OPEN

Forecasting the effect of HIV-targeted interventions on the age distribution of people with HIV in Kenya

Melissa C. Schnure[a], Parastu Kasaie[b], David W. Dowdy[b], Becky L. Genberg[b], Emily A. Kendall[a] and Anthony T. Fojo[a]

See related paper on page 1435

Objectives: To provide accurate forecasts of the age distribution of people with HIV (PWH) in Kenya from 2025 to 2040.

Design: Development of a compartmental model of HIV in Kenya, calibrated to historical estimates of HIV epidemiology.

Methods: We forecasted changes in population size and age distribution of new HIV infections and PWH under the status quo and under scale-up of HIV services.

Results: Without scale-up, new HIV infections were forecasted to fall from 34 000 (28 000–41 000) in 2,025 to 29 000 (15 000–57 000) in 2,040; the percentage of new infections occurring among persons over 30 increased from 33% (20–50%) to 40% (24–62%). The median age of PWH increased from 39 years (38–40) in 2025 to 43 years (39–46) in 2040, and the percentage of PWH over age 50 increased from 26% (23–29%) to 34% (26–43%). Under the full intervention scenario, new infections were forecasted to fall to 6,000 (3,000–12 000) in 2,040. The percentage of new infections occurring in people over age 30 increased to 52% (34–71%) in 2,040, and there was an additional shift in the age structure of PWH [forecasted median age of 46 (43–48) and 40% (33–47%) over age 50].

Conclusion: PWH in Kenya are forecasted to age over the next 15 years; improvements to the HIV care continuum are expected to contribute to the growing proportion of older PWH.

AIDS 2024, **38**:1375–1385

Keywords: Africa, aging, mathematical models

Introduction

As a result of advances in the effectiveness and coverage of antiretroviral therapy (ART), the global population of people with HIV (PWH) is aging. A PWH who initiates ART today has the same life expectancy as an HIV-negative individual of the same age [1]. This longer lifespan has shifted the global HIV age structure: one in five adults living with HIV today is over age 50; this proportion has doubled from one in ten adults in 2005 [2]. Modeling studies suggest that the number of PWH over the age of 50 will continue to increase over time [3].

As this population ages, countries must consider how to provide comprehensive care to older individuals living with HIV. These PWH are at greater risk for many age-associated comorbidities, including cardiovascular, metabolic, pulmonary, and renal conditions; as well as non-AIDS-defining cancers [4–12]. Such multimorbidity leads to increasingly complex care management and increased likelihood of polypharmacy, or the simultaneous use of multiple medications [13,14]. Although research on age-related comorbidities and the age distribution of PWH is gaining traction, studies often focus on high-income settings [15–17].

Kenya has one of the largest HIV epidemics globally, with an estimated 1.4 million PWH in 2021 [2]. Although HIV care efforts have been largely successful (over 75% of Kenyan PWH are virally suppressed [2]), management of

[a]The Johns Hopkins University School of Medicine, and [b]The Johns Hopkins Bloomberg School of Public Health, Baltimore, MD, USA.

Correspondence to Melissa C. Schnure, 1830 E Monument St, Room 8047A, Baltimore, MD, 21205, USA.

Tel: +1 301 922 4646; e-mail: mschnur3@jhmi.edu

Received: 2 October 2023; revised: 27 February 2024; accepted: 21 March 2024.

DOI:10.1097/QAD.0000000000003895

other comorbidities remains inadequate. In Kenya, an estimated 62% of PWH were living with at least one noncommunicable disease (NCD) in 2020 [18]. However, NCD awareness is low: in 2015, 88% of Kenyans had never been measured for raised blood sugar and 56% had never been measured for hypertension [19]. Therefore, a key component of investing in new care models for HIV is estimating the population size and age distribution of PWH that will require these NCD services in the future.

Therefore, we sought to forecast the effect of demographic shifts and HIV-targeted interventions on the population size and age distribution of PWH in Kenya through 2040. Specifically, we examined demographic changes under a status quo scenario representing current trends in HIV care, and a 'full intervention' scenario representing broad scale-up of HIV care continuum interventions.

Methods

We developed a dynamic, compartmental model of HIV transmission among the general population in Kenya (Fig. 1). A compartmental model is a type of mathematical model that simplifies the population into homogenous compartments and models the average behavior within each. Compartments were defined to characterize the HIV continuum of care: uninfected; infected but undiagnosed; diagnosed but unengaged in care; engaged in care but unsuppressed; and engaged in care and virally suppressed. We defined engagement in care as being on ART, based on the UNAIDS definition of receiving an ART prescription in the past 28 days [2]. We stratified the population according to age (5-year bands from 0 to 80 and an 80+ group) and sex (male/female). The full set of differential equations governing the model can be found in Appendix Text S1, http://links.lww.com/QAD/D158.

Model calibration

The model was initiated in 1970 and calibrated through 2021. Calibration is defined as the process of finding a set of input parameter values that results in a simulated HIV epidemic closely representing the observed epidemic. Parameters are the numerical variables that define a model and govern its function. Two general data types informed the model: input data for prior distributions of model parameters (e.g. the rate at which individuals disengage from HIV care) and calibration target data (e.g. the number of new HIV infections reported in Kenya annually by age and sex).

We assessed model fit via a defined likelihood function quantifying how well each simulation reproduced the calibration targets. Using an Adaptive Metropolis sampler [a Markov-chain Monte-Carlo (MCMC) approach [20,21]], the calibration ran simulations with different

