Comparison of different strategies for controlling HIV/AIDS spreading in MSM

Jie Lou [a], Jinjin Cheng [a], Yan Li [b], Chen Zhang [c], Hui Xing [d], Yuhua Ruan [e, d], Yiming Shao [d, *]

[a] Department of Mathematics, Shanghai University, 99 Shangda Road, Shanghai, China
[b] Henan Cable TV Network Group Co., Ltd, Zhengzhou Branch, Zhengzhou, China
[c] School of Nursing, University of Rochester Medical Center, 255 Crittenden Blvd, Rm 2w218, Rochester, NY, 14642, USA
[d] State Key Laboratory of Infectious Disease Prevention and Control (SKLID), Collaborative Innovation Center for Diagnosis and Treatment of Infectious Diseases, Beijing, China
[e] Guangxi Center for Disease Control and Prevention, Nanning, China

A R T I C L E   I N F O

A B S T R A C T

As proposed in the UNAIDSs 2014 report, to end global AIDS epidemic by 2030, 90% of people living with HIV need to be diagnosed, 90% of the diagnosed need to receive antiretroviral therapy (ART), and 90% of those on treatment need to achieve viral suppression (90-90-90 strategy). The strategies focus on the reservoir. It controls HIV spreading by reducing infectiousness of HIV infected individuals via diagnosis and treatment. In this manuscript, we compared the effects of HIV/AIDS interventions that focus on different individuals in MSM population through a dynamics model. Our results showed that, the success or not of the "90-90-90" strategies depends on a very important factor: the infectious strength among individuals taking ART. Without highly effective HIV treatment, the "90-90-90" strategies are likely to fail. Therefore, we call for the combination of both primary prevention among the susceptible with the 90-90-90 strategy among the infected to curb the HIV epidemic in Chinese MSM.

1. Introduction

According to the report by the United Nations Programme on HIV/AIDS (UNAIDS) in 2014, there were more than 35 million people living with HIV/AIDS (PLWHA) worldwide by the end of 2013 (UNAIDS, 2016). In 2014, UNAIDS proposed an HIV/AIDS "90-90-90" strategy: having 90% of PLWHA diagnosed, 90% of the diagnosed receiving antiretroviral therapy, and 90% of those on treatment achieving viral suppression. The final target is "ending global AIDS epidemic in 2030". The hypothesis of this strategy is that HIV spreading can be controlled by reducing infectiousness of infected individuals via treatment (UNAIDS, 2016). By the end of 2015, China reached the targets of 68%, 67% and 91% respectively (Wu, 2016). In 2016, the updated treatment criteria including all HIV infected individuals made the 90% of treatment goal promising in

China. Among the "90-90-90" strategy, diagnosing 90% of people living with HIV is the most critical and challenging step. Therefore, the main target individuals under the "90-90-90" strategy are the HIV positive population, but not the susceptible.

Despite increasing efforts to control transmission of HIV/AIDS, men who have sex with men (MSM) are the risk group with the highest HIV incidence both domestically and internationally (Estimated HIV Incidence in the United States, 2010; Hall et al., 2008; Jaffe, Valdiserri, & De Cock, 2007; Prejean et al., 2011). The epidemic of HIV in China is driven by the high prevalence among MSM, despite the ongoing efforts of the government of China (Lou et al., 2014). The unrelenting HIV epidemic among Chinese MSM urgently calls for innovative, practical, and effective HIV prevention interventions.

China has made a lot of efforts to curb the epidemic. One promising intervention combined the expanding HIV testing with timely linkage of newly diagnosed individuals to HIV care (e.g., risk reduction and antiretroviral therapy (ART)) has been carried out in MSM population (Velasco-Hernandez, Gershengorn, & Blower, 2002). Some studies also evaluated individual or joint impacts on HIV incidence of the intervention components among MSM (Ahlgren, Gorny, & Stein, 1990; Huang, Zhang, Wu, & Lou, 2017; Jacquez, Koopman, Simon, & Longini, 1994; Phillips et al., 2013; Tan & Xiang, 1999; Van Sighem et al., 2012; Wilson, Hoare, Regan, & Law, 2009; Wirtz et al., 2013). However, none of any existing strategies can curb the epidemic effectively in China (Chinese Center for Diseas, 2017).

In the current study, we explored additional components beyond the 90-90-90 strategy. Instead of focusing on HIV infected individuals, we examined the effect of behavioral interventions among susceptible individuals using a dynamic mathematical model.

