Understanding the HIV Epidemic Among MSM in Baltimore: A Modeling Study Estimating the Impact of Past HIV Interventions and Who Acquired and Contributed to Infections

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Introduction: Men who have sex with men (MSM) in the United States are disproportionately affected by HIV. We estimated the impact of past interventions and contribution of different population groups to incident MSM HIV infections.

Setting: Baltimore, US.

Methods: We used a deterministic model, parameterized and calibrated to demographic and epidemic Baltimore MSM data, to estimate the fraction of HIV infections among MSM averted by condoms and antiretroviral therapy (ART) over 1984–2017 and the fraction of infections acquired and transmission contributed by MSM from different demographic groups and disease and care continuum stages over 10-year periods from 1988 to 2017, using population attributable fractions.

Results: Condom use and ART averted 19% (95% uncertainty interval: 14%–25%) and 23% (15%–31%) of HIV infections that would have occurred since 1984 and 1996, respectively. Over 2008–2017, 46% (41%–52%) of incident infections were acquired by and 35% (27%–49%) of transmissions contributed by MSM aged 18–24 years (who constitute 27% of all MSM, 19% of HIV+ MSM). MSM with undiagnosed HIV infection, those with diagnosed infection but not in care, and those on ART contributed to 41% (31%–54%), 46% (25%–56%), and 14% (7%–28%) of transmissions, respectively.

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Conclusion: Condoms and ART have modestly impacted the HIV epidemic among Baltimore MSM to date. Interventions reaching MSM with diagnosed infection who are not in care should be implemented because the largest percentage of HIV transmissions among Baltimore MSM is attributed to this group.

Key Words: epidemic model, mathematical model, men who have sex with men, HIV/AIDS, HIV incidence, HIV treatment cascade

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INTRODUCTION

Gay, bisexual, and other men who have sex with men (collectively referred to as MSM) are disproportionately affected by HIV worldwide, with HIV prevalence estimated at 18% in sub-Saharan Africa, 25% in the Caribbean, and 15% in the United States.[1,2] New HIV diagnoses among MSM represented two-thirds of all new diagnoses occurring in the United States in 2017.[3] Although the total number of new HIV diagnoses in the United States has declined over 2010–2017, the Centers for Disease Control and Prevention (CDC) estimates that the annual number of new HIV diagnoses attributed to male-to-male sexual contact has remained constant over the same period.[3] HIV incidence among MSM has plateaued despite the increasing availability of highly active antiretroviral therapy (ART) since 1996. Trials and observational studies have shown that adherence to ART—inducing viral suppression—prevents transmission between partners.[4,5] The high HIV infection rate among US MSM has been associated with low condom use,[6] high numbers of non-steady partnerships,[7,8] and low levels of viral suppression because levels of both HIV diagnosis and retention in care among US MSM are suboptimal.[9–11]

Baltimore, Maryland, is a major US city whose population is primarily non-Hispanic black or African American (63%) (hereafter referred to as black) and non-Hispanic white (hereafter referred to as white) (28%).[12] HIV prevalence among MSM in Baltimore, MD, estimated at 43% in 2011 and 37% in 2017, is one of the highest in the United States.[13–15] In 2017, only half of the MSM with diagnosed infection living in Baltimore were virally suppressed, and condom and pre-exposure prophylaxis (PrEP) use were reported to be low.[16–18] Since the early 2000s, an increasing amount of data on sexual behaviour, HIV prevalence, and the treatment care continuum (proportion of HIV+ MSM with diagnosed infection, that are in care, on ART, or virally suppressed) have been collected among its MSM population, which can inform mathematical models to estimate the impact of interventions, and better understand the HIV epidemic.

To identify prevention gaps and design effective HIV prevention interventions, it is crucial to gain insight into the impact of past interventions, identify which groups disproportionately acquire and subsequently contribute to transmissions, and investigate the importance of factors previously suggested to be associated with higher levels of HIV transmission, such as low retention in HIV care and nonsteady partnerships.[8,19–23]

The objective of this study was to assess the impact of past interventions and estimate the contribution of different population subgroups to new HIV infections by using a recently published transmission dynamic model of the HIV epidemic among MSM in Baltimore[11] to estimate the fraction of incident HIV infections occurring in the population that have been (1) averted by the use of condoms since 1984 and by ART since its introduction in 1996, and (2) acquired and/or contributed by different population groups and different partnership types over 1988–2017.

