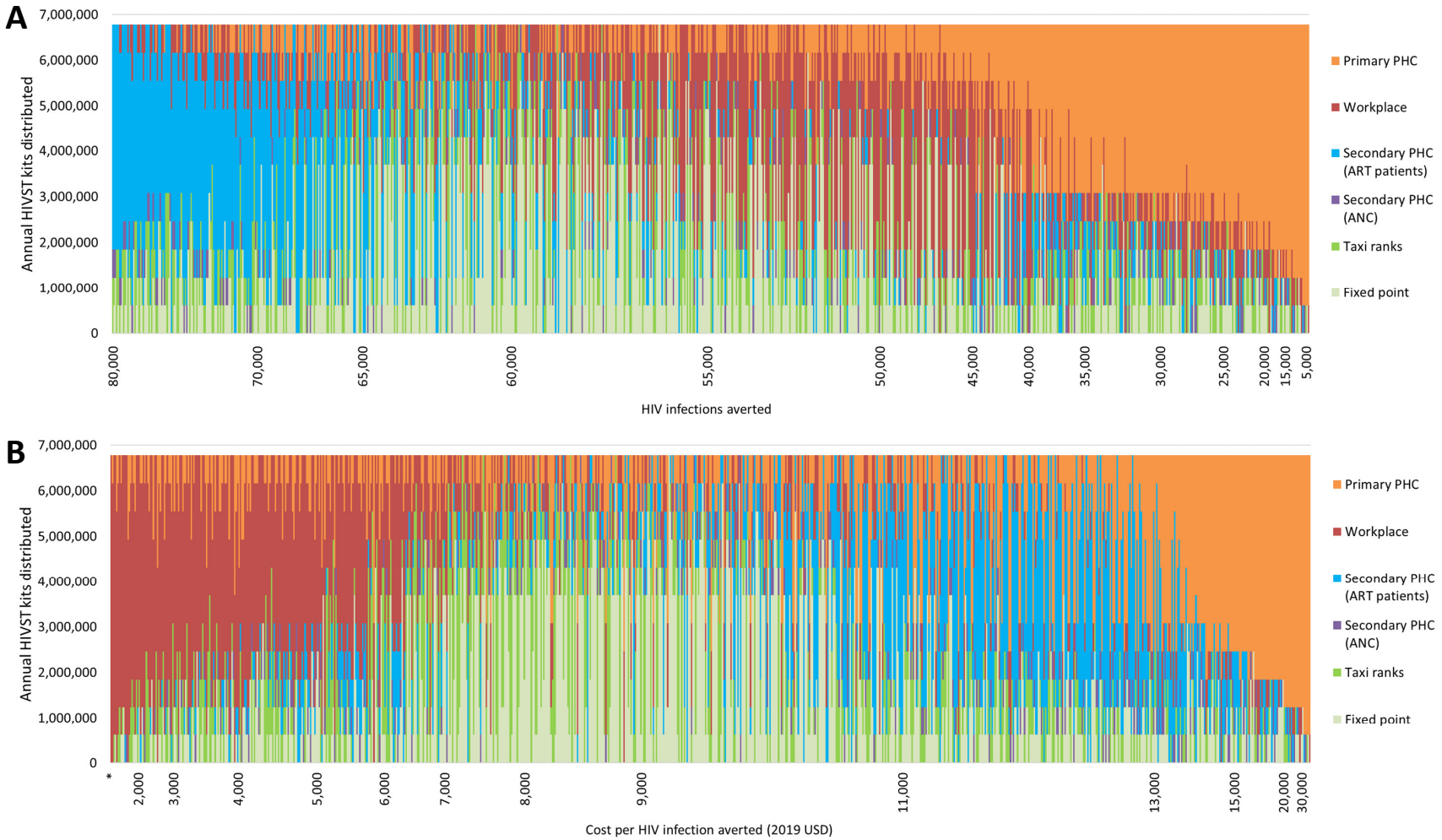

Figure S3. A) number of life years saved over baseline of no HIVST, and B) incremental cost (2019 USD) per life year saved; distributing up to 1 million HIV-ST distributed per year.