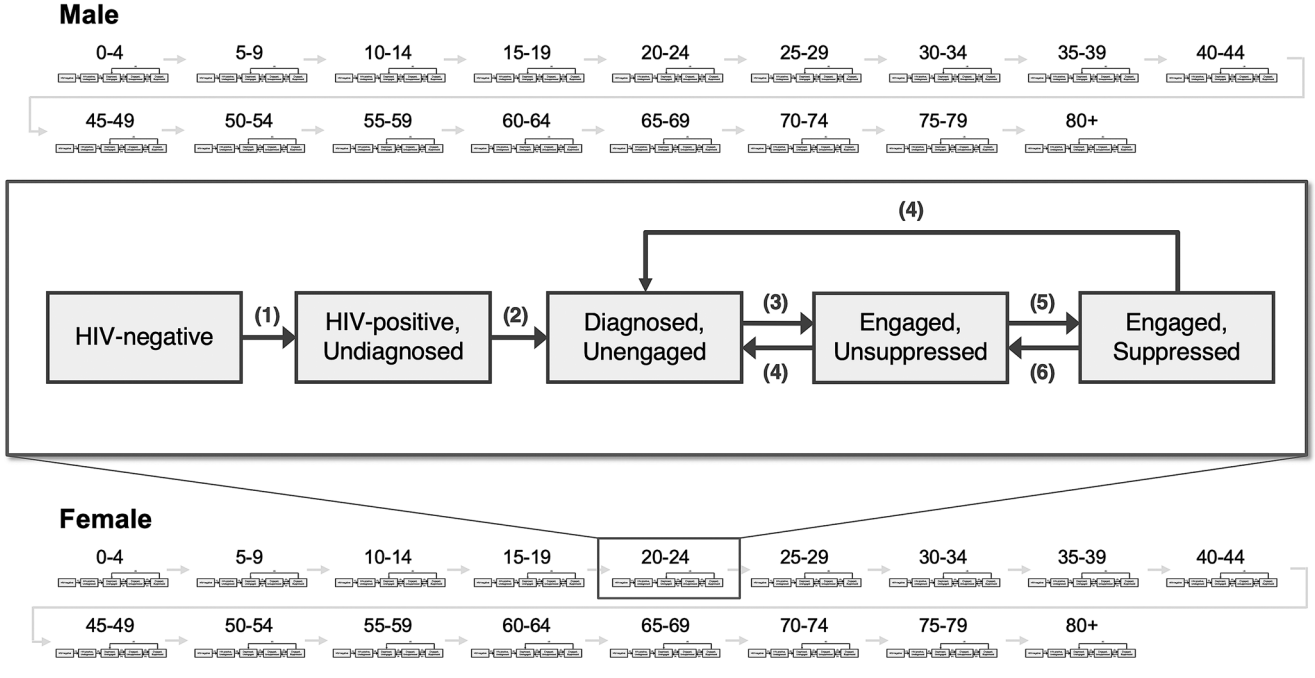

Fig. 1. Model structure. Compartmental model representing the general HIV epidemic in Kenya by sex (male, female), 5-year age groups, and relevant HIV states: HIV-negative; HIV-positive but undiagnosed; diagnosed but unengaged in care; engaged in care but unsuppressed, and engaged in care and virally suppressed. Transitions along the continuum of care include (labeled in figure): (1) HIV incidence, (2) HIV diagnosis, (3) engagement in care, (4) disengagement from care (with separate rates of disengagement from the suppressed versus unsuppressed compartments), (5) gain of viral suppression, and (6) loss of viral suppression.

sampled values of each parameter and weighted these simulations according to the likelihood function. We ran the MCMC simultaneously across four chains, with a burn-in period of 50 000 iterations followed by 50 000 iterations for analysis in each chain. The resulting 200 000 simulations (across four chains) were thinned to a final set of 1000 simulations by selecting every 200th simulation.

Input parameters and prior distributions

Model input parameter values came from available literature and survey data (see Table 1; a complete list of parameters is provided in Table S1, http://links.lww.com/QAD/D160). We parameterized the model using the simplest set of parameters that could still replicate the observed epidemic and continuum of care by age and sex over the calibration period.

Parameters governing continuum of care transitions (i.e. the probabilities of receiving an HIV test [22–24], starting or stopping ART [2,25], becoming virally suppressed [26], or losing viral suppression [27]) came from Kenya-specific sources, such as the Kenya Demographic and Health Surveys (KDHS), or cohort studies conducted among Kenyan populations. For testing, we fit logistic models to KDHS data on the probability of receiving an HIV test, with separate models by sex and by age for those under versus over 17. We included covariates for calendar year and each year of age over 17; the resulting odds ratios are in Table 1. For engagement, we fit a logistic model to UNAIDS data on the number of individuals starting ART, with separate slopes for the time periods of preuniversal ART, rollout of universal ART, and postuniversal ART. These slopes are represented as odds ratios in Table 1. Annual probabilities were transformed to per capita rates by assuming the probabilities were derived from exposure to a constant hazard, that is, $P = 1 - S(t) = 1 - e^{-(\text{rate}*\text{time})}$, where $S(t)$ is the survival function at time t.

We assumed sexual partnerships formed with a probability related to the age difference between two partners, based on a phylogenetic analysis of sexual partnerships in South Africa [28]. We allowed the relative risk of HIV transmission to vary by age as a function of the proportion in each age group reporting multiple partners or high-risk sex practices (i.e. condomless sex) [22–24,29]. Maternal–fetal transmission risk came from Kenya's Framework for Elimination of Mother-To-Child Transmission of HIV [30] for the modern era and a study of maternal–fetal risk for the pre-ART era [31].

During calibration, parameter values were sampled from prior distributions with corresponding uncertainty ranges; in most cases, this was the 95% confidence

Table 1. Prior (pre-calibration) values of key parameters[a].

Parameter	Value (median prior, with sampling range)	Reference
Transmission[b]		
Transmission rates by age/sex/time	(Calibrated)	(Calibrated)
Testing (probability of receiving an HIV test within the past year)		
Female, age 35–39, 2015	0.52 (0.24–0.73)	KDHS 2003 [22], 2008 [23], 2014 [24]
Female, age 17 and younger, 2015	0.35 (0.13–0.63)	
Yearly change in odds of receiving a test, for individuals over 17 (odds ratio)	1.26 (0.32–5.04)	
Yearly change in odds of receiving a test, for individuals age 17 and under (odds ratio)	1.23 (0.31–4.90)	
Change in odds of receiving a test for every one-year increase in age, for individuals over 17 (odds ratio)	0.96 (0.24–3.86)	
Ratio of testing rates among male versus female	1 (0.25–4)	(Calibrated)
Engagement (annual probability of starting ART)		
Female, 2015	0.32 (0.08–1)	AIDSinfo [2]
Yearly change in odds of starting ART prior to universal ART, 2016 (odds ratio)	1.34 (0.34–5.36)	
Yearly change in odds of starting ART during rollout of universal ART, 2016–2017 (odds ratio)	1.68 (0.42–6.70)	
Yearly change in odds of starting ART after initial rollout of universal ART, 2017 (odds ratio)	1.12 (0.28–4.49)	
Ratio of engagement rates among male versus female	1 (0.25–4)	(Calibrated)
Disengagement (annual probability of stopping ART)[c]		
Among suppressed	0.098 (0.026–0.329)	Lee *et al.* [25]
Among unsuppressed	0.13 (0.035–0.418)	Lee *et al.* [25]
Suppression (average time to suppression, years)[d]		
In 1993	1.49 (0.38–5.78)	Njuguna *et al.* [26]
In/after 2003	1.49 (0.38–5.78)	Njuguna *et al.* [26]
Ratio of suppression rates among male versus female	1 (0.25–4)	(Calibrated)
Viral rebound (average time to loss of suppression, years)		
All years	5.07 (1.3–19.7)	Maina *et al.* [27]

ART, antiretroviral therapy; KDHS, Kenya Demographic and Health Survey.
[a]Select parameters only; see for full parameterization of all parameter values, http://links.lww.com/QAD/D160.
[b]A composite of number of sexual encounters and rate of transmission per encounter.
[c]Same for all ages and sexes; constant over time
[d]Same for all ages.

interval of a lognormal distribution. We used lognormal distributions to reflect the intuition that rates function on a multiplicative scale; for example, simulating a rate of starting ART twice what is estimated from the literature would be as likely as a rate half of the literature estimate.

Calibration targets

The model was calibrated to HIV incidence (1990–2021), prevalence (1990–2021), mortality (1990–2021), status awareness (2015–2021), care engagement (2015–2021), and viral suppression (2019–2020) as reported by UNAIDS [2]. Incidence and prevalence were reported as totals, by age, and by age*sex; awareness, engagement, and suppression were reported as totals and by age*sex; and HIV mortality was reported as totals and by age.

General population size was calibrated to UN World Population Prospects data from 1950 to 2021, reported as totals and by age, sex, and age*sex [32]. See Appendix Text S2, http://links.lww.com/QAD/D159 and Table S2, http://links.lww.com/QAD/D161 for detailed reporting of data and likelihood methodology.