2. Methods

We used a compartmental ordinary differential equations model for simulating and projecting the HIV epidemic among MSM population under different strategies. Fig. 1 shows our intention. We would like to use the MSM population in Beijing as our target population. Using existing databases in Beijing, we formulated a baseline model that reflects some key epidemiological properties of the HIV/AIDS epidemic. In addition, we modeled several scenarios of public-health interventions (e.g., condom use, partner reduction). The left row of compartments show uninfected MSM who are Susceptible to HIV infection. They are divided into Non-interventions (S), and effective-interventions (S^e). The dotted line means the line may exist (*if the "primary prevention" holds*) or not (only the "90-90-90" strategies). The next two rows representing two stages of HIV infection: I_1 is the acute infection stage while I_2 is the chronic infection stage. Correspondingly, we have (I_1^e) and (I_2^e) for the infections who accept effective behavior interventions. The compartments in the middle of the two infection stages show HIV-infected individuals who have initiated antiretroviral therapy (T_1) and (T_2). Finally, the last column represents the HIV infected who enter into AIDs stage (A). M is the recruitment rate per year into the MSM population. They are local HIV-MSM who turn 18 years old, or those from other areas who immigrate into Beijing. China has adopted the World Health Organizations "Treat All" approach. So the diagnosis rates of HIV infected individuals are also their treatment rates ($\gamma_1, \gamma_2, \gamma_1^e$ and γ_2^e). The rates of ART failure or dropout are denoted by $\alpha_1, \alpha_2, \alpha_1^e$ and α_2^e. Movement from Susceptible to Infected ($W(t)$ or $W^e(t)$) is the HIV transmission rate. It is estimated from multiple parameters. The natural removal rate (d) represents death, being older than 60 years, or migration out of Beijing. The rate of disease progression is different for HIV-infected individuals on ART (k and σ) or not on ART (ν and ω). Finally, the effective behavior interventions rate on the susceptibles and the infected are parameterized by rates b_s, b_1 and b_2 respectively.
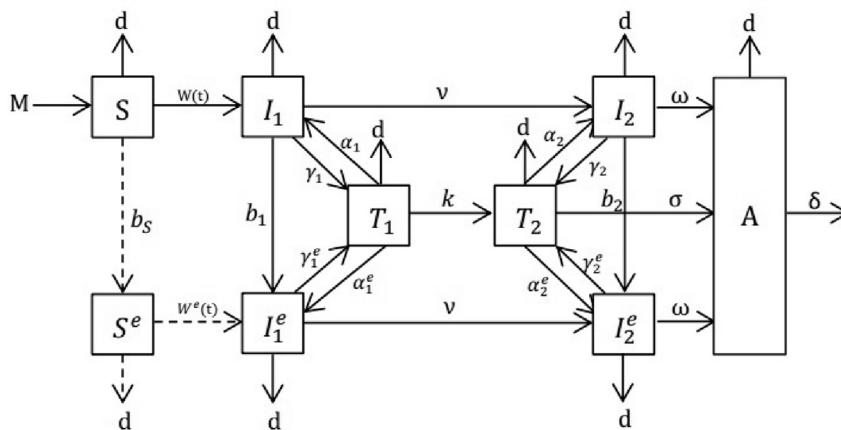

Fig. 1. Schematic diagram of HIV combination prevention intervention model in the presence of ART.

3. Results

We used data from local HIV surveillance systems and published studie (Fan et al., 2012; Liu, Liu, & Xiao, 2001; Lou et al., 2014; Ruan et al., 2009a, 2009b; Xu et al., 2010; Zhou et al., 2010) to simulate the HIV prevalence rates during 2000–2010 among MSM in Beijing. The observed HIV prevalence rates among MSM in Beijing during 2000C2010 were: 1.2% in 2000, 3.2% in 2005, 4.8% in 2006, 5.1% in 2007, 6.5% in 2008, 6.8% in 2009, and 7.8% in 2010. As available data include no identifiers that could link the data to individual subjects in the local HIV surveillance systems or participants from the published studies, consent was waived and the mathematical modeling protocol was approved by the institutional review boards of the National Center for AIDS/STD Control and Prevention of Chinese Center for Disease Control and Prevention.

The earliest HIV prevalence data among MSM in Beijing were available from 2000. The observed HIV prevalence rates among MSM in Beijing during 2000–2010 were: 1.2% in 2000 (Liu et al., 2001), 3.2% in 2005 (Ruan et al., 2009a, 2009b), 4.8% in 2006 (Ruan et al., 2009a, 2009b), 5.1% in 2007 (Ruan et al., 2009a, 2009b), 6.5% in 2008 (Xu et al., 2010; Zhou et al., 2010), 6.8% in 2009 (Fan et al., 2012), and 7.8% in 2010 (Li et al., 2012). We employed a Metropolis-Hastings algorithm to carry out extensive Markov-chain Monte-carlo simulations for estimating the mean values of some unknown parameters, including yearly recruitment rates (e.g., number of new members into the pool of the study population each year), rates of receiving treatments at acute and chronic infection stages (during 2000–2010), infectious transmission coefficients at the acute infection stage, the relative infectiousness of the chronic infection subgroup to the acute subgroup, the relative infectiousness of the acute infection subgroup who received interventions to the acute subgroup who did not receive any interventions, the relative infectiousness of chronic infection subgroup who received intervention to acute subgroups, the relative infectiousness of acute or chronic infection subgroup who received ART to acute subgroup who did not receive ART, and the initial value of each subgroup in 2000. The algorithm ran for 1,000,000 iterations, and we adapted the proposal distribution after 500,000 iterations using Gewekes method to assess convergence (Haario, Laine, Mira, & Saksman, 2006). Finally, the parameters that are known or unknown but fitted by MCMC can be found in Table 1 and Table 2 respectively.

