


## ORIGINAL RESEARCH

# Modelling the impact of an HIV testing intervention on HIV transmission among men who have sex with men in China

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### Objectives

An intervention developed through participatory crowdsourcing methods increased HIV self-testing among men who have sex with men [MSM; relative risk (RR) = 1.89]. We estimated the long-term impact of this intervention on HIV transmission among MSM in four cities (Guangzhou, Shenzhen, Jinan and Qingdao).

### Methods

A mathematical model of HIV transmission, testing and treatment among MSM in China was parameterized using city-level demographic and sexual behaviour data and calibrated to HIV prevalence, diagnosis and antiretroviral therapy (ART) coverage data. The model was used to project the HIV infections averted over 20 years (2016–2036) from the intervention to increase self-testing, compared with current testing rates.

### Results

Running the intervention once would avert < 2.2% infections over 20 years. Repeating the intervention (RR = 1.89) annually would avert 6.4–10.7% of new infections, while further increases in the self-testing rate (hypothetical RR = 3) would avert 11.7–20.7% of new infections.

### Conclusions

Repeated annual interventions would give a three- to seven-fold increase in long-term impact compared with a one-off intervention. Other interventions will be needed to more effectively reduce the HIV burden in this population.

**Keywords:** crowdsourcing, HIV, MSM, self-testing intervention

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## Introduction

Men who have sex with men (MSM) account for over a quarter of newly diagnosed people living with HIV in China (25.5% in 2017 [1]) and have high HIV prevalence (8% in 2015) [2]. Testing rates among MSM living with HIV in China remain low (54% ever tested; 2017) [3],

reducing the potential impact of HIV treatment as prevention (TasP) for MSM, due to low awareness of serostatus and reduced linkage to HIV treatment. HIV self-testing in China has been shown to reach higher-risk MSM who do not access facility-based services, but testing rates remain low (29% ever self-testing; 2015) [4]. Recent policy changes in China have resulted in increases in antiretroviral therapy (ART) coverage among those living with HIV (from 67% of HIV-diagnosed individuals on ART in 2015 to 80% in 2017) [5,6], with similar increases in MSM [7,8].

One potential way to enhance HIV-testing services uses crowdsourcing. Crowdsourcing is the process of assigning

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and engaging groups of individuals to solve a problem together and share the solutions they find with the public [9]. It can be used within public health settings as a tool to help develop novel approaches and can increase community engagement from populations not typically reached by established intervention strategies [10,11]. There are examples of municipalities and public health organizations that have made a commitment to repeated annual HIV crowdsourcing open calls [12], which have been demonstrated to be sustainable and shown to contribute to community engagement [13]. When compared with conventional methods for developing public health messages, several studies have shown that crowdsourcing approaches save money [14–16].

A large-scale intervention designed to increase HIV testing among MSM was developed using crowdsourcing methods (national image and local message contests, and regional strategy designathons) [17]. This resulted in an intervention which included local testing promotion campaigns and an online HIV self-testing service, tailored for MSM [18]. This intervention was evaluated using a stepped wedge, randomized controlled trial conducted in eight cities in China from August 2016 to August 2017 [18]. In all, 1381 HIV-status-unknown or HIV-negative MSM who had not tested for HIV in the past 3 months were recruited through Blued, a large gay mobile dating application, and subsequently completed quarterly follow-up surveys to evaluate their uptake of HIV testing [17]. The trial found an increase in HIV self-testing among those receiving the intervention [relative risk (RR)= 1.89, 95% confidence interval (CI): 1.50–2.38], with no effect on facility-based HIV testing (RR = 1.00, 95% CI: 0.79–1.26) or condom use (RR = 1.00, 95% CI: 0.86–1.17) [18]. The intervention was delivered for a 3-month period in each city, and the increase in HIV self-testing was found to persist among MSM during the 12 months of follow-up [18].

Previous studies evaluating the long-term impact of HIV self-testing are rare [19]. A mathematical model of community-based HIV self-testing was used in the context of the HIV epidemic in sub-Saharan Africa [20] to show that targeting specific groups (adult men) achieved significant impact on new HIV infections (1500 averted per year) and HIV-related deaths (520 averted per year), in a population of nine million adults. In a different mathematical modelling study, home HIV testing/counselling in combination with increasing viral suppression to 48% in KwaZulu-Natal, South Africa, was shown to reduce HIV incidence by 40.6% over 10 years [21]. To our knowledge, there are no mathematical modelling studies that assess the potential impact of implementing a self-testing HIV intervention outside of sub-Saharan Africa, or among MSM.

