

Sorbonne Université

École Doctorale Pierre Louis de Santé Publique
ED 393 – Epidémiologie et Sciences de l'Information Biomédicale

*Institut Pierre Louis d'Épidémiologie et de Santé Publique
(UMR-S 1136 Sorbonne Université & Inserm)*

Equipe Maladies transmissibles : Surveillance et modélisation

Prevention of infectious diseases in the context of effective treatment: a game-theoretic approach

*La prévention des maladies infectieuses dans le contexte de traitements efficaces :
une approche par la théorie des jeux*

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Thèse de doctorat d'Épidémiologie
Spécialité : Biomathématiques

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Présentée et soutenue publiquement le **30 juin 2021 à Paris**

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Thèse préparée dans le cadre du Réseau Doctoral en Santé Publique animé par l'École des Hautes Études en Santé Publique (EHESP).

Acknowledgements / *Remerciements*

Preface

This thesis was prepared at the Pierre Louis Institute of Epidemiology and Public Health (IPLESP – join unit of research and health UMRS 1136 of Sorbonne University (SU) & Inserm), within the team of Communicable diseases surveillance and modelling.

The first three years of PhD were funded by a doctoral contract from the French ministry of higher education and research, awarded through the Doctoral network in public health (RDSP), coordinated by the School of advanced studies in public health (EHESP). The fourth year of the PhD was funded by a research grant from the French research agency on AIDS and viral hepatitis (ANRS). During the fifth year of thesis, I held a PhD research and teaching adjunct contract (PhD ATER) at the Biology Faculty of SU and the Laboratory of Computational and Quantitative Biology (LCQB – join unit of research UMR 7238 SU & CNRS).

This thesis studies public health interventions in infectious disease epidemiology, and individual behaviors regarding prevention, from the perspective of mathematical modeling. The approach is interdisciplinary, covering epidemiological studies and the implementation of public health interventions, next to epidemiological models of disease transmission, economics models of decision-making, and data on individual behavior.

The completion of this thesis is contemporaneous with three major events of epidemiological interest. First, the resurgence of measles due to a decline in vaccine coverage, after decades of successful mitigation. Second, the authorization and rollout of pre-exposure prophylaxis against HIV infection for at-risk individuals. Third, the emergence of the SARS-CoV-2 pandemic and the development of effective vaccines against COVID-19. All these events highlight the pertinence and urgency to study epidemic control through prevention interventions accounting for the active participation of individuals.

This manuscript is structured as follows: [chapter 1](#) presents a general introduction to the subject of voluntary prevention of infectious diseases in a context where effective treatment exists, as well as the conceptual framework and modeling approaches that we used to study this subject. As part of my doctoral research, two scientific articles were produced ([Jijón et al., 2017](#); [Jijón et al., 2021](#)), which constitute the cores of [chapter 2](#) and [chapter 3](#), respectively. [Chapter 2](#) focuses on the modeling of voluntary vaccination against treatable childhood infectious diseases. [Chapter 3](#) focuses on the voluntary use of pre-exposure prophylaxis to avoid HIV infection among the population of men who have sex with men. Each of these two chapters starts with a custom introduction, where the epidemiology of the public health issue that motivates our work is presented, as well as some additional material that was not included in the articles. [Chapter 4](#) presents a general discussion and conclusions.

An interdisciplinary note was written in the context of the RDSP, and is included in [Appendix A](#). This thesis is written in English; a detailed summary in French is provided in [Appendix B](#).

Abstract

Despite the current availability of effective preventive methods, controlling epidemics of preventable infectious diseases remains a key public health challenge. When facing an ongoing epidemic, individuals may decide to use prevention, or else get treated in the case of acquiring infection. Whereas treatment is generally well accepted by infected individuals, the acceptability of prevention may vary between individuals, which may lead to preventive behaviors that differ vastly from the recommendations of the public health authorities.