METHODS

Mathematical Model

Our model represented the HIV epidemic among the MSM population in Baltimore from 1984 (when the first local prevalence surveys were conducted) to 2017.[11] The modeled population was open and decreased over time (in line with Baltimore census data) and was divided into separate groups according to their age [18–24 year olds (younger), ≥25 year olds (older)] and race (black, white) (see Figure S1, Supplemental Digital Content, http://links.lww.com/QAI/B449). MSM entered the model at 18 years of age, or upon sexual debut if later, or through migration, and left through natural and HIV-related mortality or migration. Upon acquiring HIV, HIV+ MSM in the model entered a short acute stage of infection. After that, they were assigned to 1 of the 4 set point viral load (SPVL) categories (Log_{10} copies/mL <4.0, 4–4.5, 4.5–5, >5), which they retained for life independent of their CD4 count or treatment status (see Figure S2, Supplemental Digital Content, http://links.lww.com/QAI/B449).[24,25] Different subsequent stages of infection were represented by progression through different CD4 cell count categories (CD4 ≥500, 350–500, 200–350, <200 cells/μL) off ART. Those with higher SPVL progressed more rapidly through the CD4 categories.[24] HIV-related mortality was higher among HIV+ MSM with higher SPVL and lower CD4. HIV+ MSM were further divided into 8 different mutually exclusive modeled care states: (1) never testing (ie, who never undergo routine testing), (2) testing but without diagnosed infection (ie, undiagnosed but may undergo HIV testing), (3) with diagnosed infection but not in care, (4) in care but not on ART, (5) in early months on ART and adherent but partially suppressed, (6) on ART, adherent and fully suppressed, (7) on ART but not adherent (not suppressed), and (8) stopped taking ART (see Figure S3, Supplemental Digital Content, http://links.lww.com/QAI/B449). To analyze aggregated model outcomes by care stage, these groups were aggregated into: MSM with undiagnosed infection (1 + 2), with diagnosed infection but not on ART (including in care and not in care; 3 + 4 + 8), with diagnosed infection but not in care (3 + 8), and on ART (including those adherent and suppressed or not; 5 + 6 + 7) (see Figure S3, Supplemental Digital Content, http://links.lww.com/QAI/B449). Those on ART and suppressed had reduced HIV-related mortality.

In the model, HIV was transmitted through anal sex in main, casual, and commercial partnerships. The per-capita risk of HIV infection of uninfected individuals depended on the number of new main, casual, and commercial sexual partners they acquired every year, sexual mixing preferences between race/age groups, number of sex acts per partnership, and the proportion with condoms, HIV prevalence among

their partners, infection risk per sex act, circumcision levels, and their partner's likelihood of transmission (varying by infection stage, SPVL, and ART status). Higher transmission likelihood in the model was associated with the acute HIV stage, CD4 <200 cells/μL, and with higher SPVL, whereas lower transmission likelihood with condom use and partial or full suppression on ART (see Table S1, Supplemental Digital Content, http://links.lww.com/QAI/B449).

The model was expressed as a set of differential equations, solved numerically in C++ using a variable-stepsize eighth-order Runge–Kutta method.[26] The model equations and a fuller model description are provided in the Supplementary Information.

Model Parameterization and Calibration

The model was parameterized and fitted within a Bayesian framework allowing us to take into account uncertainty in the parameters and fitting data by defining prior ranges of parameter values and fitting outcomes, from Baltimore where possible, or from other US MSM studies otherwise (Tables S1 and S2, Supplemental Digital Content, http://links.lww.com/QAI/B449). The CDC's National HIV Behavioral Surveillance (NHBS) cross-sectional surveys conducted among MSM in Baltimore in 2004, 2008, and 2011[13,27] were used to inform sexual behaviour and condom use parameters, the relative HIV testing rate of each age/race group, and to estimate ranges for the proportion of MSM within these groups and their HIV prevalence over time, which the model is fitted to. Maryland Department of Health data for Baltimore City[3,28] were used to estimate fitting ranges for levels of linkage to care and viral suppression in each race group. The model was also fitted to CDC state-level data on HIV diagnosis levels (see Figure S6 and Table S2, Supplemental Digital Content, http://links.lww.com/QAI/B449), and ART coverage, using data from a Baltimore MSM NHBS substudy that tested stored sera for antiretrovirals. Overall HIV testing rates were varied to fit CDC diagnosis data (Supplementary Information, Supplemental Digital Content, http://links.lww.com/QAI/B449). Race-specific rates of linkage to and dropout from care, ART initiation, adherence, and dropout came from other US studies (Tables S1 and S2, Supplemental Digital Content, http://links.lww.com/QAI/B449).[29–33]

Main partners were committed partners (eg, husbands), casual partners were not committed to or not known very well, and commercial partners were those with whom money or drugs were exchanged for sex.[34] In line with NHBS data, the number of new casual and commercial partners in the model decreased linearly over time until 2011 (see Table S1 and Figure S4, Supplemental Digital Content, http://links.lww.com/QAI/B449, respectively), but the number of sex acts per casual or commercial partnership increased to maintain a constant proportion of recent sex acts with main, casual, and commercial partners, in agreement with NHBS data (see Figure S5 and Table S1, Supplemental Digital Content, http://links.lww.com/QAI/B449). Condom use increased over time until 2009, then plateaued, with around 61% of acts being condom-protected from 2010, but was higher among black MSM with their main partners, and during casual sex (see Figure S7, Supplemental Digital Content, http://links.lww.com/QAI/B449). Sexual mixing in the model was moderately assortative by age and strongly assortative by race as suggested by NHBS data. All sexual behaviour parameters remained at similar levels from 2011 to 2017 (see Figure S7 and Table S7, Supplemental Digital Content, http://links.lww.com/QAI/B449).

Biological parameters and intervention efficacies were derived from the published literature, where possible from MSM populations. Condom use was assumed to reduce the probability of transmission per sex act by between 58% and 79%,[35] and achieving full viral suppression on ART to reduce the per-sex-act transmission probability by 99%–100% (see Table S1, Supplemental Digital Content, http://links.lww.com/QAI/B449).[4] ART was introduced in the model in 1996 among HIV+ MSM, and changes in eligibility by CD4 count were informed by national ART guidelines (see Supplementary Information, Supplemental Digital Content, http://links.lww.com/QAI/B449). Because different data sources provided conflicting estimates of viral suppression levels, the model was fitted separately to data on ART coverage (from the NHBS sera study) and to Department of Health viral suppression data, while simultaneously fitting to all HIV prevalence, demography, and diagnosis data.