Suppose that the dot lines in Fig. 1 do not exist at this stage during 2000–2014. Table 2 got under the assumption that maintaining the coverage of interventions as the average coverage during 2000–2010. The comparison between the reported HIV prevalence and history data of Beijing MSM population from 2000 to 2010 with maximum 95% confidence interval that is fitted by 500,000 MCMC simulations is shown in Fig. 2 (the left one). The red line is the mean of the 500,000 MCMC simulations. Since the data during 2011–2017 were critically missing except that of 2013, and also considering that some changes in HIV intervention strategies, we adjusted the model using parameters in Tables 1 and 2 but with the modified ART rates $\gamma_1 = \gamma_2 = \gamma_1^e = \gamma_2^e = 0.5$. This means, half of HIV patients in Beijing can be treated. Then the dynamics of the model under the new assumptions go as the yellow box-plot in the right figure of Fig. 2. Through Matlab code we can get some statistical data as follows. The 10,000 sets of simulations showed that the mean by 2015 is 15.66% and interquartile ranges (IQR: 25%–75%) of HIV prevalence rate by 2015 were from 14.12% to 17.38%, and the finite outliers were 10.06% and 22.26%. The red square point in the right side of Fig. 2 was the statistic data of HIV prevalence rate of 2013 (12.7% (Liu et al., 2016)), which was quite near to the predicted mean value in 2013 (13.01%). Under this simulations, the ART rate of HIV patients in Beijing would be 66% in total by 2015, which is consistent with the statistical data (68% of diagnosed and 67% of treated, respectively) in literature (Wu, 2016). Fig. 2 shows that high treatment rates do change the dynamic trend, from an exponential growth curve to a linear growth curve. However, both situations showed increasing trends. Therefore, Fig. 2 shows the robust of our dynamic results.

Considering the effects of ART used in China, we assumed the efficiency of ART is around 90% ($1 - \varepsilon_4$ and $1 - \varepsilon_5$ for the therapeutic effects of treated patients that are in acute or chronic infection stage respectively). The values of ε_4 and ε_5 can be

Table 1
Definitions, meanings and units of model parameters.

Parameter	Value	Unit	Description	Source
d	1/42	/year	Rate of removal from the sexually-active population unrelated to HIV	Lima et al. (2008)
δ	1	/year	Rate of death from AIDS	Lima et al. (2008)
ν	4	/year	Rate of transitioning from acute to chronic infection $_+$	(Chow, Wilson, & Zhang, 2012; Granich, Gillks, Dye, De Cock, & Williams, 2009; Ruan et al., 2009a, 2009b)
ω	1/10	/year	Rate of transitioning from chronic infection to AIDS	(Chow et al., 2012; Granich et al., 2009; Ruan et al., 2009a, 2009b)
k	4	/year	Rate of transitioning from acute to chronic infection under ART	Chow et al. (2012)
σ	1/20	/year	Rate of transitioning from chronic infection to AIDS under ART	Chow et al. (2012)
γ_1	0.017	/year	ART rate for acute infection stage MSM$_+$	Annual Report onV/ (2010)
γ_2	0.53	/year	ART rate for chronic infection stage MSM$_+$	Annual Report onV/ (2010)
γ_1^e	0.017	/year	ART rate for acute infection stage MSM$_+$ received intervention	Annual Report onV/ (2010)
γ_2^e	0.53	/year	ART rate for chronic infection stage MSM$_+$ received intervention	Annual Report onV/ (2010)
α	1/42	/year	Quit rate from ART	Annual Report onV/ (2010)

Table 2
Parameter values fitted by 500000 MCMC simulations.