My doctoral research concerns the mathematical modeling of infectious diseases transmission, taking into account the individuals' *prevention versus treatment dilemma*, the decision-making on whether or not to adopt prevention to avoid infection during an ongoing epidemic, in a context where efficient treatment is available. We aim to determine whether and under what conditions the voluntary adoption of prevention could avert an epidemic.

We propose a mathematical model that combines the disease transmission at the population level with the decision-making at the individual level. We model disease transmission using a compartmental model given by a system of ordinary differential equations. For the individual-level decision-making, we rely on a game-theoretic approach, which assumes that individuals solve the prevention versus treatment dilemma by choosing the strategy that benefits them the most. Individuals adopt a proposed prevention strategy provided that it is perceived as more beneficial than treatment. The decision-making thus depends on the individuals' perception of their risk of infection, as well as on their perception of the relative cost of prevention versus treatment, which includes monetary and/or non-monetary aspects such as price, reimbursement policies, accessibility, social stigma, disease morbidity, undesired secondary effects, etc.

We explore two cases of the dilemma of prevention versus treatment. First, we address voluntary vaccination in the context of preventable and treatable childhood infectious diseases. In particular, we apply our methods and findings to the epidemiology of measles. Second, we study the voluntary adoption of pre-exposure prophylaxis to avoid HIV infection by the individuals who are most at risk. In particular, we analyze the HIV epidemiology among one of the populations most at risk in France: men who have sex with men in the Paris region.

We obtain the probability that an individual voluntarily adopts prevention, as a function of the parameters of the prevention method (namely, effectiveness and cost). Our results suggest that epidemic elimination (i.e., the absence of new infections) is possible, provided that preventive methods are highly effective and that individuals perceive the relative cost of prevention

versus treatment to be low. However, epidemic elimination may be only temporary. Once the epidemic is averted, there is no long-term motivation to adopt prevention based in the individual's perception of the risk of infection. An important decrease in the number of infections may reveal less disease burden to individuals, who, in turn, perceive less benefit from prevention. In other words, epidemic elimination may induce a higher cost for prevention, as perceived by individuals. Hence, active efforts to maintain the cost of prevention low are required to preserve epidemic elimination in the long run.

Keywords. Behavioral epidemiology; Voluntary prevention; Epidemic elimination; Game theory; Compartmental model

Préface

Cette thèse a été réalisée au sein de l’Institut Pierre Louis d’Épidémiologie et de Santé Publique (IPLES – UMRS 1136 Sorbonne Université (SU) & Inserm), dans l’équipe Maladies transmissibles : surveillance et modélisation.

Les premières trois années de thèse ont été financées par un contrat doctoral du Ministère de l’enseignement supérieur et de la recherche, octroyé via le concours du Réseau Doctoral en Santé Publique (RDSP) coordonné par l’École des Hautes Études en Santé Publique (EHESP). La quatrième année de thèse a été financée par une allocation de recherche de l’Agence Nationale de Recherches sur le Sida et les Hépatites Virales (ANRS). La dernière année de thèse a eu lieu dans le cadre d’un contrat d’attaché temporaire d’enseignement et de recherche (ATER doctorant) au sein de la Faculté de Biologie de SU pour les activités d’enseignement et au sein du Laboratoire de Biologie Computationnelle et Quantitative (LCQB – UMR 7238 SU & CNRS) pour les activités de recherche.

Cette thèse étudie les interventions de santé publique contre les épidémies de maladies infectieuses du point de vue de la modélisation mathématique, en tenant compte des comportements individuels en matière de prévention. Un approche interdisciplinaire est utilisé, allant de la communication scientifique, au déroulement d’essais cliniques et la mise en place d’interventions de santé publique, à la modélisation mathématique de l’épidémie, les outils économiques modélisant la prise de décision et l’utilisation de données sur le comportement individuel.