A Latin hypercube sample of the parameters was drawn from their prior ranges, and a total of 118 different parameter combinations (baseline "model fits") were found to produce outcomes falling within each of the fitting data uncertainty bounds described above and represented our baseline scenario. We report the median and 95% uncertainty interval (UI, 2.5 and 97.5th percentiles) of model outcomes across all 118 fits.

Estimating the Impact of Past Interventions

The fraction of HIV infections averted (averted fraction, AF_{t_0-t}, Equation 1) by interventions (condoms, ART, and both), defined over a period $[t_0, t]$, was derived by comparing the estimated cumulative number of incident HIV infections over the period $[t_0, t]$ ($CI_{t_0-t} = \int_{t_0}^{t}$ new HIV infections) in the baseline scenario with interventions ($CI_{t_0-t}(\text{intervention})$) with that from a counterfactual scenario without the intervention (condoms and/or ART) over the period $[t_0, t]$, ($CI_{t_0-t}(\text{no intervention})$).

$$AF_{t_0-t} = \frac{CI_{t_0-t}(\text{no intervention}) - CI_{t_0-t}(\text{intervention})}{CI_{t_0-t}(\text{no intervention})} \quad (1)$$

The counterfactual scenarios assumed zero efficacy in reducing the likelihood of HIV transmission (condoms and ART) and HIV-related mortality (ART). We evaluated the AF_{t_0-t}over 10-year periods between 1988 and 2017, and over longer periods 1984–2017, and 1996–2017 (since ART was first introduced).

Estimating the Sources of Acquisition of and Contribution to HIV

First, we derived the fraction of cumulative incident HIV infections that are acquired by different age and race groups over a period $[t_0, t]$. Second, we derived the HIVincidence $rate_{t_0-t}$ (per 100 susceptible person-years)—Equation 2—as the cumulative

number of incident infections occurring in a group over a period CI_{t_0-t} in the baseline scenario, divided by the cumulative number of person-years lived in the susceptible state over the same period.

$$\text{HIV incidence rate}_{t_0-t} = 100 \times \frac{CI_{t_0-t}}{\int_{t_0}^{t} \text{susceptibles}} \quad (2)$$

Third, we derived the transmission population attributable fraction (PAF_{t_0-t}) using Equation 3, which estimates the fraction of all new transmissions over [t_0, t] directly or indirectly contributed by the specific group or partnership type.

$$PAF_{t_0-t} = \frac{CI_{t_0-t}(\text{risk}) - CI_{t_0-t}(\text{no risk})}{CI_{t_0-t}(\text{risk})} \quad (3)$$

Here, $CI_{t_0-t}(\text{risk})$ and $CI_{t_0-t}(\text{no risk})$ are the cumulative number of HIV infections in the presence and absence of transmission from the relevant group or partnership type, respectively. $CI_{t_0-t}(\text{no risk})$ was derived by setting to 0 the HIV transmission probability from the group or partnership type over that period. The number of excess infections includes incident infections directly transmitted by individuals from the group (or partnership type) and secondary infections transmitted by those who have acquired these direct infections, which allows us to better capture the long-term contributions of different groups and partnerships to disease transmission.[36–38] Because the calculation takes into account (indirect) secondary transmissions that may overlap for different groups, the sum of the PAFs over all risks or mutually exclusive groups can exceed 100%.[37]

Finally, we derived the per-capita HIV incidence rate_{t_0-t} (per 100 infected person-years) (Equation 4) from a specific group by dividing the total number of excess infections over [t_0, t] by the cumulative number of person-years lived in the infected group over the same period.

$$\text{HIV transmission rate}_{t_0-t} = 100 \times \frac{CI_{t_0-t}(\text{risk}) - CI_{t_0-t}(\text{no risk})}{\int_{t_0}^{t} \text{infected(risk)}} \quad (4)$$

Fractions of cumulative incident infections acquired and HIV incidence rates were estimated for different age and race groups. PAF_{t_0-t} and transmission rates_{t_0-t} were estimated for different age and race groups, and for MSM in different infection and care continuum stages. Values of PAF_{t_0-t} for main, casual, and commercial partnerships were also estimated. They were evaluated over 10-year periods between 1988 and 2017 as well as over the entire period 1984–2017.

RESULTS

Fitting the HIV Epidemic Among MSM in Baltimore

The fitted model reflected the observed demographic and HIV epidemic characteristics of the MSM population (see Figure S6, Supplemental Digital Content, http://links.lww.com/QAI/B449). For example, the model projections captured the increasing proportion of black MSM reported in NHBS survey data (from 57% in 1984 to 76% in 2017), and the higher HIV prevalence among older black MSM in 2017 (51%) compared to younger black MSM (30%) and white MSM (older: 12%, younger: 4%). The estimated proportion of HIV+ MSM with diagnosed infection and HIV+ MSM on ART increased from 51% to 78%, and from 20% to 49% over 2000–2017, respectively (see Figure S6, Supplemental Digital Content, http://links.lww.com/QAI/B449).