| Parameter	mean	std	geweke	Description
M	6556.5	866.96	0.99508	No. of recruitment nodes
b_1	0.3014	0.057691	0.97031	Rate of receiving intervention of acute infection stage
b_2	0.3011	0.05774	0.99174	Rate of receiving intervention of chronic infection stage
β	0.77691	0.050956	0.99617	Infectious transmission coefficient of acute infection stage
ε_1	0.49245	0.057145	0.99532	Modification factor in transmission coefficient of I_2 to I_1
ε_2	0.59644	0.057538	0.99867	Modification factor in transmission coefficient of I_1^e to I_1
ε_3	0.29563	0.057564	0.97477	Modification factor in transmission coefficient of I_2^e to I_1
ε_4	0.14919	0.028809	0.99328	Modification factor in transmission coefficient of T_1 to I_1
ε_5	0.14697	0.028581	0.99974	Modification factor in transmission coefficient of T_2 to I_1
S_0	1.0071e+05	14367	0.99069	Initial value of susceptible MSM
I_1	252.98	36.892	0.98941	Initial value of acute infection stage MSM$_+$
I_2	381.86	55.662	0.99203	Initial value of chronic infection stage MSM$_+$
I_1^e	50.789	7.328	0.9974	Initial value of acute infection stage MSM$_+$ received intervention
I_2^e	77.12	11.087	0.98251	Initial value of chronic infection stage MSM$_+$ received intervention
T_1	5.9998	2.3281	0.94814	Initial value of acute infection stage MSM$_+$ received ART
T_2	254.76	37.044	0.9939	Initial value of chronic infection stage MSM$_+$ received ART
A	255.89	36.947	0.99677	Initial value of AIDS stage MSM$_+$
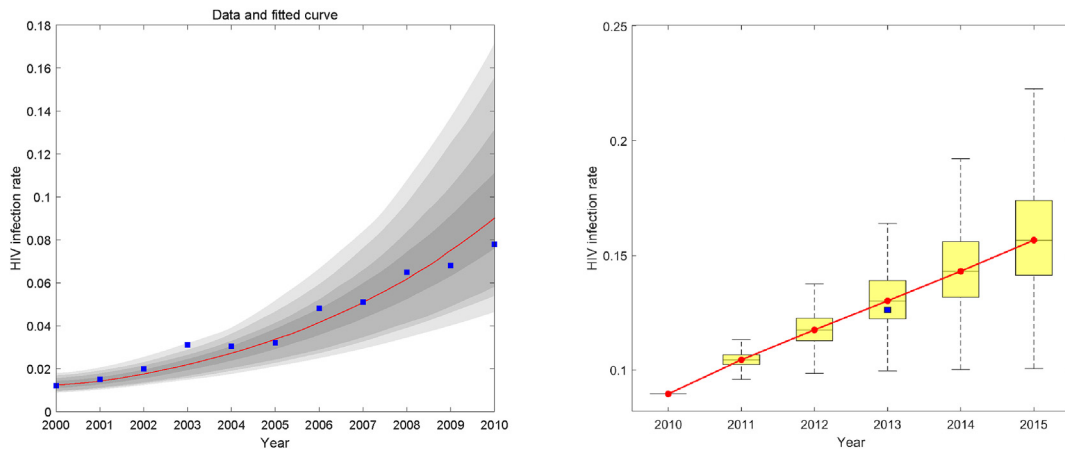
Fig. 2. Left: The comparison between the reported HIV prevalence and history data of Beijing MSM population from 2000 to 2010 with maximum 95% confidence interval that is fitted by 1000000 MCMC simulations. Right: The predicted curve of HIV prevalence in Beijing MSM population from 2010 to 2015. The red dot is the history data.

found in Table 2. In the following, we use the final population that were predicted in 2015 as our new initial values to predict HIV prevalence from 2015 to 2025 and the distribution of basic reproduction number (R_0) under six different scenarios (here we suppose the dot-lines in Fig. 1 can exist under certain scenarios):

1. **S**1: It maintains the coverage of interventions as that during 2010−2015 and has not considered the "primary prevention" among the susceptible population ($b_s = 0$).
2. **S**2: Similar to the "90-90-90" strategy: the positive diagnosis rate (and also the ART rate because of the policy "treatment once diagnosis") of HIV infected individuals increase to 90% for all kinds of HIV positive individuals (i.e., $\gamma = 0.9$). It assumes 90% HIV positive individuals receive enhanced behavioral interventions ($b_1 = b_2 = 0.9$), but has not considered the "primary prevention" among susceptible individuals ($b_s = 0$).
3. **S**2*: It is the same as the **S**2 except that it assumes the ART sub-populations lost their infectivity ($\varepsilon_4 = \varepsilon_5 = 0$).
4. **S**3: It considers effective "primary prevention" among susceptible individuals (the dot-lines exist in Fig. 1). It assumes that half of the susceptible population receives effective behavioral interventions each year ($b_s = 0.5$). These people can reduce their risk behaviors by half ($\eta = 0.5$) (e.g., by using condoms or reducing their sexual partners). We still maintain the coverage rate of interventions to another subpopulation as that during 2010−2015.
5. **S**3*: The same as **S**3 except suppose the ART sub-populations lost their infectivity ($\varepsilon_4 = \varepsilon_5 = 0$).
6. **S**4: The joint use of **S**2 and **S**3.

In extensive uncertainty analyses, 10,000 parameter sets were randomly sampled from corresponding uncertainty ranges (Table 2 and other parameters that we specified for the ranges). Fig. 3 shows the results of the basic reproduction number (R_0) under six different scenarios: **S**1 − **S**4. In Fig. 3, the red histogram is of **S**1, the blue histogram and the brown histogram are of
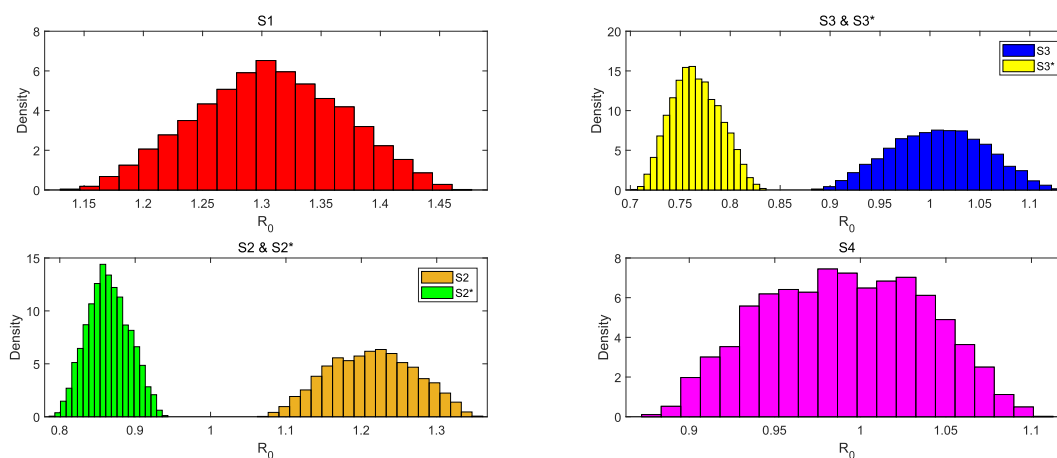
Fig. 3. Uncertain analysis of reproduction number R_0 under four different scenarios and their comparisons. Distribution of R_0 values obtained from Latin Hypercube Sampling for parameters as shown in Table 2 and six scenarios' assumptions, with 10000 simulations.