HIV-testing promotion campaigns often show immediate but transient effects, with a tapering effectiveness over longer time periods [22]. Crowdsourced HIV contests or annual open calls are used to inform HIV programmes, leading to robust community engagement [12]. This study aims to quantify the relative effectiveness of a single one-off HIV-testing intervention and a series of annual repeated interventions. The trial demonstrated that crowdsourcing methods are an effective tool for increasing HIV self-testing rates among MSM in China [18]. However, the subsequent impact on HIV transmission was not measured [17]. This study uses mathematical modelling to estimate the impact on HIV incidence among MSM of implementing the crowdsourced intervention in four cities in China. The four cities we study were the largest cities in the randomized controlled trial – Guangzhou, Shenzhen, Jinan and Qingdao – which were also chosen for their availability of high-quality data and higher frequency of in-person events during the trial.

## Methods

We built a deterministic compartmental model of ordinary differential equations (ODEs) to describe HIV transmission amongst MSM in four cities in China (schematic in supplement; Fig. S1). The model divides MSM into uninfected and five HIV-positive infection stages (acute,  $CD4 > 500$ ,  $CD4 \ 351\text{--}500$ ,  $CD4 \ 200\text{--}350$ ,  $CD4 < 200$  cells/ $\mu\text{L}$ ) and five separate states of engagement with HIV care and treatment (undiagnosed and never tested, undiagnosed and ever tested, diagnosed via self-test but not on ART, diagnosed via facility test but not on ART, on ART), existing for all  $CD4$  classes. MSM living with HIV have increased infectiousness in the acute [23] and  $CD4 < 200$  cells/ $\mu\text{L}$  stages [24,25], and reduced infectiousness on ART [5,26].

We further divide MSM into three groups according to the role taken in anal sex with men: always insertive, always receptive, and versatile (insertive and receptive). We also categorize MSM into two risk groups according to the number of male anal sex partners in the last 3 months (low-risk: two or fewer; high-risk: three or more). New MSM join the modelled sexually active uninfected MSM population on sexual debut. HIV transmission between MSM occurs via anal sex, which is dependent on role behaviour [27–29], total partners [18] (and their respective ART status, viral suppression, disease stage and infectiousness), number of anal sex acts (with efficacy and use of condom data [30]). See the supplementary information for further description of the model structure, model schematic (Fig. S1), HIV transmission, model equations and sexual mixing (Fig. S2).

## Model calibration

We found estimates of seven metrics to calibrate our model to: city-level HIV prevalence (up to 12 estimates per city) [31–34] (CDC), incidence (one estimate) [35,36], MSM population size (two estimates) [37,38] (CDC), percentage of MSM in each risk and role group in 2016 [18], HIV prevalence by role group (two estimates in Shenzhen, one in Guangzhou) [34,39,40], national estimates of the proportion of diagnosed MSM on ART (six data estimates) [5,41], and provincial estimates (from Shandong only) of the total percentage of MSM living with HIV who were diagnosed in 2013 [42]. A summary of these data is included in Table 1 and in the supplementary information (model calibration).

We ran the model using one million different parameter combinations in turn. We then selected those runs which fell within fitting bounds for levels of diagnosis and MSM population size and calculated log-likelihoods for each available data point for the other fitting metrics (HIV prevalence, incidence, percentage in each risk group, percentage in each role group, HIV prevalence by role). We summed these log-likelihoods across each data point and selected the 100 model runs with the largest combined likelihood as our model fits.

## Intervention impact

The model fits were used to estimate the impact of each intervention in comparison to a base case – the ‘standard of care’ scenario, which assumes that all parameters in the model remain at their original values in 2016, including testing rates and ART initiation. For the intervention and standard-of-care scenarios, we projected the long-term epidemic trajectory from 1990 to 2036, with the interventions starting in 2016.

We simulated the following interventions for each city (upscaled to all MSM in each city who have not been tested in the past 3 months):

### Interventions

- A One-off crowdsourced intervention which increased self-testing ( $RR = 1.89$ ) for a period of 1 year, with self-testing rates subsequently returning to their pre-intervention values.
- B Annual repeated crowdsourced intervention which increased self-testing ( $RR = 1.89$ ) for a period of 20 years. This effect over time is hypothetical but is chosen to show the potential impact of sustained annual repeated crowdsourcing activities (as conducted in other settings [12,13]).