Impact of Past Interventions

The model results suggest that over 1984–2017, condom use averted 19% (95% UI 14%–25%) of all incident HIV infections that would have occurred among MSM without any condom use (Fig. 1A, see Table S3, Supplemental Digital Content, http://links.lww.com/QAI/B449). The proportion of infections averted increased over time from 13% (6%–18%) over the decade 1988–1997 to 37% (29%–46%) over 2008–2017 (Fig. 1A), reflecting overall increases in condom use from ~18% to ~60% (see Figure S7, Supplemental Digital Content, http://links.lww.com/QAI/B449). In comparison, we estimated that ART averted 23% (15%–31%) of all incident infections that would have occurred without it over 1996–2017. The averted fraction also increased over time as the coverage of ART increased, reaching 36% (26%–46%) over 2008–2017 (Fig. 1B). Condoms and ART combined may have averted 36% (29%–43%) of all incident infections since 1996, and 54% (43%–64%) over 2008–2017 (Fig. 1C, see Table S3, Supplemental Digital Content, http://links.lww.com/QAI/B449).

Sources of HIV Acquisition

We estimated that black MSM are disproportionately affected by HIV, representing 75% of the MSM population in 2008–2017 (see Table S4, Supplemental Digital Content, http://links.lww.com/QAI/B449), and acquiring 93% (90%–96%) of all new HIV infections (Fig. 2A, see Table S5, Supplemental Digital Content, http://links.lww.com/QAI/B449). Older MSM, who constituted 73% of the MSM population between 2008 and 2017 (see Table S4, Supplemental Digital Content, http://links.lww.com/QAI/B449), acquired 54% (48%–59%) of HIV infections (Fig. 2B, see Table S5, Supplemental Digital Content, http://links.lww.com/QAI/B449). The fractions of incident infections acquired by black MSM and younger MSM populations have increased over time due to relative population size increases (Table 1, see Table S4, Supplemental Digital Content, http://links.lww.com/QAI/B449). We also estimated that HIV incidence rates among black MSM over the period 2008–2017 were 8 times higher than among white MSM, and were 1.7-fold higher among younger MSM than older MSM over the same period (Table 1).

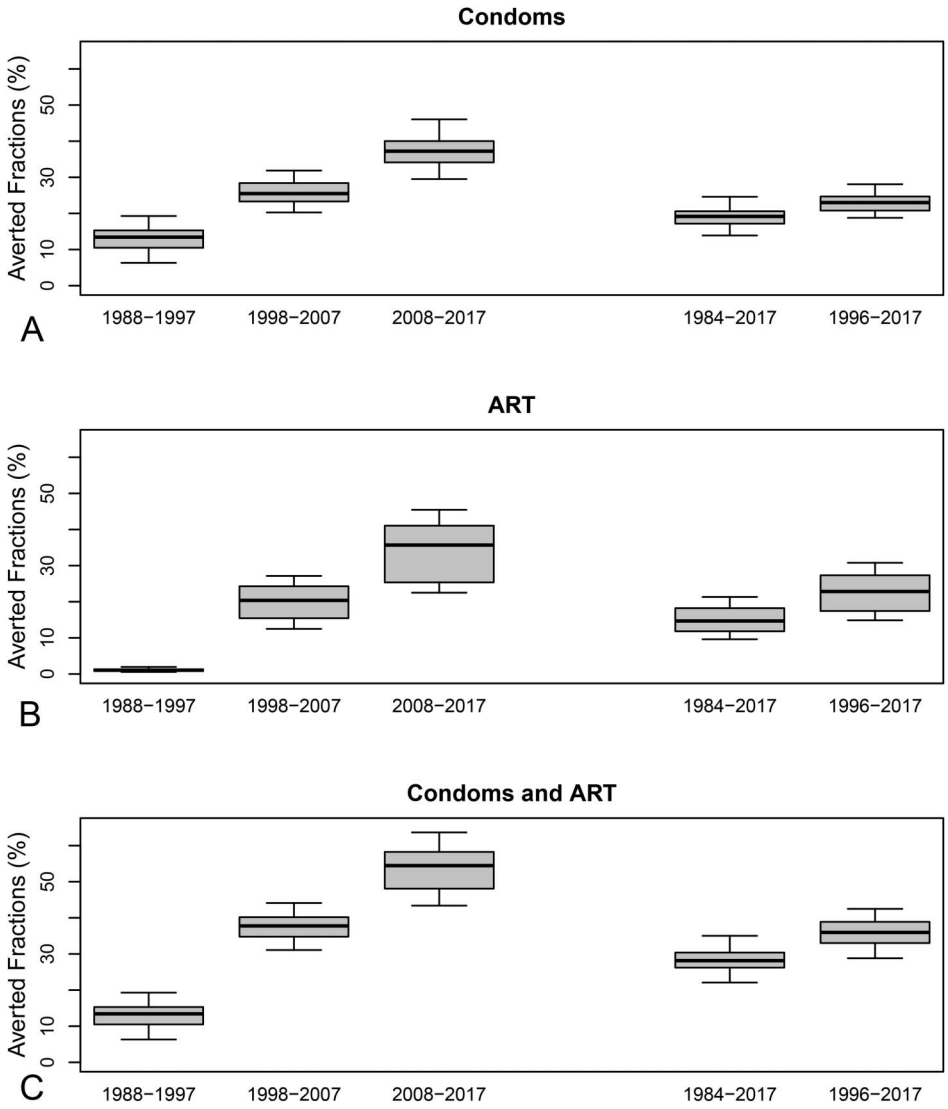

FIGURE 1. Fraction of incident HIV infections averted by the use of interventions against HIV. Estimated fractions of HIV infections averted by the use of (A) condoms, (B) ART, and (C) both, for successive 10-year periods (AF_{t_0-t}) and over the total period since their introduction. The thick bar represents the median, the box represents the interquartile range (25th–75th percentiles) of model estimates, and whiskers represent 95% UI of model estimates (2.5th–97.5th percentiles) across all 118 model fits.