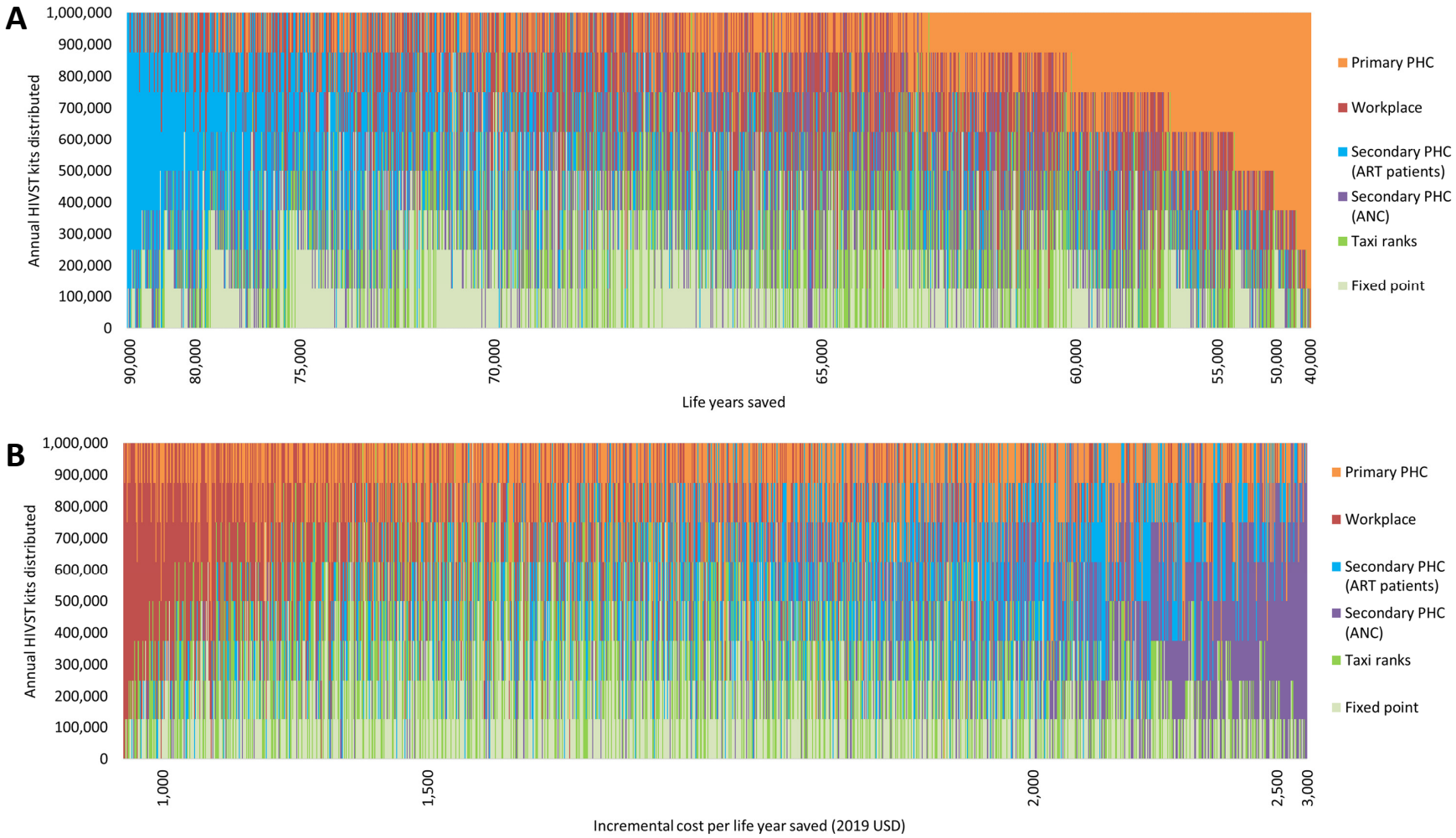

Figure S4. A) number of life years saved over baseline of no HIVST, and B) incremental cost (2019 USD) per life year saved; distributing up to ~6.7 million HIV-ST distributed per year.