- C Annual repeated crowdsourced intervention with hypothetical higher impact on self-testing ( $RR = 3.00$ ) for a period of 20 years. This hypothetical scenario is chosen to show the potential impact of a more effective intervention.
- D Annual repeated crowdsourced intervention which increased self-testing ( $RR = 1.89$ ) for a period of 20 years, alongside a hypothetical intervention that doubles the rate of ART initiation among diagnosed MSM from 2016 onwards (resulting in the percentage of MSM initiating treatment in the last 6 months increasing from 17–41% to 31–65%). The counterfactual scenario for this intervention was a standard-of-care scenario with doubled ART initiation rates from 2016 onwards, but no increase in self-testing.

Scenarios A, B and C assume that rates of ART initiation remain constant from 2016 onwards, with 17–41% of MSM initiating treatment over 6 months.

## Measuring impact

We measure the impact of each intervention scenario (A–D) using the total projected number and percentage of infections averted among MSM in each city compared with the current standard of care.

## Results

### Model fits

For the selected 100 model fits for each city, the model outputs agreed well with the data on HIV prevalence, percentage diagnosed, percentage on ART, population size, percentage in each risk and role group, and HIV prevalence by role, but underestimated the HIV incidence rate (Fig. 1 and Fig. S8). The discrepancy between the HIV incidence estimates and the model may be due to the incidence estimates coming from different cohorts of MSM. The best fits underestimated ART coverage early on (2005–2006) but captured more recent levels (Fig. 1). The full prior and posterior parameter ranges can be found in Table S1 and Figs S9–S12.

### Standard of care (no intervention)

Figure 1 shows the expected prevalence trends under the standard-of-care (no intervention) scenario. The model projects that HIV prevalence among MSM peaked around 2015, before declining due to earlier increases in testing, ART eligibility and viral suppression (or remaining constant in Qingdao – due to lower condom use, self-testing

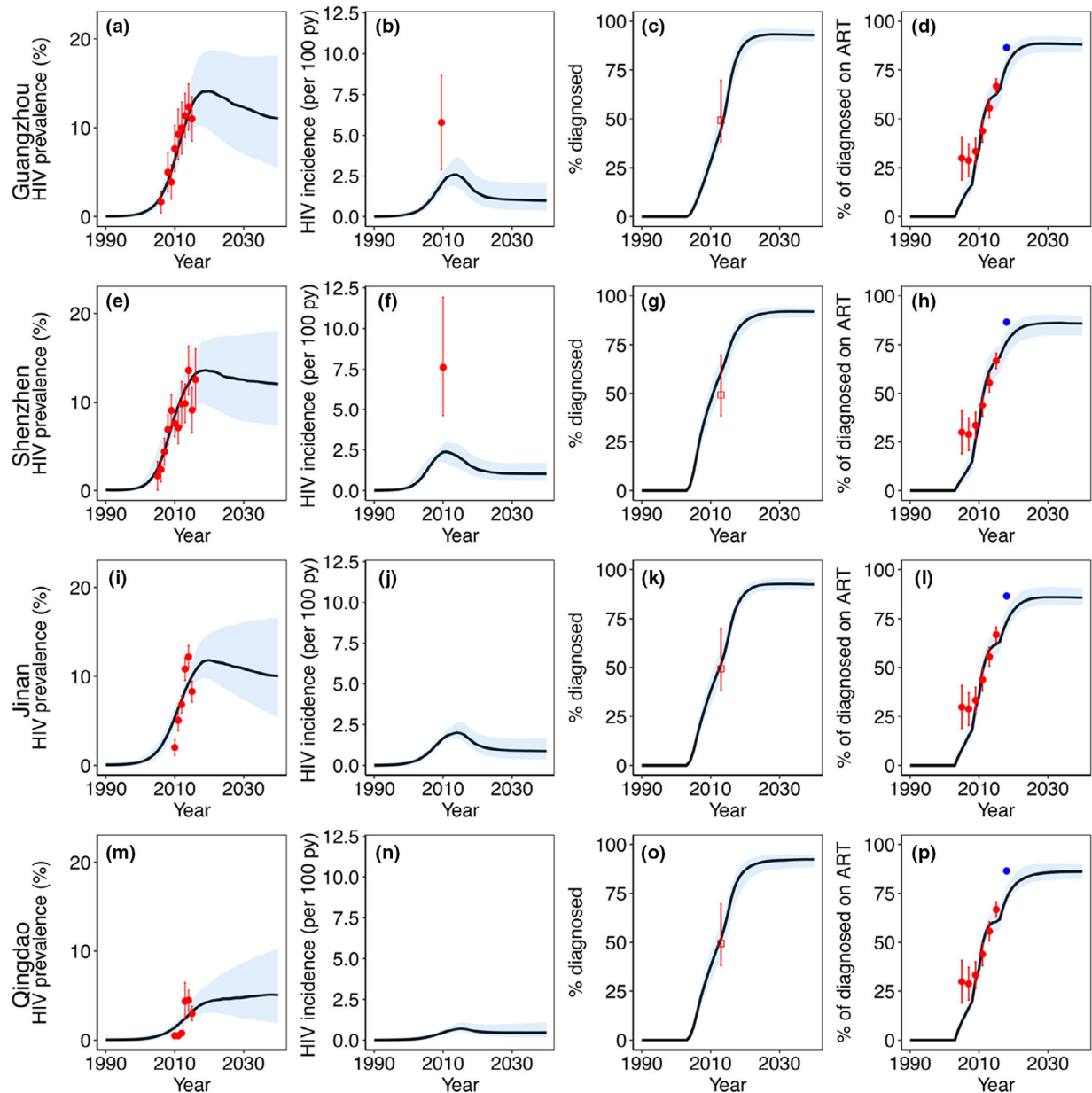
**Table 1** Key parameters (a) and fitting metrics (b) used in the model (summary of 95% confidence interval uncertainty ranges) for Guangzhou, Shenzhen, Jinan and Qingdao cities