Cette thèse a eu lieu pendant trois événements d’intérêt épidémiologique majeurs, qui mettent en évidence la pertinence et l’importance d’étudier l’impact potentiel des interventions de prévention sur les épidémies, en prenant en compte la participation active et volontaire des individus. Premièrement, la résurgence de cas de rougeole due à une diminution de la couverture vaccinale, après des décennies de contrôle. Deuxièmement, le déploiement de la prophylaxie pré-exposition contre l’infection par le VIH et sa recommandation aux individus reconnaissant être à haut risque

d'infection. Troisièmement, l'émergence de la pandémie du SARS-CoV-2, qui a donné lieu à l'implémentation d'interventions non pharmaceutiques avant le développement de vaccins et de la mise en place des programmes de vaccination massive.

Cette thèse est une thèse sur articles. Elle est structurée comme suit : le [chapitre 1](#) présente une introduction générale du sujet de la prévention volontaire des maladies infectieuses dans le cadre où des traitements efficaces existent, ainsi que le cadre conceptuel et les approches de modélisation que nous avons utilisées pour étudier ce sujet. Dans le cadre de la thèse, deux articles scientifiques ont été rédigés ([Jijón et al., 2017](#); [Jijón et al., 2021](#)) et constituent les deux parties principales de ce manuscrit ; ainsi, le [chapitre 2](#) et le [chapitre 3](#) présentent respectivement ces deux travaux. Le [chapitre 2](#) est dédié à la vaccination volontaire contre les maladies infectieuses infantiles. Le [chapitre 3](#) est dédié à la modélisation de l'utilisation volontaire de la prophylaxie pré-exposition afin d'éviter l'acquisition du VIH, dans la population des hommes qui ont des rapports sexuels avec des hommes. Chacun de ces deux chapitres comprend une introduction spécifique, où l'épidémiologie du problème de santé publique qui motive notre travail est présentée, ainsi que du matériel supplémentaire qui n'a pas été inclus dans les articles. Le [chapitre 4](#) présente la discussion générale et les conclusions.

Une note interdisciplinaire a été préparée dans le cadre du RDSP, et est présentée dans l'[Appendice A](#). Cette thèse a été rédigée en anglais, et inclut un résumé détaillé en français dans l'[Appendice B](#).

Résumé

Malgré la disponibilité actuelle de méthodes préventives efficaces, le contrôle des épidémies de maladies infectieuses reste un défi majeur pour la santé publique. Face à une épidémie en cours, les individus peuvent décider d'utiliser la prévention ou de se faire traiter en cas d'infection. Alors que le traitement est généralement bien accepté par les individus infectés, l'acceptabilité de la prévention peut varier considérablement d'un individu à l'autre, ce qui peut conduire à des comportements préventifs qui diffèrent des recommandations des autorités de santé publique.

Mon sujet de thèse porte sur la modélisation mathématique de la transmission des maladies infectieuses, en prenant en compte le *dilemme de la prévention versus le traitement*, la prise de décision d'adopter ou non la prévention pour éviter l'infection, dans un contexte où un traitement efficace existe. L'objectif est de déterminer si la prévention volontaire pourrait prévenir une épidémie, et sous quelles conditions.

Nous proposons un modèle mathématique combinant la transmission de la maladie au niveau de la population et la prise de décision au niveau individuel. Nous modélisons la transmission de la maladie à l'aide d'un modèle compartimental donné par un système d'équations différentielles ordinaires. Pour la prise de décision au niveau individuel, nous utilisons une approche par la théorie des jeux, qui suppose que l'individu choisit la stratégie qui lui bénéficie le plus, à long terme. La prise de décision dépend de la perception individuelle of the risque d'infection ainsi que la perception du coût relatif de la prevention versus le traitement, qui concerne des aspects monétaires et/ou non monétaires, comme le prix, les politiques de remboursement, l'accessibilité, le stigma social, la morbidité de la maladie, les effets secondaires indésirables, etc.