Modeled interventions

Calibrated models were followed to 2040 under two scenarios: a 'status quo' scenario assuming no additional scale-up of HIV interventions, but allowing current trends in transmission rates, HIV testing, and care engagement to continue, and a 'full intervention' scenario with the following improvements to the HIV care continuum:

1. HIV testing: 75% of the population tested for HIV annually [average preintervention value: 32% (95% credible interval: 27–37%)].
2. Engagement in HIV care: 90% of diagnosed, unengaged PWH engage in care annually [preintervention: 40% (23–60%)].
3. Viral suppression gain: 90% of engaged, unsuppressed PWH gain suppression annually [preintervention: 88% (71–98%)].
4. Maintain viral suppression: 90% of engaged, suppressed PWH maintain suppression annually [preintervention: >90% (83–97%)].
5. Retention: 90% of all engaged PWH (regardless of suppression status) remain engaged annually [preintervention: >90% (91–98%)].

Preintervention values of each intervention are population-weighted averages; however, model values varied within strata of age and sex. For some age-specific and sex-specific strata of certain interventions (especially maintenance of suppression and retention), the preintervention value was greater than the intervention target; in these cases, the preintervention value was carried forward in the intervention scenario as well. All interventions began in 2025, scaled up linearly to reach full effect by 2030, and remained at the target level through 2040. We chose a linear scale-up for the simplicity of representing a phased roll-out, as opposed to assuming immediate implementation at full scale.

Outcomes

Our primary outcomes were the median forecasted age of all PWH and PWH engaged in HIV care in 2040 under both the 'status quo' and 'full intervention' scenarios (overall and by sex). We also reported the median age of people with incident infections, the median age of individuals entering care, the number of new HIV infections, and total prevalence in 2040. For each outcome, we calculated the median value and the 95% credible interval (2.5th and 97.5th quantiles) from the final set of 1000 simulations.

Sensitivity analyses

We conducted sensitivity analyses to identify parameters with the strongest influence on the percentage of PWH over age 50 in 2040. We assessed the monotonicity of these parameter–outcome relationships visually using scatterplots and calculated partial rank correlation coefficients (PRCCs, a measure of the correlation between each parameter and the outcome). To complement the PRCCs, we ranked simulations based on each parameter value and compared the percentage of PWH over age 50 from the 25% of simulations with the lowest versus highest values of each parameter. This method of comparing outcomes helps depict how much results might change if key parameter values are changed, and has been described elsewhere [33].

Results

New HIV infections and total prevalence

Assuming continuation of status quo, annual new HIV infections in Kenya were forecasted to fall from 34 000 [95% credible interval (CrI): 28 000–41 000] in 2025 to 29 000 (15 000–57 000) in 2040 (Fig. 2, red line). Assuming implementation of the full intervention, new HIV infections fell to 6000 (3000–12 000) by 2040, representing 78% (54–90%) fewer incident infections than in the status quo scenario. Under the status quo, HIV prevalence fell from 1.44 million (1.39–1.50 million) in 2025 to 1.38 million (1.27–1.65 million) in 2040. Under the intervention scenario, prevalence fell to 1.11 million (1.01–1.25 million) by 2040, representing 20% (10–30%) fewer prevalent infections than in the status quo scenario. (See Figures S1–2, http://links.lww.com/QAD/D163, http://links.lww.com/QAD/D164 for full calibration period 1990–2020 and additional stratifications.)

Age structure of people with HIV

The median forecasted age of PWH (both diagnosed and undiagnosed) in 2025 was 39 (38–40), and 376 000

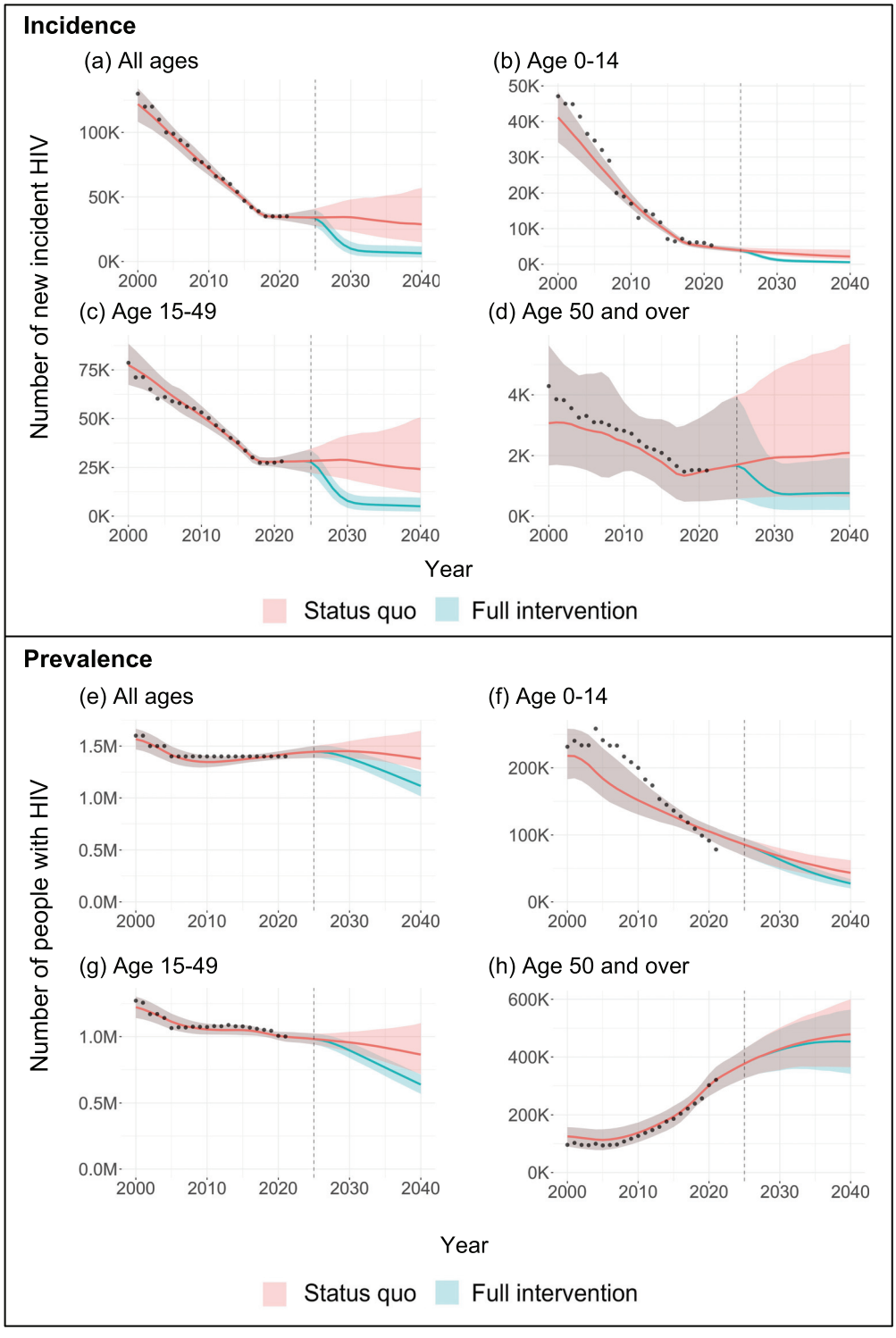

Fig. 2. Forecasted HIV incidence (top panel) and HIV prevalence (bottom panel) under status quo scenario versus full combined interventions, overall and by age, overlaid with calibration data. The median value across 1000 model simulations is shown as a red line for the 'status quo' scenario and green line for the 'full intervention' scenario, with 95% credible intervals shown as the shaded ribbons. Black dots indicate calibration target data. The vertical dashed line indicates the intervention start year in 2025, at which point the two scenarios diverge.