S2 and **S**2*, respectively. The distribution of the R_0 of **S**1 is with a mean of 1.3067 (standard deviation: 0.0613), and with an interquartile range of 1.263−1.351. No possibility of estimates falls below the epidemic threshold ($R_0 < 1$). The distribution of R_0 of **S**2 is with a mean of 1.2135 (standard deviation: 0.0569), and with an interquartile range of 1.1698−1.2560. Again, no possibility of the estimates falls below the epidemic threshold ($R_0 < 1$).

This result shows that, without other interventions assist, the present "90-90-90" cannot control the HIV/AIDS spreading in MSM in Chinese settings. As a contrast, the distribution of R_0 of **S**2* is with a mean of 0.86443, and with an interquartile range of 0.8446−0.8840). Percentage of the estimates falls above the epidemic threshold is 0. The results show that, the success of the "90-90-90" strategy depends on a very important factor: the infectious strength of the ART sub-population. Even if a quite "low infectiousness" assumption in our model, the infectious ability is only as low as 15% of what it was before treatment (see ε_4 and ε_5 in Table 2). Even with the lower infectiousness, the HIV spreading in this population cannot be curbed yet, as the green histogram (Fig. 3) shows, although we assumed the sub-population using ART can completely lose their infectivity prior to this analysis. Literature (Lou, Wu, Chen, Ruan, & Shao, 2009) states that the relation between R_0 and the lifespan of HIV patients follows the power law distribution, $P(k) \sim k^{-2-\gamma}$, with $0 < \gamma \leq 1$. R_0 is a decreasing function of the disease mortality. This means that longer life of HIV patients, the more likely they bring new infections, even if the infectivity of patients is quite low.

Similarly we explored the possibility of the "primary prevention" intervention **S**3. It's distribution of R_0 (the blue histogram in Fig. 3) is with a mean of 1.0087 (standard deviation: 0.0471 and interquartile range: 0.9737−1.0437). Percentage of the R_0s that falls above the epidemic threshold is 57%. If we assumed that all ART sub-populations completely lost their infectivity (**S**3*), the mean of the R_0 s is only 0.7659 with an interquartile range of 0.7480−0.7831 (the yellow histogram in Fig. 3). The percentage of the R_0 s that falls above the epidemic threshold is 0 again, similar to that of the **S**2*. This result states the significance of treatment effectiveness in China. We may control HIV spreading in MSM easily with efficient treatments, even if we only implement behavioral interventions in susceptible populations.

Suppose we cannot get more efficient HIV medicines at this moment. **S**4 (the magenta histogram in Fig. 3) tell us that we have possibility to control HIV spreading in MSM in Beijing under this strategy since its distribution of R_0 is with mean 0.9907 (standard deviation: 0.0468 and interquartile range: 0.9538−1.0272). A quite big percentage (56.38%) of estimates falls below the epidemic threshold ($R_0 < 1$).

This results indicated that, neither the "90-90-90" strategy that focuses on HIV infected individuals works effectively, nor the "primary prevention" that focuses on the susceptible individuals does. Even if we suppose that half of the susceptible population receives effective behavioral interventions each year and these people can reduce their risk behaviors by half), if we can not get more efficient treatment. Therefore, the optimal strategy is to combine the "90-90-90" and the "primary prevention" strategies among this high-risk population.