Contributions to HIV Transmission

Demography

Our model results suggest that over 2008–2017, black MSM and older MSM directly or indirectly contributed to the greatest number of HIV transmissions, with $PAF_{2008–2017}$ of 97% (95%–98%) and 75% (67%–81%), respectively, compared with 4% (2%–6%) for white and 35% (27%–49%) for younger MSM (note that the PAFs take into account secondary transmissions, which can overlap for different groups; Fig. 2, see Table S5, Supplemental Digital Content, http://links.lww.com/QAI/B449), reflecting the higher HIV prevalence and larger population size of these groups. Similarly to HIV acquisition, the PAF for black MSM increased slightly over time, whereas the PAF for older MSM was slightly lower during 1998–2007 than during 1988–1997, and then increased again. However, we estimated that the per-capita transmission rate (expressed per 100 infected person-years) for younger MSM was twice that of older MSM (12.7 vs 6.2, Table 1), and also twice as high for black HIV+ MSM as for white MSM (7.0 vs 3.3), reflecting the reported higher sexual activity and lower ART coverage of younger and black MSM in Baltimore (see Table S1, Supplemental Digital Content, http://links.lww.com/QAI/B449).

Types of Partnerships

Around half of HIV transmissions were contributed by main partnerships, with $PAF_{2008–2017}$ estimated at 55% (48%–63%), compared to 44% (35%–55%) and 16% (10%–26%) for casual and commercial partnerships, respectively (Fig. 3 and see Table S5, Supplemental Digital Content, http://links.lww.com/QAI/B449); main, casual, and commercial partners accounted for 22%, 56%, and 22% of all new partners, respectively. The estimated proportion of transmissions contributed by the different partnership types remained stable over time, reflecting stability in NHBS data in the proportion of recent sex acts reported to be with different partner types.

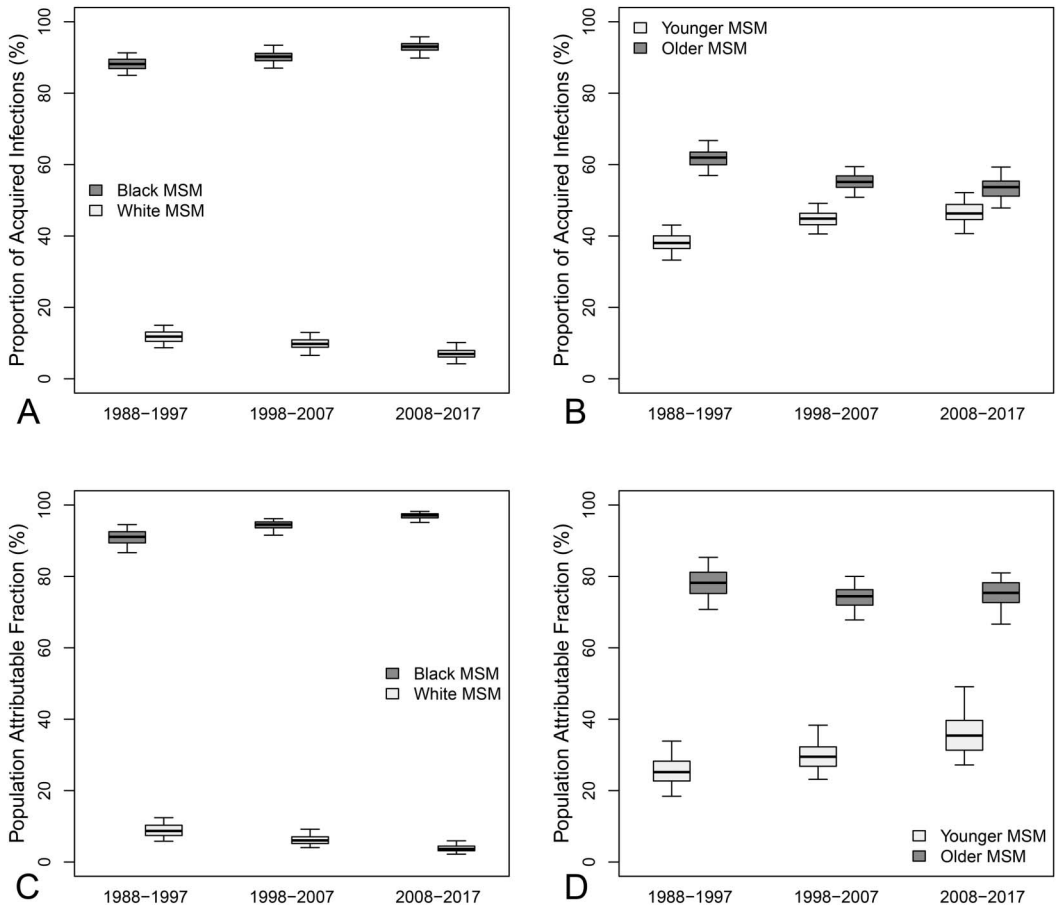

FIGURE 2. Sources of HIV acquisition and transmission by demographic characteristics: Estimated fractions of cumulative incident HIV infections occurring over successive 10-year periods that were acquired by (A) black (dark gray boxes) and white (light gray boxes) MSM, and (B) younger (18–24 year old; light gray boxes) and older (25+ year old; dark gray boxes) MSM. Estimated PAF calculated over successive 10-year periods and over 1984–2017 for (C) black (dark gray boxes) and white (light gray boxes) MSM, and (D) younger (light gray boxes) and older (dark gray boxes) MSMs. Thick bar represents the median, the box represents the 25th and 75th percentiles of model estimates, and whiskers represent 95% UI of model estimates (2.5th and 97.5th percentiles) across all 118 model fits.