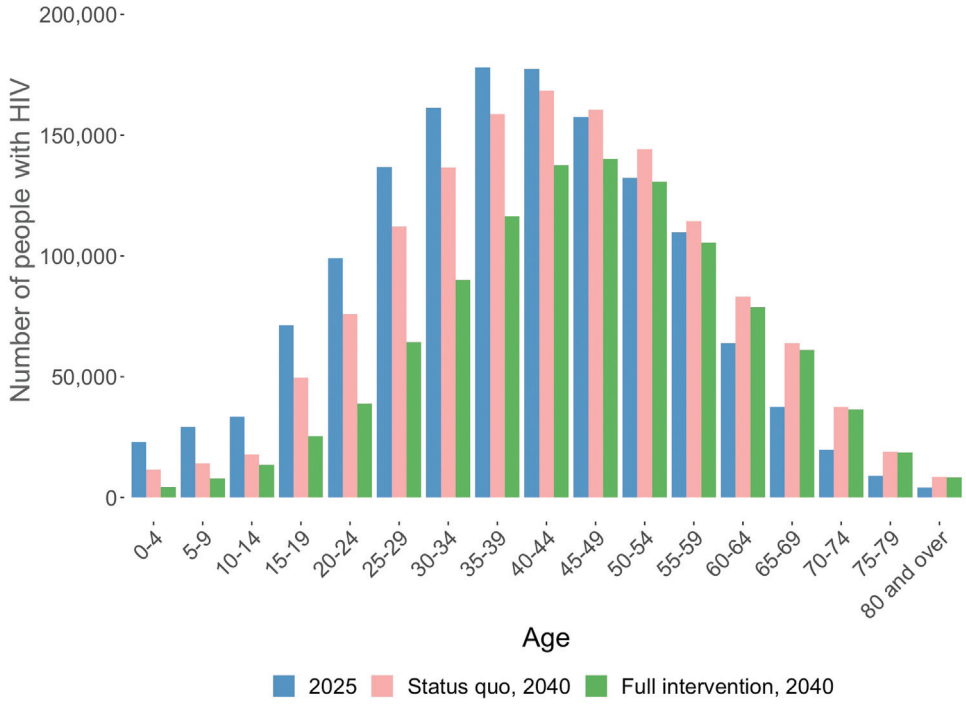

Fig. 3. Age structure of people with HIV in Kenya. Age structure of people with HIV in Kenya in 2025, prior to intervention (blue, left bars), in 2040 under the status quo scenario (pink, center), and in 2040 under the full intervention scenario (green, right).

(325 000–429 000) PWH were over age 50, representing 26% (23–29%) of all PWH. Without additional intervention, the median age increased to 43 (39–46) in 2040, with 479 000 (364 000–600 000) over age 50 (or 34% (26–43%) of all PWH, Fig. 3; Table S3, http://links.lww.com/QAD/D162). Under the full intervention scenario, the age structure of PWH was forecasted to shift even older, reaching a median age of 46 (43–48) by 2040, with 453 000 (341 000–564 000) over age 50, or 40% (33–47%) of all PWH.

We also found a shift in the age distribution of new HIV infections: in 2025, only 33% (20–50%) of new infections were forecasted to occur among individuals over age 30. Without intervention, this percentage increased to 40% (24–62%) by 2040, and further to 52% (34–71%) under the full intervention scenario (Figure S4, http://links.lww.com/QAD/D166).

Relative to the population of PWH, the forecasted age distribution of the Kenya's general population was much younger, with a median age of 22 (21–22) in 2025 and 25 (24–26) in 2040 (Figure S3, http://links.lww.com/QAD/D165). Additionally, the percentage of the general population over age 50 was considerably lower in comparison [10% (9–11%) in 2025 and 13% (11–15%) in 2040].

Age structure of people engaged in HIV care

As most PWH in Kenya are engaged in care, the age structure of people engaged in HIV care was similar to that of all PWH: the median forecasted age shifted from 40 (39–42) in 2025 to 44 (41–47) in 2040 without any intervention and 46 (43–49) with full intervention (Figure S5, http://links.lww.com/QAD/D167). Of those engaged in in care, 28% (25–31%) were over 50 in 2025, increasing to 36% (28–44%) in 2040 without intervention and 41% (34–48%) with full intervention.

In 2025, the median age of individuals entering into care (either for the first time or re-entering care after disengagement) was 35 (32–38), with 63% (57–69%) over age 30. In the full intervention scenario, the median age of those entering care was 44 (41–47) by 2040, with 81% (77–85%) over age 30.

Differences in age structure by sex

Despite a similar median age of women and men living with HIV in 2025 (38 [37–40] for women, 41 [39–42] for men), the percentage of HIV-positive men over age 50 was forecasted to grow more rapidly in the next 15 years, from 28% (24–31%) in 2025 to 40% (32–48%) in 2040 [versus 25% (22–28%) to 31% (22–39%) among women, Figures S6–S7, http://links.lww.com/QAD/D168, http://links.lww.com/QAD/D169). This growth is primarily due to the older age at HIV infection among men (29 [26–34]) versus women (22 [19–24]).

Sensitivity analysis

Under the intervention scenario, the parameters most strongly associated with the percentage of PWH over age 50 in 2040 were related to general (i.e. non-HIV-specific)