Parameters	Guangzhou	Shenzhen	Jinan	Qingdao	Source
<b>(a) Sexual behaviour parameters</b>					
Average number of partners per year					
Low risk, always insertive	1.6–2.6	1.6–2.6	1.3–2.2	1.6–2.7	Baseline trial data [13]
Low risk, versatile	1.4–2.1	1.6–2.3	1.4–2.2	1.5–2.2	Baseline trial data [13]
Low risk, always receptive	1.2–2.2	1.2–2.3	1.4–2.5	1.7–2.8	Baseline trial data [13]
High risk, always insertive	11.8–18.9	14.6–22.4	3.6–22.4	12.3–24.0	Baseline trial data [13]
High risk, versatile	12.4–19.9	12.5–20.8	9.3–19.5	12.6–22.9	Baseline trial data [13]
High risk, always receptive	11.2–19.9	10.0–27.2	7.6–20.7	10.7–23.9	Baseline trial data [13]
Anal sex acts per MSM partnership per year (assumed same for all cities)					
Low risk			17–22		Baseline trial data [13]
High risk			11–16		Baseline trial data [13]
Percentage of sex acts in which a condom is used					
Low risk	64–81	68–83	64–80	67–82	Baseline trial data [13]
High risk	73–92	67–89	61–88	60–87	Baseline trial data [13]
<b>(b) Intervention parameters</b>					
Initial rate of facility-based testing per year	0.1–0.2 (2005)	0.4–0.6 (2006)	0.3–0.4 (mid 2005)	0.3–0.4 (2006)	City-level estimates [24–28]
Annual testing rates					
First self-test, low risk	0.14–0.30	0.07–0.15	0.19–0.23	0.10–0.30	Baseline trial data [13]
First facility test, low risk	0.10–0.20				Baseline trial data [13]
Self-test if not tested last 3 months	0.1–0.2	0.1–0.2	0.1–0.3	0.2–0.4	Baseline trial data [13]
Self-test, if tested in last 3 months	0.7–1.4	0.7–1.2	0.7–1.4	0.6–0.9	Baseline trial data [13]
Overall facility testing	0.5–0.6				Baseline trial data [13]
Relative risk ratio for testing among high-risk MSM vs. low-risk MSM					
Self-testing	1.1–1.5				Baseline trial data [13]
Facility testing	1.2–1.5				Baseline trial data [13]
Rate of dropout from ART per year	0.02–0.04				National and Guangdong [23,32]
<b>(c) Fitting metrics</b>					
Size of MSM population at two time points	12 249–49 698 (2008) 38 570–57 856 (2011)*	45 801–107 082 (2006)* 120 000–180 000 (2016)*	9687–19 373 (2009) 12 676–18 830 (2017)	29 300–46 200 (2016) 28 000–51 000 (2018)	[42,43], Shenzhen CDC 2016 [48], Shandong CDC 2019
HIV prevalence (%; 95% CI)					
2005	ND	0.0–3.3	ND	ND	SZ CDC
2006	0.4–2.9	1.0–3.8	ND	ND	GZ, SZ CDC, [36]
2007	ND	2.9–5.9	ND	ND	SZ CDC
2008	2.3–7.2	5.2–8.5	ND	ND	GZ, SZ CDC [37]
2009	2.0–5.8	7.2–10.9	ND	ND	GZ, SZ CDC [37]
2010	5.0–10.2	6.1–9.0	1.2–2.9	0.0–1.2	GZ, SZ, SD CDC [37]
2011	6.4–12.1	5.3–8.9	3.9–6.2	0.0–1.2	GZ, SZ, SD CDC [37,39]
2012	7.0–12.9	7.2–12.4	5.9–7.8	0.0–1.6	GZ, SZ, SD CDC [37,39]
2013	8.9–13.8	7.6–12.1	9.5–12.1	2.3–6.5	GZ, SZ, SD CDC [37,39]
2014	9.7–14.9	10.9–16.4	10.9–13.5	3.3–5.6	GZ, SZ, SD CDC [38,39]
2015	8.5–13.5	6.5–11.6	7.1–9.5	2.2–3.8	GZ, SZ, SD CDC [38,39]
2016	ND	9.1–16.0	ND	ND	SZ CDC, [39]
HIV incidence rate (per 100 person-years)	2.9–8.7 (2009.5)	4.6–11.9 (2010)	ND	ND	[40,41]
Percentage of infected MSM diagnosed, 2013	38–70				Shandong province estimate [35]
Percentage of diagnosed MSM on ART					
2005	18.9–40.8				National estimate [5]
2007	20.5–37.1				National estimate [5]
2009	26.7–40.0				National estimate [5]
2011	38.0–49.6				National estimate [5]
2013	50.7–60.4				National estimate [5]
2015	62.9–70.6				National estimate [5]