Stages of Infection of Untreated Individuals

We estimated that untreated HIV+ MSM (with infection, diagnosed or not) directly or indirectly contributed to almost 90% of the HIV transmissions occurring over 2008–2017 (Table 1). Most transmissions were contributed by untreated MSM with CD4 <200 cells/μL, with $PAF_{2008–2017}$ of 40% (24%–56%), and CD4 200–350 cells/μL, with $PAF_{2008–2017}$ of 21% (14%–32%). The HIV transmission rate was highest among acutely infected untreated MSM (per-capita rate of 54 per 100 infected person-years), who were estimated to have contributed to 20% (8%–35%) of transmissions over 2008–2017, despite representing only 2% (1%–3%) of HIV+ MSM (Table 1, see Table S5–6, Supplemental Digital Content, http://links.lww.com/QAI/B449).

The estimated contribution of the different SPVL level categories has remained fairly constant over time (see Table S5, Supplemental Digital Content, http://links.lww.com/QAI/B449). Untreated HIV+ MSM with $\log_{10}$ 4.5–5 viral copies/mL were always the largest contributor, with $PAF_{2008–2017}$ of 33% (23%–44%). The small group of untreated MSM with high viral load (SPVL $>\log_{10}$ 5.0 copies/mL) had higher HIV transmission rates than those with lower viral load, but made a smaller contribution to overall transmission, with $PAF_{2008–2017}$ = 21% (11%–31%).

Care Continuum Stages

MSM with diagnosed HIV infection might have contributed more to transmissions than MSM with undiagnosed infection since the early 2000s (Fig. 4 and see Table S5, Supplemental Digital Content, http://links.lww.com/QAI/B449), despite their HIV transmission rate being lower, because they comprised an increasingly larger fraction of the HIV+ MSM population. The PAF of MSM with undiagnosed infection declined from 90% (67%–98%) over 1988–1997 to 41% (31%–54%) over 2008–2017 (Fig. 4), whereas the PAF of MSM with diagnosed infection increased, from 13% (3%–34%) over 1988–1997 to 80% (71%–87%)

TABLE 1. HIV Incidence and Transmission Rates Among MSM Residing in Baltimore Over 2008–2017, by Demography and Care Status, Median and 95% UI Across all 118 Model Fits

	HIV Incidence Rate (per 100 Susceptible Person-Years)	HIV Transmission Rate (per 100 Infected Person-Years)
Demography		
Black	6.4 (5.0–8.2)	7.0 (5.85–8.23)
White	0.8 (0.5–1.3)	3.3 (2.11–4.87)
Younger	6.2 (5.1–8.9)	12.7 (10.5–16.0)
Older	3.6 (2.6–4.6)	6.2 (4.9–7.43)
Black younger	8.1 (6.6–10.9)	13.0 (10.8–16.4)
Black older	5.6 (3.7–7.2)	6.5 (5.1–7.8)
White younger	0.9 (0.4–1.7)	5.7 (3.0–9.3)
White older	0.8 (0.5–1.3)	3.2 (2.0–4.8)
Care status		
With undiagnosed infection	na	12.1 (9.6–15.5)
With diagnosed infection	na	7.0 (5.2–8.7)
Untreated (not on ART)	na	10.3 (8.7–11.9)
Treated (on ART)	na	2.4 (1.3–3.4)
With diagnosed infection and untreated	na	12.1 (10.2–14.5)
With diagnosed infection but not in care	na	12.6 (10.2–15.7)
In care but not on ART	na	10.5 (8.4–13.2)

over 2008–2017, when MSM with diagnosed infection represented 13% (4%–32%) and 78% (74%–80%) of HIV+ MSM, respectively (see Tables S5–S6, Supplemental Digital Content, http://links.lww.com/QAI/B449) [the sum of the PAFs exceeds 100% because PAFs take into account secondary transmissions (see methods and Ref. 37)]. In the past decade, most of the transmissions from MSM with diagnosed infection were contributed by HIV+ MSM not on ART [$PAF_{2008–2017}$ = 64% (44%–74%)] (Fig. 4).

Around half of the transmissions over the last decade may have been contributed by HIV+ MSM that were not in care despite their infection being already diagnosed [$PAF_{2008–2017}$ = 46% (24%–56%)] (Fig. 4B and see Table S5, Supplemental Digital Content, http://links.lww.com/QAI/B449), whereas MSM in care but not on ART contributed to 18% (10%–25%) of transmissions (Fig. 4B). As expected, MSM on ART modestly contributed to transmissions: 14% (7%–28%) over 2008–2017, while representing 49% (30%–56%) of all HIV+ MSM (see Figure S8, Supplemental Digital Content, http://links.lww.com/QAI/B449). Among them, those adhering to ART and partially or fully suppressed contributed to few transmissions [$PAF_{2008–2017}$ = 2.5% (1%–5%)], despite comprising 42% (25%–50%) of HIV+ MSM (not shown). The per-capita HIV transmission rate for MSM with diagnosed infection was around half that of MSM with undiagnosed infection (7 vs 12 per 100 infected person-years), but around 3 times as high as for HIV+ MSM on ART (2.4, Table 1).