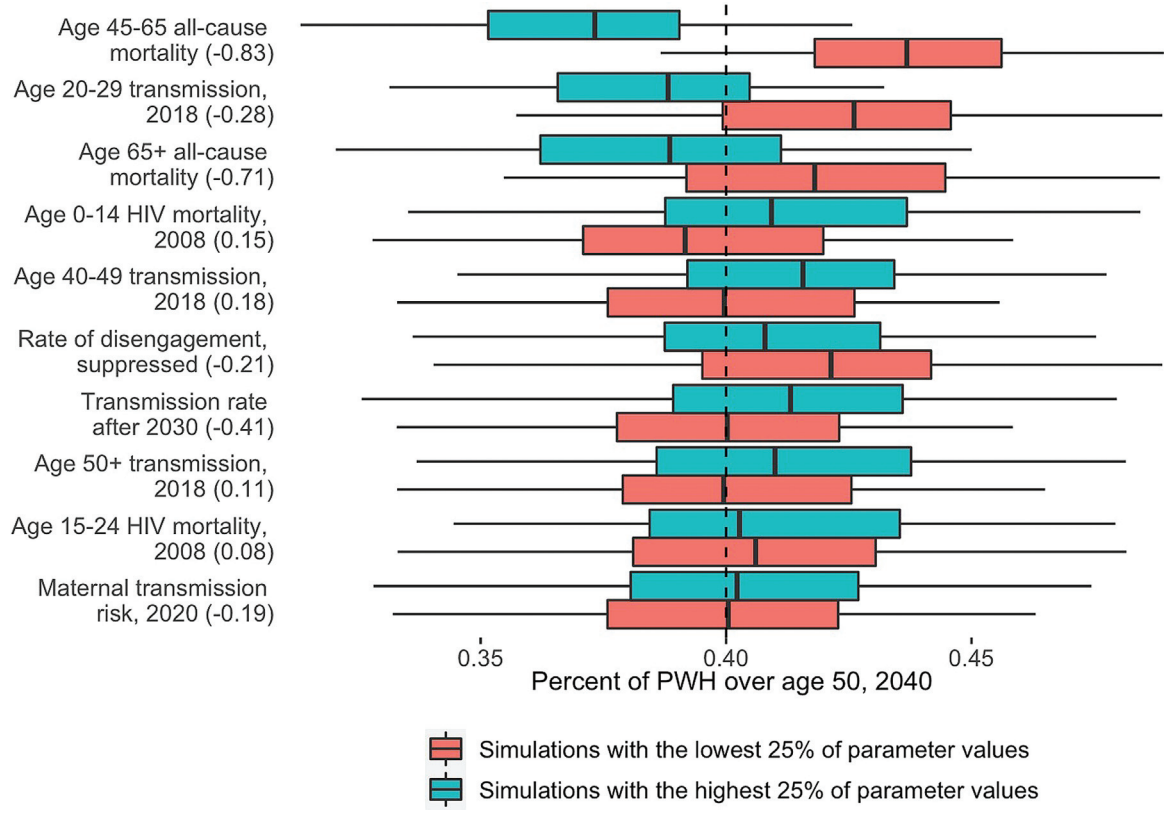

Fig. 4. Sensitivity analysis for parameters most strongly associated with the percentage of people with HIV (PWH) over age 50. The red (lower) bars represent the estimate of the change in this percentage for the 25% of simulations with the lowest values of each parameter in 2040; the blue (upper) bars represent the estimate for the 25% of simulations with the highest values. The solid vertical line of each bar represents the median, the box spans the interquartile range, and the whiskers span the 95% credible interval. Parameters are ordered by the univariate difference between the lowest and highest estimates, that is, in one-way sensitivity analyses, age 20–29 transmission was the second most influential parameter. The vertical dashed line represents the median value from the main analysis. Parameters are labeled with their partial rank correlation coefficient in parentheses, a multivariate estimate of the correlation between each parameter and the outcome. Values closer to 1 or −1 indicate stronger correlation.

mortality by age (PRCCs: −0.83, mortality age 45–65 years old; −0.71, mortality age 65 and older, Fig. 4). In the 25% of simulations with the lowest general mortality age 45–65, the percentage of PWH over age 50 in 2040 was 44% (39–49%). Conversely, in the 25% of simulations with the highest general mortality age 45–65, the percentage of PWH over age 50 was 38% (32–43%). We conducted an additional sensitivity analysis with select model outputs; these results are shown in Figure S8, http://links.lww.com/QAD/D170.

Discussion

This analysis illustrates the effect of demographic shifts and HIV-specific interventions on the age distribution of PWH in Kenya over the next 15 years. Assuming no additional scale-up of HIV interventions, new infections are forecasted to fall by 2040, a product of historically strong HIV programming and a hopeful sign for future health system needs. This reduction in new HIV infections – typically clustered among younger ages – combined with longer survival among persons receiving ART will lead to an aging HIV population: our results suggest that by 2040, the population of PWH over age 50 will grow by nearly one-third, from 376 000 to 479 000. Moreover, this population over 50 will constitute a greater percentage of all PWH, increasing from 26 to 34%.

The addition of HIV-specific interventions was forecasted to further reduce new infections and prevalence of HIV. Because younger PWH tend to have greater room for improvement along the care continuum, interventions that brought all ages up to a common level (as implemented in this model) led to an even older population living with HIV by 2040.

Men with HIV were forecasted to have an older median age than women with HIV in 2040, both with and without intervention. The pattern of a higher age at

infection among men versus women has been seen in other countries across eastern and southern Africa [34] and is important for both HIV-specific programming and NCD screening, given the elevated risk of cardiovascular disease in men [35].

This analysis adds to the literature on the aging HIV population and, importantly, focuses on a lower middle-income country. Research on healthy aging among PWH is growing; however, studies in African populations remain sparse [17]. Although other models have similarly evaluated HIV outcomes by age, many models in Africa have not included finer age strata above 50 [36,37]. Those studies that have done so have found both increases in prevalence as well as greater progress towards reaching care continuum targets among those over 50 [38,39] – both results that align with our findings.

Additional research in this setting will hopefully lead to a reevaluation of the care needs of African PWH. For instance, recent studies of NCDs among PWH in Africa have found high rates of elevated blood pressure, dysglycemia, renal insufficiency, and obesity [40–44]. Combined with factors such as increased inflammation from viral replication, PWH may have increased risk for cardiovascular events such as myocardial infarction and stroke [5,6,8,45]. Therefore, interventions mitigating noncommunicable risk factors among PWH will likely rise in importance over time. Our sensitivity analysis found that the parameters most strongly influencing the percentage of PWH over 50 were those related to all-cause mortality, suggesting that future challenges of HIV care may focus more on managing other comorbidities driving general mortality than managing HIV itself.

Lessons learned from other settings with aging PWH suggest prioritizing overall health-related quality of life by integrating HIV and NCD screening and treatment [46–65]. Different service delivery modalities have proven effective in different settings: in western Kenya, the Academic Model Providing Access to Healthcare (AMPATH) program has leveraged experience in managing HIV to address NCDs by training nurses and clinical officers in diabetes and hypertension care [50]. The Sustainable East Africa Research in Community Health (SEARCH) program in rural Uganda and Kenya has improved outcomes through mobile, multi-disease community health campaigns [66–68]. Therefore, our analysis can be used to compare the potential impact of such integration options at a national level in Kenya.

Our analysis is subject to limitations. Although the UNAIDS data are the official estimates for Kenya and we believe they represent the best estimates of HIV epidemiology in the country, these estimates of incidence, prevalence, and mortality are in fact themselves generated from the Spectrum/AIM model [69,70]. Using model-generated projections as calibration data is a limitation; however, Spectrum has been validated across settings. Furthermore, a comparison of incidence estimation approaches in Kenya found that Spectrum estimates compared reasonably well with survey-derived and assay-derived methodologies [71]. We have used Spectrum in previous modeling analyses in Kenya [72,73], but developed this new model to allow more flexibility and control over model assumptions, parameters, and calibration.

We did not conduct model validation against external datasets in Kenya, as we aimed to include as much data as possible in the calibration targets themselves. However, our results can be compared with future estimates of Kenya's HIV age distribution – particularly among finer age strata over 50 – as they become available. As our calibration targets are all Kenya-specific, the generalizability of our results to other settings may require model recalibration.

We forecast 15-year trends in the HIV epidemic using data from the recent past; findings should be interpreted with consideration for the challenges of forecasting HIV incidence beyond the immediate term. In the United States, for instance, incidence patterns have changed in the past decade, owing to a concentration and persistence of transmission in key populations, such as men who have sex with men and persons who inject drugs [74]. Although we model HIV in the general population, effective HIV programs must reach key populations (which vary geographically, including female sex workers in Kenya, e.g.) who may benefit the most.