The dynamics of the HIV prevalence under different situations are shown in Fig. 4. Assuming that the baseline levels of HIV prevalent in 2015 are sustained (i.e., under **S**1), HIV prevalence among MSM in Beijing will increase as high as 35.1% by 2025 (the median value of 10,000 simulations, the blue line of the **S**1 in Fig. 4). Under the **S**2 (the "90-90-90" intervention), HIV prevalence among MSM in Beijing keeps increasing to 27.43% by 2025 (the red line of **S**2 in Fig. 4). However, under the "primary prevention" **S**3, the median value of 10,000 simulations of HIV prevalence has a slow increasing at the beginning and then followed by a decrease, and finally arrives at 16.84% by 2025 (the black line of **S**3 in Fig. 4). The prevalence is lower than both the base line situation **S**1 as well as the "90-90-90" situation **S**2. Therefore, the HIV/AIDS epidemic still keeps sky-rocketing in this population. Combinations of the two strategies together may curb the HIV transmission among this at-risk population. The mean of the 10,000 sets of prevalence under **S**4 is 15.27% by 2025, which is lower than that in 2015 (the brown line of **S**4 in Fig. 4).
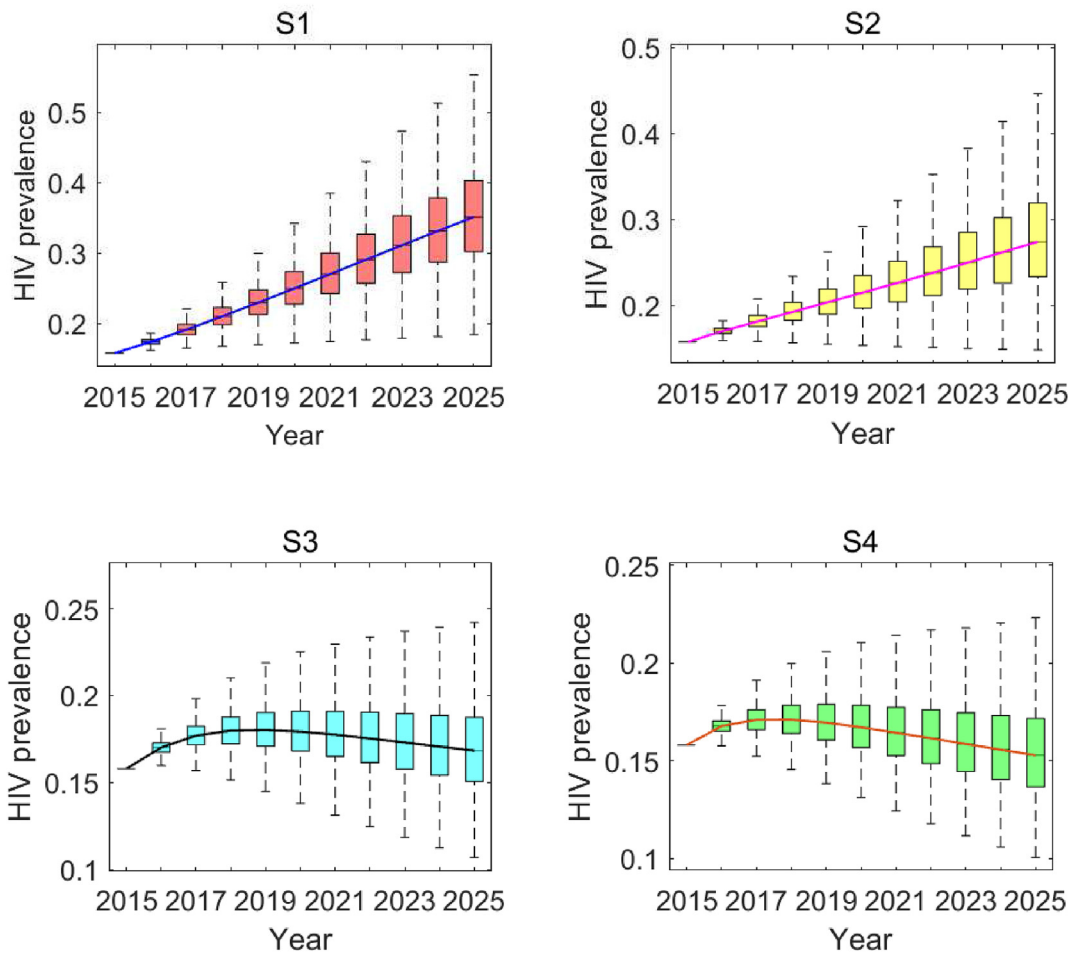
Fig. 4. Projections of HIV prevalence and time-dependent uncertainty analyses of four different scenarios. Each box-plot represents the results of 10000 simulations. These plots show median values (horizontal black, blue, brown and red lines), upper and lower quartiles (red, green, yellow and blue boxes), and outlier cutoffs (dashed lines).

4. Discussion

In this manuscript, we explored the effect of HIV/AIDS intervention among Chinese MSM through a dynamics model. We found that compared to the effect of the "90-90-90" strategy proposed by the UNAIDS that targets HIV patients, HIV/AIDS can be better controlled if we can target both susceptible and infected individuals using the primary prevention and the 90-90-90 strategy, respectively. The "primary prevention" may include sexual health education, behavioral interventions (e.g., sexual partners reduction, condom use promotion). In the current study, however, we did not compare costs of these two types of interventions.

One plausible explanation of the under-effective 90-90-90 strategy is that HIV treatment cannot cover across the long life span among HIV patients. Therefore, ART in China does not means zero infectivity. Literature (Lou et al., 2009) also states that the relation between R_0 and the lifespan of HIV patients follows a power law: R_0 is a decreasing function of the disease mortality. As a consequence, the longer life expectancy of the HIV infected individuals, the higher probability that they may spread more infections.

Based upon our findings from the current study, we strongly call for interventions targeting susceptible and infected individuals using both "primary prevention" and the "90-90-90" strategy. Only targeting both susceptible and infected individuals, can the HIV epidemic be curbed in China.