Deux cas de dilemme de prévention versus le traitement sont explorés. Premièrement, nous abordons la vaccination volontaire dans le contexte des maladies infectieuses infantiles évitables et pouvant être traitées. En particulier, nous appliquons nos méthodes et résultats à l'épidémie de la rougeole. Deuxièmement, nous étudions l'utilisation volontaire de la prophylaxie pré-exposition pour éviter l'acquisition du VIH par les individus à haut risque d'infection. En particulier, nous analysons l'épidémie du VIH parmi l'une des populations les plus à risque en France : les hommes qui ont des rapports sexuels avec les hommes en Île-de-France.

Nous avons obtenu la probabilité d'adopter volontairement la prévention, en fonction des paramètres de la méthode préventive (notamment, l'efficacité et le coût). Nos résultats suggèrent que l'élimination des épidémies (i.e., l'absence de nouvelles infections) est possible, à condition que les méthodes de prévention soient très efficaces et que les individus perçoivent le coût de la

prévention comme étant bas. Néanmoins, l'élimination de l'épidémie n'est que temporaire. Une fois l'épidémie éliminée, il n'y a plus de motivation à long terme pour adopter la prévention, basée sur la perception du risque d'infection. Une diminution importante du nombre d'infections peut amener les individus à ne plus percevoir les conséquences de l'infection et donc, à moins percevoir les avantages de la prévention. Autrement dit, l'élimination de l'épidémie peut amener aux individus à percevoir un coût de la prévention plus élevé. Par conséquent, des efforts pour maintenir le coût de la prévention bas sont nécessaires pour préserver l'élimination de l'épidémie à long terme.

Mots-clés. Épidémiologie comportementale ; Prévention volontaire ; Élimination épidémique ; La théorie des jeux ; Modèle compartimental.

Scientific production

Articles

Jijón, S., Supervie, V., and Breban, R. (2017). Prevention of treatable infectious diseases: a game-theoretic approach. *Vaccine*, 37(40):5339–5345.
doi: [10.1016/j.vaccine.2017.08.040](https://doi.org/10.1016/j.vaccine.2017.08.040)

Jijón, S., Supervie, V., and Breban, R. (2020). Can HIV epidemics among men who have sex with men be eliminated through participation to PrEP rollouts? *[Submitted to AIDS in January 2021; currently under peer-review]*.

Other scientific contributions

Oral communications

Jijón, S., Molina, J.-M., Costagliola, D., Supervie, V., and Breban, R. Can HIV epidemics be eliminated through voluntary participation to PrEP rollouts?. EACS 2019 (Basel, Switzerland), November 6–9, 2019.

Abstract in EACS 2019 – Abstract book. *HIV Medicine*, 20(S9):35. DOI: 10.1111/hiv.12814.

Jijón, S., Prevención de enfermedades infecciosas en el contexto del tratamiento eficiente: un acercamiento por la teoría de juegos y una aplicación al VIH. *[Prevention of infectious diseases in the context of efficient treatment: a game-theoretic approach and an application to HIV epidemic]*. Seminar organized by the MODEMAT Mathematical Modeling Centre (Quito, Ecuador), February 23, 2017.

Jijón, S. Can you prevent an epidemic by getting vaccinated?. Pint of Science Festival (Paris), May 21, 2019. [Vulgarization of science].

Poster communications

Jijón, S., Molina, J.-M., Costagliola, D., Supervie, V., and Breban, R. Can HIV epidemics be eliminated through voluntary participation to PrEP rollouts?. Presented at ANRS seminar, November 25–26, 2019.

Jijón, S., Supervie, V., and Breban, R. Prévention des maladies infectieuses : une approche par la théorie des jeux. Presented at the Université des Jeunes Chercheurs organized by Sidaction (Carry-le-Rouet, France), October 14–20, 2017, and at the ED 393 seminar (Saint-Malo, France), October 23–25, 2017.

Winner of the ED 393 Posters awards.

Jijón, S., Supervie, V., and Breban, R. Prevention of infectious diseases in the context of efficient treatment: a game-theoretic approach. Partial results presented at the ED 393 seminar (Saint-Malo, France), October 24–26, 2016.