Kenya's programs will have to maintain annual rates of engagement, viral suppression, and retention as proposed in this article in order to reach the UNAIDS 95–95–95 targets [75]. However, though we described the potential impacts of meeting the targets, this analysis did not cover the specific strategies that Kenya may use to reach them. Literature on best practices – such as CDC's compendium of evidence-based interventions or UNAIDS' checklist for developing a national strategic plan – will be crucial to achieving these targets [76,77]. Improving testing rates from 32 to 75%, for instance, will require differentiated and innovative modalities to reach those who are missing, such as those focused on men, adolescents, or key populations. Our decision to linearly scale up interventions to full effect by 2030 may also not reflect implementation realities, with harder-to-reach risk groups often requiring more effort.

As our model collapses rural and urban settings, we are modeling the average behavior across all settings in Kenya. Our predictions might overstate or underestimate the effectiveness of interventions depending on how future trends in HIV epidemiology deviate from past patterns and how interventions are differentially implemented in these settings. With devolution of power from the

national government, Kenyan counties are responsible for intervention implementation, likely resulting in heterogeneous rollout. Reaching care continuum targets may be significantly harder in areas where transmission persists. For instance, while 15 counties saw new HIV infections reduce by 75% or more from 2013 to 2021, five counties – including four rural counties in the Western region and Nairobi – all had an increase in new infections [78].

Our findings suggest that Kenya will face an aging HIV population over the next 15 years, owing to demographic shifts and declining HIV infections. Successful HIV programming in the coming years may further accelerate these trends. Although HIV policy in Kenya has historically focused on preventing new infections and providing HIV treatment to those infected, new policy must also consider the needs of an aging HIV population as a whole – including healthy aging and the treatment of age-associated comorbidities.

Acknowledgements

Authors' contributions: conception and design: M.S., P.K., D.D., A.F. Model development: M.S., P.K., A.F. Analysis: M.S., P.K., A.F. Interpretation and important intellectual input: all authors. First draft of manuscript: M.S., P.K., A.F. Manuscript review and revision: all authors.

This research was funded by the National Institutes of Health, including grants T32AI102623 (M.C.S.); T32HL007024 (M.C.S.); K01AI138853 (P.K.); K08MH118094 (A.T.F.); R01MD018539 (A.T.F.).

Conflicts of interest

There are no conflicts of interest.

References

1. HIV/AIDS JUNPo. HIV treatment. Available at: https://www.unaids.org/en/topic/treatment. [Accessed 30 August 2019].
2. HIV/AIDS JUNPo. AIDSInfo. Available at: http://aidsinfo.unaids.org/. Published 2019. [Accessed 30 August 2019]
3. Hontelez JA, de Vlas SJ, Baltussen R, Newell ML, Bakker R, Tanser F, *et al*. **The impact of antiretroviral treatment on the age composition of the HIV epidemic in sub-Saharan Africa.** *AIDS* 2012; **26 (Suppl 1)**:S19–S30.
4. Schouten J, Wit FW, Stolte IG, Kootstra NA, van der Valk M, Geerlings SE, *et al.*, AGEhIV Cohort Study Group. **Cross-sectional comparison of the prevalence of age-associated comorbidities and their risk factors between HIV-infected and uninfected individuals: the AGEhIV cohort study.** *Clin Infect Dis* 2014; **59**:1787–1797.
5. Althoff KN, McGinnis KA, Wyatt CM, Freiberg MS, Gilbert C, Oursler KK, *et al.*, Veterans Aging Cohort Study (VACS). **Comparison of risk and age at diagnosis of myocardial infarction, end-stage renal disease, and non-AIDS-defining cancer in HIV-infected versus uninfected adults.** *Clin Infect Dis* 2014; **60**:627–638.
6. Freiberg MS, Chang C-CH, Kuller LH, Skanderson M, Lowy E, Kraemer KL, *et al*. **HIV infection and the risk of acute myocardial infarction.** *JAMA Intern Med* 2013; **173**:614–622.
7. Abraham AG, Althoff KN, Jing Y, Estrella MM, Kitahata MM, Wester CW, *et al.*, North American AIDS Cohort Collaboration on Research and Design (NA-ACCORD) of the International Epidemiologic Databases to Evaluate AIDS (IeDEA). **End-stage renal disease among HIV-infected adults in North America.** *Clin Infect Dis* 2015; **60**:941–949.
8. Drozd DR, Kitahata MM, Althoff KN, Zhang J, Gange SJ, Napravnik S, *et al*. **Increased risk of myocardial infarction in HIV-infected individuals in North America compared to the general population.** *J Acquir Immune Defic Syndr* 2017; **75**:568.
9. Klein MB, Althoff KN, Jing Y, Lau B, Kitahata M, Lo Re V, *et al.*, North American AIDS Cohort Collaboration on Research and Design of IeDEA, North American AIDS Cohort Collaboration on Research and Design (NA-ACCORD) of IeDEA. **Risk of end-stage liver disease in HIV-viral hepatitis coinfected persons in North America from the early to modern antiretroviral therapy eras.** *Clin Infect Dis* 2016; **63**:1160–1167.
10. Lewden C, Salmon D, Morlat P, Bévilacqua S, Jougla E, Bonnet F, *et al*. **Causes of death among human immunodeficiency virus (HIV)-infected adults in the era of potent antiretroviral therapy: emerging role of hepatitis and cancers, persistent role of AIDS.** *Int J Epidemiol* 2005; **34**:121–130.
11. Mahale P, Engels EA, Coghill AE, Kahn AR, Shiels MS. **Cancer risk in older persons living with human immunodeficiency virus infection in the United States.** *Clin Infect Dis* 2018; **67**:50–57.
12. Wong C, Gange SJ, Buchacz K, Moore RD, Justice AC, Horberg MA, *et al.*, North American AIDS Cohort Collaboration on Research and Design (NA-ACCORD). **First occurrence of diabetes, chronic kidney disease, and hypertension among North American HIV-infected adults, 2000–2013.** *Clin Infect Dis* 2017; **64**:459–467.
13. Edelman EJ, Gordon KS, Glover J, McNicholl IR, Fiellin DA, Justice AC. **The next therapeutic challenge in HIV: polypharmacy.** *Drugs Aging* 2013; **30**:613–628.
14. Althoff KN, Stewart C, Humes E, Gerace L, Boyd C, Gebo K, *et al*. **The forecasted prevalence of comorbidities and multimorbidity in people with HIV in the United States through the year 2030: A modeling study.** *Plos Med* 2024; **21**:e1004325.
15. Althoff KN, Stewart CN, Humes E, Zhang J, Gerace L, Boyd CM, *et al*. **The shifting age distribution of people with HIV using antiretroviral therapy in the United States.** *AIDS* 2022; **36**:459–471.
16. Kasaie P, Stewart C, Humes E, Gerace L, Zhang J, Silverberg MJ, *et al*. **Projecting the age-distribution of men who have sex with men receiving HIV treatment in the United States.** *Ann Epidemiol* 2022; **65**:46–55.
17. Harris TG, Rabkin M, El-Sadr WM. **Achieving the fourth 90: healthy aging for people living with HIV.** *AIDS* 2018; **32**:1563.
18. Smit M, Perez-Guzman PN, Mutai KK, Cassidy R, Kibachio J, Kilonzo N, Hallett TB. **Mapping the current and future non-communicable disease burden in Kenya by human immunodeficiency virus status: a modeling study.** *Clin Infect Dis* 2020; **71**:1864–1873.
19. STEPS. Kenya STEPwise Survey for Non Communicable Diseases Risk Factors 2015. 2015.
20. Haario H, Saksman E, Tamminen J. **An adaptive Metropolis algorithm.** *Bernoulli* 2001; **7**:223–242.
21. Andrieu C, Thoms J. **A tutorial on adaptive MCMC.** *Stat Comput* 2008; **18**:343–373.
22. Central Bureau of Statistics - CBS/Kenya, Ministry of Health - MOH/Kenya, ORC Macro. *Kenya Demographic and Health Survey 2003*. Calverton, Maryland, USA: CBS, MOH, and ORC Macro; 2004.
23. Kenya National Bureau of Statistics, Ministry of Health/Kenya, National AIDS Control Council/Kenya, Kenya Medical Research Institute, Population NCf, Development/Kenya Kenya Demographic and Health Survey 2014. Rockville, MD, USA 2015.
24. Kenya National Bureau of Statistics - KNBS, National AIDS Control Council/Kenya, National AIDS/STD Control Programme/Kenya, Health MoP, Sanitation/Kenya, Kenya Medical Research Institute. *Kenya Demographic and Health Survey 2008-09*. Calverton, Maryland, USA: KNBS and ICF Macro; 2010.