GZ, Guangzhou; SZ, Shenzhen; JN, Jinan; QD, Qingdao; SD, Shandong; CDC, Center for Disease Control; ND, no data; MSM, men who have sex with men; ART, antiretroviral therapy.

More detailed information can be found in Table S1.

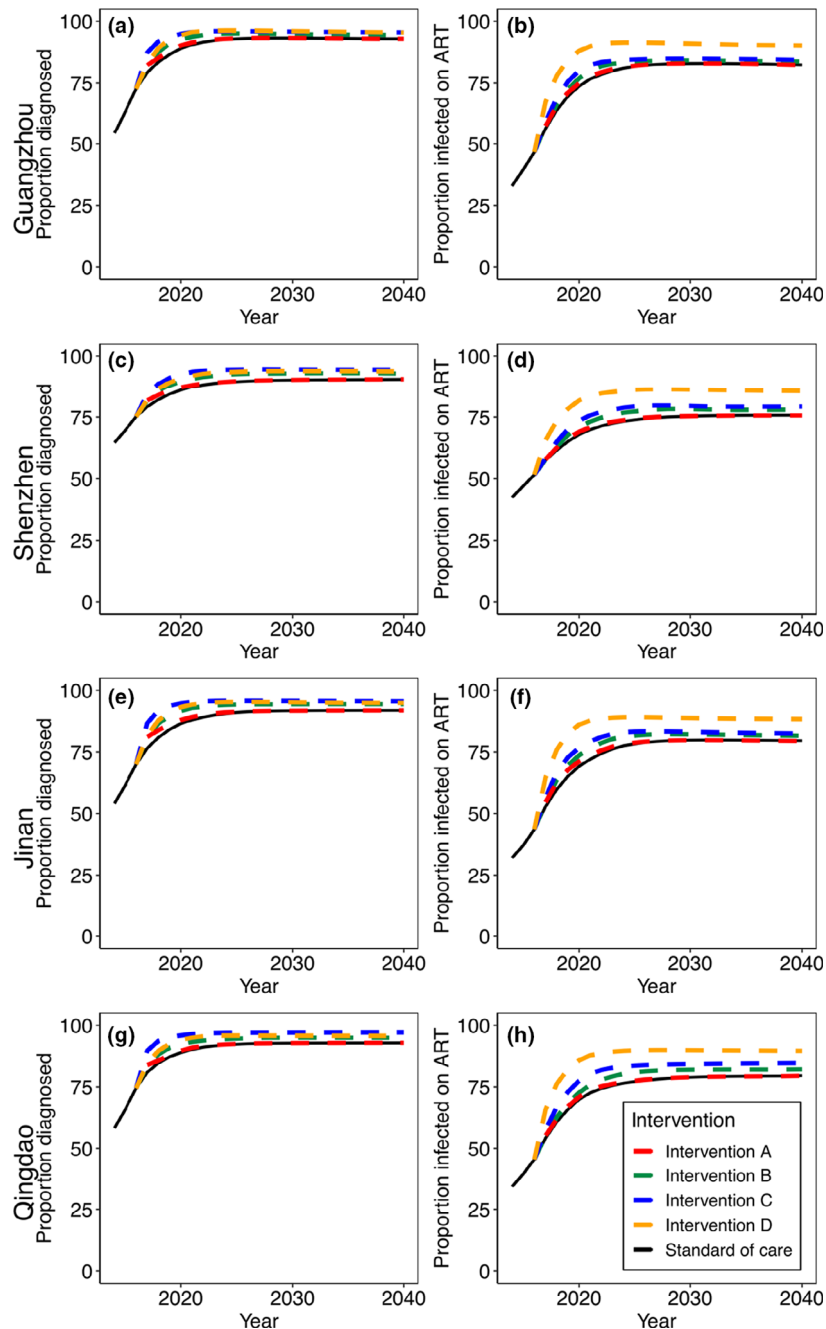
\*Indicates  $\pm$  20% on lower and upper bounds.