Jijón, S., Supervie, V., and Breban, R. Prévention dans le contexte de traitement efficace : quel sera l'impact de la prophylaxie pré-exposition sur l'épidémie du VIH ? Presented at the ED 393 seminar (Saint-Malo, France), October 19–21, 2015.

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Acronyms and abbreviations

Acronyms

AIDS	Acquired immunodeficiency syndrome
ANSM	Agence française de sécurité sanitaire des produits de santé (French agency for the safety of health products)
ANRS	Agence nationale de recherches sur le sida et les hépatites virales / Maladies infectieuses émergentes (French agency for research on emerging infectious diseases)
ART	Anti-retroviral therapy
CDC	Centers for disease control and prevention
CI	Confidence interval
DFS	Disease-free state
ECDC	European centre for disease prevention and control
ES	Endemic state
GVAP	Global vaccine action plan
HIV	Human immunodeficiency virus
ÎdF	Île-de-France
MCV	Measles-containing vaccine
MMR	Measles-mumps-rubella vaccine
MMWR	Morbidity and mortality weekly CDC journal
MSM	Men who have sex with men
ODE	Ordinary differential equations

(Continued on next page)

Acronyms (continuation)

PAHO	Pan American health organization
PrEP	Pre-exposure prophylaxis
SM	Supplementary material
STI	Sexually-transmitted infections
SDG	Sustainable Development Goals
TDF/FTC	Tenofovir disoproxil fumarate/Emtricitabine
UK	United Kingdom
US	United States
UNAIDS	Joint united nations program on HIV/AIDS
WHO	World health organization

Abbreviations

Eq(s). Equation(s)

Fig(s). Figure(s)

Ref(s). Reference(s)

Chapter 1

General introduction

1.1 Prevention interventions aiming to the elimination of infectious diseases

The prevention of infectious diseases has greatly improved, not only as a result of the development of safe, highly-effective preventive methods, but also thanks to regional and global public health programs aiming at infectious diseases' elimination. Immunization alone can now prevent more than 20 life-threatening diseases ([WHO, 2019](#)). Mass immunization programs achieved the eradication of smallpox in 1980¹ ([CDC, 2001](#)). The number of cases of poliomyelitis (commonly known as polio) has decreased from an estimated 350 000 cases in 1988, to 33 reported cases in 2018 ([WHO, 2019c](#)). Between 2000 and 2018, vaccination against measles prevented an estimated 23 million deaths ([WHO, 2019b](#)). During the same period, the number of new HIV infections fell by 39%, thanks to preventive interventions ([WHO, 2019a](#)). Preventive interventions have decreased the overall number of new infections worldwide ([Global Public Health Achievements Team, 2011](#)) and placed some communicable diseases, such as measles and poliomyelitis, in the path towards elimination ([Global Public Health Achievements Team, 2011](#)).

During the last decade, the World Health Organization (WHO) developed the Global Vaccine Action Plan (GVAP) 2011–2020, aiming to ensure individuals to live free from vaccine-

¹During the pre-vaccination era, the mortality rate due to smallpox infection were about 30% ([CDC, 2001](#)).

preventable diseases (WHO, 2020). As a result, vaccine coverage among children and vaccine development have shown a remarkable progress, but many other objectives remained unmet (WHO, 2020). Disease-specific programs were also developed to fight infectious diseases' epidemics; for instance, the Global Measles and Rubella Strategic Plan 2012–2020 (WHO, 2012) and the Fast Track to end AIDS epidemic (UNAIDS, 2011).