25. Lee H, Hogan JW, Genberg BL, Wu XK, Musick BS, Mwangi A, Braitstein P. **A state transition framework for patient-level modeling of engagement and retention in HIV care using longitudinal cohort data.** *Stat Med* 2018; **37**:302–319.
26. Njuguna N, Mugo N, Anzala O, Mureithi M, Irungu E, Wamicwe J, *et al*. **An empiric tool to identify Kenyans living with HIV who will have unsuppressed viremia 18 months following treatment initiation to guide differentiated care models.** *PLoS One* 2022; **17**:e0271520.
27. Maina E, Mureithi H, Adan A, Muriuki J, Lwembe R, Bukusi E. **Incidences and factors associated with viral suppression or rebound among HIV patients on combination antiretroviral therapy from three counties in Kenya.** *Int J Infect Dis* 2020; **97**:151–158.
28. De Oliveira T, Kharsany AB, Gräf T, Cawood C, Khanyile D, Grobler A, *et al*. **Transmission networks and risk of HIV infection in KwaZulu-Natal, South Africa: a community-wide phylogenetic study.** *Lancet HIV* 2017; **4**:e41–e50.
29. Mojola SA, Williams J, Angotti N, Gómez-Olivé FX. **HIV after 40 in rural South Africa: a life course approach to HIV vulnerability among middle aged and older adults.** *Social Sci Med* 2015; **143**:204–212.
30. (NACC) NACC. Kenya Framework for Elimination of Mother-To-Child Transmission of HIV and Syphilis 2016–2021. 2016.
31. **Rates of mother-to-child transmission of HIV-1 in Africa, America, and Europe: results from 13 perinatal studies.** *J Acquir Immune Defic Syndr Hum Retrovirol* 1995; **8**:506–510.
32. Nations U. *World Population Prospects 2022: Methodology of the United Nations population estimates and projections*. Department of Economic and Social Affairs, Population Division; 2022.
33. Fojo AT, Kendall EA, Kasaie P, Shrestha S, Louis TA, Dowdy DW. Mathematical modeling of ''chronic'' infectious diseases: unpacking the black box. Paper presented at: Open forum infectious diseases 2017.
34. Risher KA, Cori A, Reniers G, Marston M, Calvert C, Crampin A, *et al*. **Age patterns of HIV incidence in eastern and southern Africa: a modelling analysis of observational population-based cohort studies.** *Lancet HIV* 2021; **8**:e429–e439.
35. WHO CVD Risk Chart Working Group. **World Health Organization cardiovascular disease risk charts: revised models to estimate risk in 21 global regions.** *Lancet Glob Health* 2019; **7**:e1332–e1345.
36. Omondi E, Mbogo R, Luboobi L. **A mathematical modelling study of HIV infection in two heterosexual age groups in Kenya.** *Infect Dis Model* 2019; **4**:83–98.
37. Eaton JW, Johnson LF, Salomon JA, Bärnighausen T, Bendavid E, Bershteyn A, *et al*. **HIV treatment as prevention: systematic comparison of mathematical models of the potential impact of antiretroviral therapy on HIV incidence in South Africa.** *PLoS Med* 2012; **9**:e1001245.
38. Mahy M, Autenrieth CS, Stanecki K, Wynd S. **Increasing trends in HIV prevalence among people aged 50 years and older: evidence from estimates and survey data.** *AIDS* 2014; **28**:S453.
39. Farley SM, Wang C, Bray RM, Low AJ, Delgado S, Hoos D, *et al*. **Progress towards the UNAIDS 90-90-90 targets among persons aged 50 and older living with HIV in 13 African countries.** *J Int AIDS Soc* 2022; **25**:e26005.
40. Chang D, Esber AL, Dear NF, Iroezindu M, Bahemana E, Kibuuka H, *et al*. **Noncommunicable diseases by age strata in people living with and without HIV in four African countries.** *J Int AIDS Society* 2022; **25**:e25985.
41. Achwoka D, Waruru A, Chen T-H, Masamaro K, Ngugi E, Kimani M, *et al*. **Noncommunicable disease burden among HIV patients in care: a national retrospective longitudinal analysis of HIV-treatment outcomes in Kenya, 2003–2013.** *BMC Public Health* 2019; **19**:372.
42. Okello S, Amir A, Bloomfield GS, Kentoffio K, Lugobe HM, Reynolds Z, *et al*. **Prevention of cardiovascular disease among people living with HIV in sub-Saharan Africa.** *Progress Cardiovasc Dis* 2020; **63**:149–159.
43. Xu Y, Chen X, Wang K. **Global prevalence of hypertension among people living with HIV: a systematic review and meta-analysis.** *J Am Soc Hypertens* 2017; **11**:530–540.
44. Phillips-Howard PA, Laserson KF, Amek N, Beynon CM, Angell SY, Khagayi S, *et al*. **Deaths ascribed to noncommunicable diseases among rural Kenyan adults are proportionately increasing: evidence from a health and demographic surveillance system, 2003–2010.** *PLoS One* 2014; **9**:e114010.
45. Triant VA, Lee H, Hadigan C, Grinspoon SK. **Increased acute myocardial infarction rates and cardiovascular risk factors among patients with human immunodeficiency virus disease.** *J Clin Endocrinol Metab* 2007; **92**:2506–2512.
46. Njuguna B, Vorkoper S, Patel P, Reid MJA, Vedanthan R, Pfaff C, *et al*. **Models of integration of HIV and noncommunicable disease care in sub-Saharan Africa: lessons learned and evidence gaps.** *AIDS* 2018; **32**:S33–S42.
47. Duffy M, Ojikutu B, Andrian S, Sohng E, Minior T, Hirschhorn LR. **Noncommunicable diseases and HIV care and treatment: models of integrated service delivery.** *Trop Med Int Health* 2017; **22**:926–937.
48. Havlir DV, Balzer LB, Charlebois ED, Clark TD, Kwarisiima D, Ayieko J, *et al*. **HIV testing and treatment with the use of a community health approach in rural Africa.** *New Engl J Med* 2019; **381**:219–229.
49. Aksam R. Reaching men with multi-disease testing. Commission for Quality and Innovation (CQUIN). Available at: https://cquin.icap.columbia.edu/wp-content/uploads/2018/11/1.-Aksam_CQUIN-Session-7_FINAL.pdf. Published 2018. Updated 6 November 2018. [Accessed 5 December 2020]
50. Osetinsky B, Genberg BL, Bloomfield GS, Hogan J, Pastakia S, Sang E, *et al*. **Hypertension control and retention in care among HIV-infected patients: the effects of co-located HIV and chronic noncommunicable disease care.** *J Acquir Immune Defic Syndr* 2019; **82**:399–406.
51. Rawat A, Uebel K, Moore D, Yassi A. **Integrated HIV-care into primary healthcare clinics and the influence on diabetes and hypertension care: an interrupted time series analysis in Free State, South Africa over 4 years.** *J Acquir Immune Defic Syndr* 2018; **77**:476–483.
52. Edwards JK, Bygrave H, Van den Bergh R, Kizito W, Cheti E, Kosgei RJ, *et al*. **HIV with noncommunicable diseases in primary care in Kibera, Nairobi, Kenya: characteristics and outcomes 2010–2013.** *Trans R Soc Trop Med Hyg* 2015; **109**:440–446.
53. Golovaty I, Sharma M, Van Heerden A, van Rooyen H, Baeten JM, Celum C, Barnabas RV. **Cost of integrating noncommunicable disease screening into home-based HIV testing and counseling in South Africa.** *J Acquir Immune Defic Syndr* 2018; **78**:522–526.
54. Khabala KB, Edwards JK, Baruani B, Sirengo M, Musembi P, Kosgei RJ, *et al*. **Medication Adherence Clubs: a potential solution to managing large numbers of stable patients with multiple chronic diseases in informal settlements.** *Trop Med Int Health* 2015; **20**:1265–1270.
55. Wroe EB, Kalanga N, Dunbar EL, Nazimera L, Price NF, Shah A, *et al*. **Expanding access to noncommunicable disease care in rural Malawi: outcomes from a retrospective cohort in an integrated NCD–HIV model.** *BMJ Open* 2020; **10**:e036836.
56. Gupta N, Bukhman G. **Leveraging the lessons learned from HIV/AIDS for coordinated chronic care delivery in resource-poor settings.** *Healthc (Ams)* 2015; **3**:215–220.
57. Haldane V, Legido-Quigley H, Chuah FLH, Sigfrid L, Murphy G, Ong SE, *et al*. **Integrating cardiovascular diseases, hypertension, and diabetes with HIV services: a systematic review.** *AIDS Care* 2018; **30**:103–115.
58. Hyle EP, Naidoo K, Su AE, El-Sadr WM, Freedberg KA. **HIV, tuberculosis, and noncommunicable diseases: what is known about the costs, effects, and cost-effectiveness of integrated care?** *J Acquir Immune Defic Syndr* 2014; **67**:S87–S95.
59. Kruk ME, Nigenda G, Knaul FM. **Redesigning primary care to tackle the global epidemic of noncommunicable disease.** *Am J Public Health* 2015; **105**:431–437.
60. Pfaff C, Singano V, Akello H, Amberbir A, Berman J, Kwekwesa A, *et al*. **Early experiences integrating hypertension and diabetes screening and treatment in a human immunodeficiency virus clinic in Malawi.** *Int Health* 2018; **10**:495–501.
61. Pfeiffer J, Montoya P, Baptista AJ, Karagianis M, Pugas Mde M, Micek M, *et al*. **Integration of HIV/AIDS services into African primary healthcare: lessons learned for health system strengthening in Mozambique-a case study.** *J Int AIDS Soc* 2010; **13**:1–9.
62. Piot P, Caldwell A, Lamptey P, Nyrirenda M, Mehra S, Cahill K, Aerts A. **Addressing the growing burden of non–communicable disease by leveraging lessons from infectious disease management.** *J Glob Health* 2016; **6**:010304.