**Fig. 1** Comparison of the model projections for each city against data on HIV prevalence, incidence per 100 person-years (py), percentage on antiretroviral therapy (ART) if diagnosed and percentage diagnosed. Projections are shown for Guangzhou (a–d), Shenzhen (e–h), Jinan (i–l) and Qingdao (m–p), with median (black line) and 95% credible interval (blue shaded area) being displayed for 100 model fits for each city. Empty red squares indicate HIV diagnosis data that were fitted to (accepted if confidence interval) and red circles indicate those data that are included in the likelihood estimation to determine the best-fitting model runs. The blue dot represents validation data from 2018 [86.5% of diagnosed men who have sex with men (MSM) on ART in a recently published UNAIDS report [8]]. Other metrics used in model fitting can be seen in Fig. S8.

and higher partner numbers) and by 2036 would reach 11.4% in Guangzhou, 12.2% in Shenzhen, 10.2% in Jinan and 5.0% in Qingdao, while the model suggests that HIV incidence peaked in each city around 2013 (due to increases in ART coverage). We project that the total

percentage of MSM diagnosed would reach 92–93% in all cities by 2036, the percentage of diagnosed MSM on ART would be 86–88%, the percentage of all infected MSM on ART would be 79–82% (Fig. 2) and viral suppression rates would be 78–81% (ranges are median values for each city).



**Fig. 2** The effect of each of the four interventions introduced in 2016 on diagnosis levels and percentage of men who have sex with men (MSM) living with HIV on antiretroviral therapy (ART) in Guangzhou (a, b), Shenzhen (c, d), Jinan (e, f) and Qingdao (g, h) for the 1-year HIV self-testing intervention A (red dashed), the 20-year intervention B (green dashed), the higher-impact 20-year intervention C (blue dashed), intervention D (orange) and the standard of care (black).

#### Intervention A: One-off crowdsourced intervention

Over twenty years (2016–2036), a one-off crowdsourced intervention in 2016 (given to those MSM who have not tested in the past 3 months) increasing self-testing for

1 year (intervention A) was projected to avert 0.9–2.2% of new HIV infections among MSM compared with the standard of care (Table 2). The total infections averted by the one-off intervention would be 215 in Guangzhou, 266 in Shenzhen, 59 in Jinan and 85 in Qingdao, with

**Table 2** Intervention impact compared with existing standard of care over 20 years (2016–2036) in four cities in China. Data are medians (95% credible interval)

Intervention	Guangzhou	Shenzhen	Jinan	Qingdao
<i>Intervention A: One-off intervention (RR = 1.89)</i>				
% of infections averted	2.1 (0.8–5.4)	0.9 (0.3–3.2)	2.1 (0.7–4.5)	2.2 (0.6–5.6)
Total infections averted	215 (70–442)	266 (88–703)	59 (19–154)	85 (23–226)
<i>Intervention B: Annual repeated intervention (RR = 1.89)</i>				
% of infections averted	7.3 (3.5–17.5)	6.4 (2.8–15.7)	8.7 (4.1–15.0)	10.7 (3.4–18.3)
Total infections averted	776 (300–1601)	1798 (753–3571)	256 (110–529)	411 (119–1000)
<i>Intervention C: Repeated annual intervention with higher impact (RR = 3.00)</i>				
% of infections averted	12.0 (6.8–26.5)	11.7 (5.4–23.2)	14.9 (9.2–25.6)	20.7 (10.9–34.6)
Total infections averted	1213 (605–2325)	3341 (1618–5848)	438 (241–826)	724 (310–1651)
<i>Intervention D: Repeated annual intervention (RR = 1.89) in the context of doubled ART initiation rates (31–65% initiating within 6 months compared with 17–41%)</i>				
% of infections averted	9.2 (4.1–22.2)	8.2 (3.7–20.0)	10.8 (5.2–19.0)	12.3 (4.4–22.1)
Total infections averted	712 (290–1492)	1797 (838–3472)	228 (103–470)	310 (93–848)

more infections averted in the cities with higher MSM population sizes (Fig. S8). The model projected that there would be very little change after 20 years in relative diagnosis levels, or ART coverage (< 0.1%) under intervention A in all cities as compared with the base case (Fig. 2).