Nowadays, disease-prevention interventions are included in the WHO's 17 Sustainable Development Goals; specifically, in the 3rd goal: "To ensure healthy lives and promote well-being for all at all ages" (WHO, 2020). The objectives concerning communicable diseases include to end, by 2030, the epidemics of AIDS, tuberculosis, malaria and neglected tropical diseases, as well as to end preventable deaths of newborns and children under 5 years of age (WHO, 2020). As a result, the currently ongoing Immunization Agenda 2030, the successor of the GVAP 2011–2020, places immunization in the core of national strategies for primary health care and universal health coverage (WHO, 2019). In parallel, a global program to end sexually transmitted diseases by 2030 is ongoing, aiming, for instance, at the elimination of cervical cancer through vaccination interventions against human papillomavirus (WHO, 2016a). The Fast Track initiative to end the AIDS epidemic is still ongoing, setting more ambitious and inclusive targets (UNAIDS, 2014).

1.1.1 Declaring epidemic elimination

Unlike infectious disease *eradication*, defined as the complete termination of disease transmission or the elimination of the infectious agent (Porta, 2013), there is no consensus for the definition of disease *elimination*. Global (respectively, regional) epidemic elimination often refers to the end of an epidemic as a public health concern, through a high or a complete reduction of the infectious disease transmission worldwide (respectively, in the region), during a period of active surveillance (Porta, 2013; Nishiura, 2016). Global and regional programs aiming at disease elimination set specific targets to be met in a certain amount of time and thus, declaring disease elimination may depend on the specific infectious disease and its context. See table 1.1 for some disease-specific targets currently included in WHO programs aiming at regional and/or global elimination.

The classical approach of the WHO to declare the end of an epidemic is to observe a significant period of time (for instance, twice as long as the empirical maximum of the incubation period) passed after the last reported case (Nishiura, 2016). However, the case-free period ap-

proach to determine disease elimination may depend highly on the sample size, be inappropriate for diseases with high proportions of asymptomatic cases ([Nishiura, 2016](#)), and depend greatly on prevention coverage ([Eichner and Dietz, 1996](#)). Other, rather heuristic ways to determine the end of an epidemic may also be used, depending on specific settings. For instance, the declaration of the elimination of the Middle East respiratory syndrome (MERS) in Korea was made after the removal of movement restriction for the last quarantined case ([Nishiura, 2016](#)).

These difficulties could be overcome using mathematical models to estimate the end of an epidemic. For instance, modeling studies have found that asymptomatic cases of poliomyelitis infection may still occur with a probability lower than 1%, 5 years after having no symptomatic cases within a population of 200 000 ([Eichner and Dietz, 1996](#)). In addition, mathematical modeling may provide estimates of unobserved variables and parameters, as well as identify the criteria to be met to end an epidemic; thus being useful to set public health targets for epidemic elimination.

Infectious disease	Main targets	Target year	Ref.
AIDS	<ul style="list-style-type: none"> • 95% of infected people to know their HIV status • 95% of diagnosed people to be on treatment • 95% of people on treatment to have suppressed viral load 	2030	UNAIDS (2014)
Measles	<ul style="list-style-type: none"> • Absence of cases for at least 3 years • High regional coverage of vaccination 	2020 ^{a,b}	(WHO, 2018a)
Poliomyelitis	<ul style="list-style-type: none"> • Absence of cases for at least 3 years • No circulation of wild strains 		(Eichner and Dietz, 1996)
Rubella	<ul style="list-style-type: none"> • 95% reduction in the regional number of cases • Absence of cases for at least 3 years • High regional coverage of vaccination 	2020 ^b	(WHO, 2018a)
Yellow fever	<ul style="list-style-type: none"> • Reduction of the number of outbreaks to none 	2026	(WHO, 2019)

Table 1.1 – Targets of some recent, global WHO programs aiming to end infectious diseases epidemics

^a The American region was certified as having eliminated measles in 2016, after high vaccination coverage efforts, but lost its certification in 2018, after observing several outbreaks. Measles is currently endemic in all regions (WHO, 2020).

^b Unmet targets.