Acknowledgments

Supporting information: the model and the basic reproductive number R_0

The model equations of Fig. 1 are as the follows:

$$
\begin{cases}
\dfrac{dS}{dt} = M - W(t) - dS - b_S S \\[4pt]
\dfrac{dI_1}{dt} = W(t) + \alpha_1 T_1 - dI_1 - b_1 I_1 - \nu I_1 - \gamma_1 I_1 \\[4pt]
\dfrac{dI_2}{dt} = \nu I_1 + \alpha_2 T_2 - dI_2 - b_2 I_2 - \omega I_2 - \gamma_2 I_2 \\[4pt]
\dfrac{dS^e}{dt} = b_S S - dS^e - W^e(t) \\[4pt]
\dfrac{dI_1^e}{dt} = W^e(t) + b_1 I_1 + \alpha_1^e T_1 - \nu I_1^e - dI_1^e - \gamma_1^e I_1^e \\[4pt]
\dfrac{dI_2^e}{dt} = \nu I_1^e + b_2 I_2 + \alpha_2^e T_2 - dI_2^e - \omega I_2^e - \gamma_2^e I_2^e \\[4pt]
\dfrac{dT_1}{dt} = \gamma_1 I_1 + \gamma_1^e I_1^e - dT_1 - kT_1 - \alpha_1 T_1 - \alpha_1^e T_1 \\[4pt]
\dfrac{dT_2}{dt} = kT_1 + \gamma_2 I_2 + \gamma_2^e I_2^e - dT_2 - \sigma T_2 - \alpha_2 T_2 - \alpha_2^e T_2 \\[4pt]
\dfrac{dA}{dt} = \omega I_2 + \omega I_2^e + \sigma T_2 - dA - \delta A
\end{cases}
\tag{1}
$$

where

$$
W(t) = \frac{S}{N}\left(\beta I_1 + \beta\varepsilon_1 I_2 + \beta\varepsilon_2 I_1^e + \beta\varepsilon_3 I_2^e + \beta\varepsilon_4 T_1 + \beta\varepsilon_5 T_2\right),
$$

$$
W^e(t) = \frac{S^e}{N}(1-\eta)\left(\beta I_1 + \beta\varepsilon_1 I_2 + \beta_1\varepsilon_2 I_1^e + \beta\varepsilon_3 I_2^e + \beta\varepsilon_4 T_1 + \beta\varepsilon_5 T_2\right),
$$

$$
N = S + I_1 + I_2 + S^e + I_1^e + I_2^e + T_1 + T_2 + A.
$$

The definitions for parameters in the equation (1) are described in Tables 1 and 2 above.

From this model, we can calculated the basic reproduction number in terms of model parameters using the "next-generation operator" method (Van den Driessche & Watmough, 2002). R_0 is the number of secondary cases produced by a typical HIV-infected MSM during his entire period of infectiousness in a demographically steady susceptible population. Calculating R_0 is critical to determine whether HIV will increase, stabilize, or decline among the MSM population. But considering the calculation of R_0 is traditional and tedious, we omit the calculation here.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.idm.2018.10.002.

References

Ahlgren, D. J., Gorny, M. K., & Stein, A. C. (1990). Model-based optimization of infectivity parameters: A study of the early epidemic in San Francisco. *Journal of Acquired Immune Deficiency Syndromes, 3*, 631–643.

Annual report on HIV/AIDS in Beijing. (2010). CDC.

Chinese Center for disease control and prevention: Analysis of HIV/STD epidemic in 2017. Beijing, China.

Chow, E. P., Wilson, D. P., & Zhang, L. (2012). Patterns of condom use among men who have sex with men in China:a systematic review and meta-analysis. *AIDS and Behavior, 16*, 653–663 (1999).

Estimated HIV Incidence in the United States, 2007-2010 (Vol. 17., (pp. 2007–2010). (2010) pp. 2007–2010) (4).

Fan, S., Lu, H., Ma, X., Sun, Y., He, X., et al. (2012). Behavioral and serologic survey of men who have sex with men in Beijing, China: Implication for HIV intervention. *AIDS Patient Care and STDs, 26*, 148–155.

Granich, R. M., Gillks, C. F., Dye, C., De Cock, K. M., & Williams, B. G. (2009). Universal voluntary HIV testing with immediate antiretroviral therapy as a strategy for elimination of HIV transmission:a mathematical model. *The Lancet, 373*, 48–57.

Haario, H., Laine, M., Mira, A., & Saksman, E. (2006). DRAM: Efficient adaptive MCMC. *Statistics and Computing, 16*, 339–354.

Hall, H., Song, R., Rhodes, P., et al. (2008). Estimation of HIV incidence in the United States. *The Journal of the American Medical Association, 300*(5), 520–529. https://doi.org/10.1001/jama.300.5.520.

Huang, Y., Zhang, C., Wu, J., & Lou, J. (2017). Modelling the HIV persistence through the network of lymphocyte recirculation in vivo. *Infectious Disease Modelling, 2*, 90–99.

Jacquez, J. A., Koopman, J. S., Simon, C. P., & Longini, I. M. (1994). Role of the primary infection in epidemics of HIV infection in gay cohorts. *Journal of Acquired Immune Deficiency Syndromes, 7*, 1169–1184.