DISCUSSION

We investigated the acquisition and contribution to transmission of HIV to and by partnership types and for MSM in different demographic groups, and HIV infection and care continuum stages over time among the Baltimore MSM population, and estimated the impact of past and ongoing HIV interventions. We estimated that high levels of HIV incidence in this population are maintained by high prevalence of unprotected sex with virally unsuppressed partners, with many new transmissions contributed by MSM not on ART despite their infection being diagnosed.

We estimated that due to initially low levels of use, past condom and ART use have had a modest population-level impact, together preventing about a third of all HIV infections that would have otherwise occurred since 1996, and half over 2008–2017. This relatively low preventative impact was mainly due to most HIV infections occurring early on, when condom use was extremely low (vs ~61% currently). The estimated population-level impact of condom use and ART has increased over time, reflecting improved intervention coverage over time. The impact of condom use estimated in this study was much lower than predicted by a UK MSM modeling study[22] (where cessation of all condom use resulted in a 424% increase in incidence),

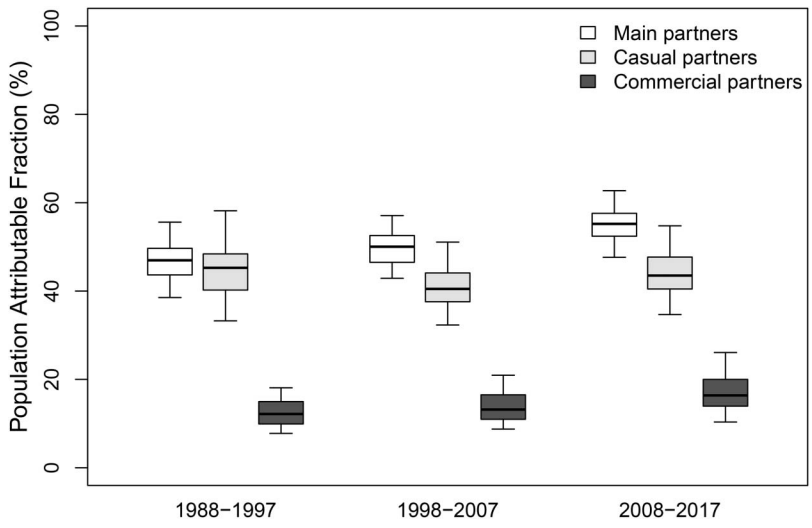

FIGURE 3. Sources of HIV transmission by partnership characteristics. PAF estimates for main (white boxes), casual (light gray boxes), and commercial (dark gray boxes) partnerships, calculated over 10-year periods. Thick bar represents the median, and the box represents the 25th and 75th percentiles of model estimates, and whiskers represent 95% UI of model estimates (2.5th and 97.5th percentiles) across all 118 model fits.

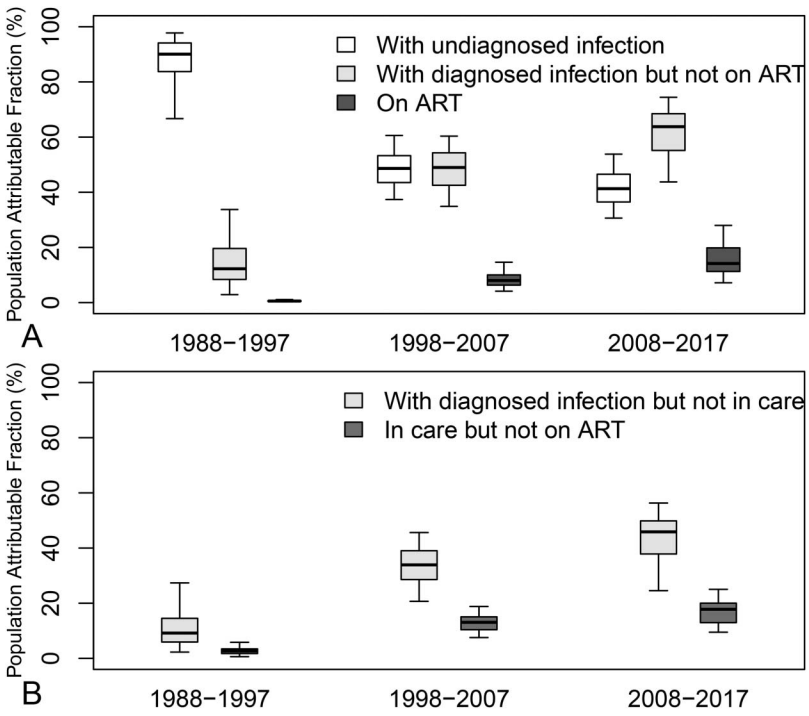

FIGURE 4. Sources of HIV transmission by care continuum characteristics. PAF estimates for (A) MSM with undiagnosed infection (white boxes), with diagnosed infection but not on ART (light gray boxes), on ART (dark gray boxes) MSM living in Baltimore; (B) MSM who have diagnosed infection but are not on ART: not in care (light gray boxes) and in care but not on ART (dark gray boxes), calculated over 10-year periods. Thick bar represents the median, the box represents the 25th and 75th percentiles of model estimates, and whiskers represent 95% UI of model estimates across all 118 model fits.

which however assumed perfect protection compared to partial protection in our analysis.[35]

Our model results suggest that the HIV transmission rate among younger MSM (18–24 years old) was twice as high as older MSM. Despite this, older MSM are estimated to consistently acquire and contribute more to HIV infections due to their large population size and higher HIV prevalence. The higher per-capita contribution of younger MSM may be explained by the fact that they report more partners than older MSM. We found that black MSM were particularly vulnerable to HIV, with higher incidence and greater total numbers of HIV infections acquired and contributed, mainly due to their larger population size and higher HIV prevalence, but also their lower ART coverage, and greater annual number of new sexual partners (reported in 2008–2014 Baltimore NHBS data, contrasting with other US studies finding fewer sexual partners reported by black vs white MSM[15,39–41]).