#### Intervention B: Annual repeated crowdsourced intervention

Repeating the crowdsourced intervention each year for 20 years (increasing self-testing over the 20 years) averted a total of 7.3% HIV infections in Guangzhou, 6.4% in Shenzhen, 8.7% in Jinan and 10.7% in Qingdao over that period (Table 2). Across the cities, intervention B averted three- to seven-fold more infections than the 1-year intervention A (with similar increases in total infections averted: four- to seven-fold). While Qingdao had the highest percentage of infections averted (10.7%), this only equated to 411 infections, while Shenzhen had the lowest percentage of infections averted (6.4%) but the highest total infections averted (1798), due to higher population size. The model also projected that intervention B would lead to small increases in relative diagnosis levels (1.6–2.2%; Fig. 2) and ART coverage (1.5–2.2% among all infected MSM) in all four cities by 2036. The city with the greatest increase in ART coverage, Qingdao (2.2%), also had the highest percentage of infections averted (10.7%).

#### Intervention C: Hypothetical annual repeated crowdsourced intervention with higher impact on self-testing

If we assume that the repeated annual crowdsourced intervention has a higher impact (RR = 3.00) on self-testing (i.e. a hypothetically more effective future

intervention) then we achieve a further increase in the percentage of infections averted to 11.7–20.7% across the different cities over 20 years, showing a 1.6- to 1.9-fold increase in both percentage of infections averted and total infections averted when compared with intervention B. Again, Shenzhen had the highest total of infections averted (3341) and the lowest percentage of infections averted (11.7%) among the four cities. Intervention C also increased diagnosis levels in 2036 by 2.6–4.2% and increased the proportion of all infected MSM on ART by 2.4–4.4% (relative increase) in all cities as compared with the standard of care (Fig. 2).

#### Intervention D: Annual repeated crowdsourced intervention in the context of expanded ART initiation

The incremental impact of the repeated annual crowdsourced intervention in the context of expanded ART coverage averted 8.2–12.3% of infections across the four modelled cities. The incremental impact on percentage of infections averted was 1.1–1.3 times greater than that of intervention B (the same repeated annual crowdsourced intervention but with stable ART initiation rates) but was equal or 1.3 times smaller for total infections averted (as fewer infections occurred in the standard-of-care arm with expanded ART initiation). After 20 years, when compared with the counterfactual of doubling ART initiation alone, diagnosis levels were increased by 1.4–1.9%, and ART coverage among all infected MSM by 1.4–2.0%.

## Discussion

This mathematical modelling study estimated that a one-off crowdsourced testing intervention [18] would marginally reduce cumulative HIV incidence, preventing a total of 0.9–2.2% new infections over a 20-year period (2016 –

2036) across all four cities in the study (Guangzhou, Shenzhen, Jinan and Qingdao). These impact projections substantially increased (three- to seven-fold) if the intervention was repeated each year over a 20-year period (intervention B), or if the intervention increased the likelihood of self-testing three-fold rather than 1.89-fold (up to 1.6–1.9 times more effective than intervention B). The incremental impact of the long-duration intervention on new infections would be maintained if ART initiation rates were increased as might be expected in future years (1.1- to 1.3-fold on infections averted).

Between cities, there was variability in our predicted levels of impact despite implementing the same intervention in each city, due to different initial conditions, data and parameters within each city (each representing different baseline levels of testing, sexual behaviour, HIV prevalence, diagnosis and ART coverage data). The total percentage of infections averted varied up to 2.5-fold between cities, with higher impact achieved in Qingdao, which had lower baseline condom use and self-testing rates, as well as higher partner numbers. Likewise, the total infections averted varied up to eight-fold between cities, with higher impact achieved in cities with larger population size (Shenzhen). For example, Guangzhou and Shenzhen have similar absolute impact (215 and 266 infections averted in intervention A), even though Guangzhou has a larger relative impact (2.1% and 0.9% of infections averted) due to Shenzhen having a larger MSM population size.