63. Rabkin M, Nishtar S. **Scaling up chronic care systems: leveraging HIV programs to support noncommunicable disease services.** *J Acquir Immune Defic Syndr* 2011; **57**:S87–S90.
64. Rabkin M, El-Sadr WM. **Why reinvent the wheel? Leveraging the lessons of HIV scale-up to confront noncommunicable diseases.** *Global Public Health* 2011; **6**:247–256.
65. Topp SM, Chipukuma JM, Chiko MM, Matongo E, Bolton-Moore C, Reid SE. **Integrating HIV treatment with primary care outpatient services: opportunities and challenges from a scaled-up model in Zambia.** *Health Policy Plan* 2013; **28**:347–357.
66. Chamie G, Kwarisiima D, Clark TD, Kabami J, Jain V, Geng E, *et al*. **Leveraging rapid community-based HIV testing campaigns for noncommunicable diseases in rural Uganda.** *PLoS One* 2012; **7**:e43400.
67. Chamie G, Kamya MR, Petersen ML, Havlir DV. **Reaching 90-90-90 in rural communities in East Africa: lessons from the Sustainable East Africa Research in Community Health Trial.** *Curr Opin HIV AIDS* 2019; **14**:449–454.
68. Kwarisiima D, Atukunda M, Owaraganise A, Chamie G, Clark T, Kabami J, *et al*. **Hypertension control in integrated HIV and chronic disease clinics in Uganda in the SEARCH study.** *BMC Public Health* 2019; **19**:511.
69. HIV/AIDS JUNPo. *Methods for deriving UNAIDS estimates.* Geneva: United Nations2016.
70. Stover J, Glaubius R, Kassanjee R, Dugdale CM. **Updates to the Spectrum/AIM model for the UNAIDS 2020 HIV estimates.** *J Int AIDS Soc* 2021; **24**:e25778.
71. Kim AA, Hallett T, Stover J, Gouws E, Musinguzi J, Mureithi PK, *et al*. **Estimating HIV incidence among adults in Kenya and Uganda: a systematic comparison of multiple methods.** *PLoS One* 2011; **6**:e17535.
72. Kasaie P, Weir B, Schnure M, Dun C, Pennington J, Teng Y, *et al*. **Integrated screening and treatment services for HIV, hypertension and diabetes in Kenya: assessing the epidemiological impact and cost-effectiveness from a national and regional perspective.** *J Int AIDS Soc* 2020; **23**:e25499.
73. Schnure M, Kasaie P, Dowdy D, Weir B, Dun C, Beyrer C. Assessing the impact of targeted screening and treatment of diabetes and hypertension among adults living with HIV in Nairobi, Kenya. In Bae K-H, Feng B, Kim S, Lazarova-Molnar S, Zheng Z, Roeder T, and Thiesing R, editors *Proceedings of the 2020 Winter Simulation Conference*, 2020; pp. 980–991.
74. CDC data confirm: Progress in HIV prevention has stalled [press release]. 27 February 2019. 2019.
75. HIV/AIDS JUNPo. *Fast-Track - Ending the AIDS epidemic by 2030.* Geneva: United Nations2014.
76. Prevention USCfDCa. Compendium of Evidence-Based Interventions and Best Practices for HIV Prevention. Available at: https://www.cdc.gov/hiv/research/interventionresearch/compendium/index.html. Published 2022. [Accessed 18 December 2023], 2023.
77. HIV/AIDS JUNPo. *Checklist and reference list for developing and reviewing a national strategic plan for HIV*. Geneva: United Nations2020.
78. (NACC) NACC. *Kenya World AIDS Day Progress Report* 2013–2021. 2021.