Our results highlight progress and gaps in the HIV care continuum. MSM with diagnosed infection in Baltimore have contributed to more than 3 quarters of HIV transmissions over 2008–2017, with almost half of the transmissions contributed by MSM with diagnosed infection but not in care. These findings are consistent with CDC model estimates where 62% and 38% of all HIV transmissions occurring in the United States in 2016 were generated by individuals aware and unaware of their HIV status, respectively.[42] However, they contrast with higher model estimates for the contribution of MSM with undiagnosed infection in the United Kingdom (63%[21] and 82%[22]), probably reflecting higher levels of treatment among MSM with diagnosed infection in the United Kingdom (>90%) than Baltimore (~69%).[21,43]

Notably, more than half of the HIV transmissions were estimated to be contributed by main partnerships (55% over 2008–2017), which qualitatively agrees with previous studies.[7,8,21,23] One study estimated a larger proportion (68%) of new HIV infections among MSM in 5 US cities in 2005 occurring within main partnerships, whereas another estimated the same proportion in the late 2000s to be between 35% and 40%.[8] Differences between these studies in assumptions about the duration and frequency of sex acts within these partnerships probably explain the heterogeneity in study estimates. Commercial partnerships seemed to play a non-negligible role in HIV transmissions among Baltimore MSM, reflecting the high prevalence of commercial sex partners reported by this population in NHBS surveys.[34]

The contribution to transmission by acutely infected MSM did not increase over time in our analysis because the size of this group decreased over time with decreasing incidence, while individuals in other disease stages accessed treatment. Our estimates are in line with estimates of 10%–20% obtained from studies of MSM in other developed countries.[21,44,45] Also, a modeling study of US and Peruvian MSM provided estimates ranging from 5% to 29%.[8] However, other studies using complex individual-based models or HIV sequence data suggested substantially larger contributions of up to 50%,[22,46] but some of these studies also assumed a longer acute stage duration, or higher transmissibility.

The data on which our model relies were taken from Baltimore MSM populations wherever possible. However, our estimates might be less accurate before 2004 because few input parameters and data points were available during this period. This also means that our estimates over the full period 1984–2017 may be less accurate due to the sparse data before 2004. For simplicity and due to limited sample sizes, only (self-reported) black and white MSM were modeled because these groups comprise 90% of the MSM population included

within the NHBS surveys of Baltimore MSM[6]; as such, we might slightly overestimate the proportions of incident HIV infections acquired and contributed by these 2 race groups.[47] The NHBS venue sampling protocol may not be fully reflective of the general population of MSM in Baltimore because it misses MSM who rarely or never attend MSM-associated venues. Importantly, data on the number of sex acts within all partnerships, and condom use within commercial partnerships, were scarce,[23] highlighting critical data gaps. Thus, our model may overestimate or underestimate their contribution. Also, our model did not reflect further heterogeneity in sexual risk behaviour within race/age groups, such as MSM engaging in commercial sex. We model only sexual transmission and as a result do not account for alternative routes of infection such as injection drug use and might slightly overestimate PAFs and AFs; in Baltimore, 14% of reported HIV+ MSM are identified as persons who inject drugs.[28] Finally, although PrEP, which has started to be used in this population, is not included in the model, this is not expected to greatly affect our estimates because only 2.8% of MSM in Baltimore reported any PrEP use in the 2014 NHBS survey (12% in 2017).[18] A strength of our study is that we were able to model a population that is extremely burdened by HIV, while matching a large variety of empirical descriptions of local population demography, sexual behaviours, and care continuum engagement.

Our results suggest that in Baltimore, health authorities should continue working with black MSM communities to offer prevention services that meet the needs of black MSM and the context of their lives. Compared to black MSM in nearby cities, black MSM in Baltimore were more likely to have experienced homelessness, unemployment, incarceration, and exchange sex.[48] These and other socioeconomic, structural, and epidemiological factors create barriers and competing priorities to HIV prevention. To be successful, HIV prevention efforts must address the complex lived experiences of the people they serve. For black MSM, who face compounded discrimination and disadvantage from racial and sexual minority status, it is especially important that prevention efforts are empowering, affirming, and accessible.[48]

Similarly, continuing to invest in and expand interventions[48] that increase the proportion of MSM living with HIV who are in care would be extremely beneficial because our analysis suggests that MSM living with HIV, with both diagnosed or undiagnosed infection, but not in care contributed to the majority of transmissions in Baltimore during the past 10 years. Such efforts could include expanded HIV testing, telemedicine, better integrating mental health and social services, or using more intensive case-management approaches. The Baltimore city health department has been identified as one of the early recipients of the CDC End the HIV Epidemic Strategy funding,[49] which will further facilitate the expansion of these and other interventions. A better understanding of barriers to HIV testing, linkage to care, and retention in care among MSM along with novel interventions that address those barriers may be needed to achieve HIV prevention goals.

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