Our model predicts that HIV prevalence among MSM in 2036 under the current standard of care would be 11.4% in Guangzhou, 12.2% in Shenzhen, 10.2% in Jinan and 5.0% in Qingdao. These estimates are in line with projections from other recent China-specific MSM HIV modelling studies focusing on the national level (11% [43] to 22% [44] in 2037), suggesting that the HIV prevalence among MSM living in China will gradually decrease from current levels, although slowly and with some uncertainty. Our model predictions account for recent policy changes since 2016, making ART available to everyone and increasing testing rates (e.g. introduction of self-testing in 2013 [45]). This standard-of-care result highlights the need to prioritize interventions that continue to focus on reducing the HIV disease burden among MSM in China. Another modelling study focusing on MSM living in Beijing [46] predicted that if 70% of MSM were tested in a year, and if, of those tested, 70% were treated, then new HIV infections would decline by 50–70%, a greater impact than any of the scenarios we model in this study. However, their model did not take into account historical changes in HIV-testing and ART coverage, which can greatly affect HIV incidence trends,

and looked at a ‘test and treat’ intervention rather than increasing testing alone. Another study in sub-Saharan Africa showed that targeting adult men with community-based HIV self-testing could avert 1500 HIV infections per year in the context of a country of nine million adults [20], which equates to an 8.5% reduction, similar to the impact predicted in our study with a repeated annual intervention. The sub-Saharan African study assumed that 30% of HIV-testing services for men were replaced with community-based self-testing.

This study is a rare example [19,47] of a model estimating how increasing HIV self-testing impacts HIV transmission and is the first model to assess the potential impact of implementing a crowdsourced HIV-testing intervention over a long time period. Our mathematical model made use of a wide variety of data sources, specific to MSM in China and specific to the individual cities we studied. In combination with the crowdsourced trial data at baseline [18] and Shandong and Guangdong CDC data, this ensured that our model results were feasible and realistic.

However, in some cases, we were unable to use local estimates, and instead used parameters from similar studies wherever possible. ART dropout rates were not available for all cities and were taken from national or regional estimates [48,49], and in the absence of local data, diagnosis and ART coverage levels were fitted to Shandong [42] and national estimates [5], respectively, meaning that we may not have fully captured the care cascade in each city. This means that if we have overestimated levels of diagnosis or ART coverage, we will have underestimated the potential intervention impact. If these fitted estimates were to change dramatically then this would have consequences for our impact measures and, ideally, we would have city-specific parameters for all cities. Most of the sexual behavioural data used to inform the model parameters came from trial participants, who may not be representative of the wider MSM population in these cities. National estimates for partner numbers [50,51] and condom use [51] among MSM fall within the overall ranges used in our model, although our city-specific estimates suggest slightly higher partner numbers and lower condom use than these national estimates.

We also had no data on the initial size of the MSM population in 1990, the rate at which new MSM joined the sexually active population, and the ART initiation rate from both self-testers and facility testers. However, we ensured that we captured the underlying parameter value by allowing the maximum range of variation in our sampling method. For the ART initiation rate, we also assumed identical behaviour for those diagnosed via



facility and self-testing in the absence of data on the differences between linkage following facility/self-testing in China. If slower ART initiation follows from being diagnosed via self-testing, then our model would have overestimated the impact of the crowdsourced testing intervention. Although crowdsourcing involves local community engagement, we had no pre-specified metrics to measure the extent of community engagement. We also did not include changes in behaviour following HIV diagnosis because this was not the focus of the trial or this analysis, which means our findings could underestimate the potential impact of a self-testing intervention if substantial reductions in risk behaviour did occur after a man is diagnosed with HIV. Pre-exposure prophylaxis (PrEP) use was also not considered, as PrEP has only recently been licensed for HIV prevention in China [52]. It will be important for future modelling studies to assess the impact of PrEP for MSM on the HIV epidemic in China.

## Conclusions

Our modelling study suggests that the crowdsourced self-testing intervention with impacts lasting for a 1-year period would only have a small long-term impact on HIV transmission among MSM in China. Repeating the intervention annually would have a greater impact (three- to seven-fold). These results, in parallel with our projections of the HIV prevalence (gradually decreasing from current levels, although slowly) among MSM in each of the four cities (5–12% in 2036 without further intervention), indicate the need to prioritize increasing the proportion of diagnosed MSM on ART and increasing viral suppression on ART, in order to reduce the HIV burden in the MSM population in China.

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## Author contribution

All authors conceived and designed the study. A Lee, A Liu, WH, CW, WT, WM and JDD acquired the data. RDB, PV and KMM carried out the mathematical modelling. RDB and KMM performed the coding and simulations. All authors carried out the analysis and interpretation of results, drafted and wrote the manuscript, and approved the submitted version.

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