Jaffe, H. W., Valdiserri, R. O., & De Cock, K. M. (2007). The reemerging HIV/AIDS epidemic in men who have sex with men. *The Journal of the American Medical Association, 298*(20), 2412–2414. https://doi.org/10.1001/jama.298.20.2412.

Li, X., Lu, H., Raymond, H. F., Sun, Y., Jia, Y., et al. (2012). Untested and undiagnosed: Barriers to HIV testing among men who have sex with men, Beijing, China. *Sexually Transmitted Infections, 88*, 187–193.

Lima, V. D., Johnston, K., Hogg, R. S., Levy, A. R., Harrigan, P. R., et al. (2008). Expanded access to highly active antiretroviral therapy:a potentially powerful strategy to curb the growth of the HIV epidemic. *Infect Dis, 198*, 59–67.

Liu, H., Liu, Y., & Xiao, Y. (2001). A survey on knowledge, attitude, belief and practice related to HIV/AIDS among MSM. *Journal of China AIDS/STD Prevent Control, 7*, 289–291.

Liu, Yu, Qian, Han-Zhu, Ruan, Yuhua, et al. (2016). Frequent HIV testing:impact on HIV risk among Chinese men who have sex with men. *Journal of Acquired Immune Deficiency Syndromes, 72*, 453–461.

Lou, J., et al. (2014). Modeling the Impact on HIV Incidence of Combination Prevention Strategies among Men Who Have Sex with Men in Beijing. *PloS One, 9*(3), e90985.

Lou, J., Wu, J. H., Chen, L., Ruan, Yh, & Shao, Y. (2009). A sex-role-preference model for HIV transmission among men who have sex with men in China. *BMC Public Health, 9*(Suppl 1), S10.

Phillips, A. N., Cambiano, V., Nakagawa, F., Brown, A. E., Lampe, F., Rodger, A., et al. (2013). Increased HIV incidence in men who have sex with men despite high levels of ART-induced viral suppression: Analysis of an extensively documented epidemic. *PloS One, 8*, e55312.

Prejean, J., Song, R., Hernandez, A., et al. (2011). Estimated HIV incidence in the United States, 2006-2009. *PloS One, 6*(8), e17502. https://doi.org/10.1371/journal.pone.0017502.

Ruan, Y., Luo, F., Jia, Y., Li, X., Li, Q., et al. (2009). Risk factors for syphilis and prevalence of HIV, hepatitis B and C among men who have sex with men in Beijing, China: Implications for HIV prevention. *AIDS and Behavior, 13*, 663–670.

Ruan, Y., Luo, F., Jia, Y., Li, X., Li, Q., et al. (2009). Risk factors for syphilis and prevalence of HIV,hepatitis Band C among men who have sex with men in Beijing, China:implications for HIV prevention. *AIDS and Behavior, 13*, 663–670.

Tan, W. Y., & Xiang, Z. (1999). The state-space model of the HIV epidemic with variable infection in the homosexual populations. *J Stat Plan Inference, 78*, 71–87.

UNAIDS. (2016). *Global gains made towards the 90C90C90 targets.* http://www.unaids.org/en/resources/presscentre/featurestories/2016/july/2016071790-90-90. (Accessed 4 May 2017).

Van Sighem, A., Vidondo, B., Glass, T. R., Bucher, H. C., Vernazza, P., Gebhardt, M., et al. (2012). Resurgence of HIV infection among men who have sex with men in Switzerland: Mathematical modelling study. *PloS One, 7*, e44819.

Van den Driessche, P., & Watmough, J. (2002). Reproduction numbers and subthreshold endemic equilibria for compartmental models of disease transmission. *Mathematical Biosciences, 180*, 29–48.

Velasco-Hernandez, J. X., Gershengorn, H. B., & Blower, S. M. (2002). Could widespread use of combination antiretroviral therapy eradicate HIV epidemics? *The Lancet Infectious Diseases, 2*, 487–493.

Wilson, D. P., Hoare, A., Regan, D. G., & Law, M. G. (2009). Importance of promoting HIV testing for preventing secondary transmissions: Modelling the Australian HIV epidemic among men who have sex with men. *Sexual Health, 6*, 19–33.

Wirtz, A. L., Walker, D. G., Bollinger, L., Sifakis, F., Baral, S., Johns, B., et al. (2013). Modelling the impact of HIV prevention and treatment for men who have sex with men on HIV epidemic trajectories in low-and middle-income countries. *International Journal of STD & AIDS, 24*(1), 18–30.

Wu, Z. (2016). The progress and challenges of promoting HIV/AIDS 90-90-90 strategies in China. *Chinese Journal of Disease Control & Prevention, 20*(12), 1187–1189.

Xu, J., Han, D. L., Liu, Z., Ma, X. Y., Wang, L. L., et al. (2010). The prevalence of HIV infection and the risk factors among MSM in 4 cities, China. *Zhonghua Yufang Yixue Zazhi, 44*, 975–980.

Zhou, Z. H., Li, S. M., Liu, Y. J., Jiang, S. L., Zhang, X. X., et al. (2010). Study on the relationship between behavioral factors, psychological status and HIV infection among men who have sex with men in Beijing. *Zhonghua Liuxingbingxue Zazhi, 31*, 273–276.