1.2 The prevention versus treatment dilemma

“An ounce of prevention is worth a pound of cure”, goes the popular saying. Yet, the individuals’ preference for prevention over treatment may not be guaranteed. Some studies have indeed found a preference for prevention (Bosworth et al., 2010; Mortimer and Segal, 2008), while others have found a preference for treatment (Corso et al., 2002; Schwappach, 2002) or not a significant preference (Ubel et al., 1998). Preference has also been found to vary widely depending, for instance, on age and health state (Luyten et al., 2015) or the perception of the urgency of adopting a preventive intervention (Meertens et al., 2013). Individuals’ attitudes towards prevention may thus differ from the public health authorities’ recommendations. Therefore, when facing the risk of an epidemic, in a context where efficient treatment is available, individuals who find themselves at risk of infection may engage in a *prevention versus treatment dilemma*, and make the decision between adopting prevention or not, while having the option for treatment in the case of infection.

Voluntary prevention is defined as the preventive methods adopted voluntarily by individuals to avoid infection, that is, by willingly following the recommendations of public health authorities’ — in contrast to mandatory prevention (i.e., required by law or community rules). The voluntary adoption of prevention mainly depends on the individuals’ perception of its benefits and inconveniences versus those of treatment, as well as their perception on their own risk of infection. Public health authorities and healthcare providers may play an essential role shaping these perceptions: by sharing information about epidemics and disease burden, as well as providing information on the available preventive and therapeutic tools, and increasing their availability and access.

To evaluate the impact of voluntary prevention on the epidemic dynamics, in the context where efficient treatment exists, it is thus essential to account for individuals’ resolution of the prevention versus treatment dilemma. Here, we focus on the role of decision-making by individuals facing epidemic threat in a context where efficient preventive and therapeutic methods are available, from the epidemiological and mathematical modeling perspective.

1.3 Mathematical and behavioral epidemiology

Mathematical modeling of infectious diseases was used to assist public health decision-making for the first time in 1760², when Daniel Bernoulli (1700–1782) studied the smallpox epidemic and recommended universal variolation to prevent smallpox-related mortality: "...it has been noticed that, on the one hand, the more natural smallpox spreads, the more dangerous it is; and, on the other, that inoculation carried out at the height of an epidemic is not by any means as reliable as if it were done quite outside any epidemic" (Blower and Bernoulli, 2004). Bernoulli's recommendation was based on his estimation of the number of lives saved by universal inoculation against smallpox (Blower and Bernoulli, 2004). The model proposed by Bernoulli consisted in analyzing surveillance data on the yearly number of individuals who had been infected, the number of deaths due to smallpox infection, etc. Then, he compared the number of smallpox deaths before and after the adoption of inoculation amid the population (Blower and Bernoulli, 2004; Dietz and Heesterbeek, 2002). In his paper, Bernoulli also acknowledged that individuals could be interested in being inoculated because of the benefits it offered at the individual level (such as avoiding lethal infection), versus those offered at the population level (such as increasing the average life expectancy).

Since the 18th century, different kinds of mathematical models have been developed to describe epidemic dynamics (Brauer, 2017). Models are useful to understand the transmission mechanisms behind surveillance data, to estimate the values of parameters that cannot be directly measured, to predict disease epidemiology and to select intervention designs aiming to control the epidemic and/or the disease burden (Valleron, 2000). Mathematical epidemiology has thus become a powerful tool for public health decision-making and epidemic control (Valleron, 2000).

Behavioral epidemiology is a relatively recent branch of mathematical epidemiology arising from the need to include, explicitly, the behavioral changes of individuals facing epidemics. Epidemic dynamics are coupled to behavioral dynamics, which are determined, for instance, by the individuals' attitudes towards preventive and therapeutic tools and/or compliance to public health policies. Behavioral epidemiology thus studies the interplay between human behavior and the course of an epidemic, by considering human behavior as a key component of both epidemic spread and the implementation of public health policies (Bauch et al., 2013). The

²The paper was first presented at the Royal Academy of Sciences in Paris in 1760 and then published in 1766 (Bernoulli, 1766).

scientific production in the field may be found in an overview of the early growth of behavioral epidemiology by Bauch et al. (2013) and an article review of the period 2010–2015 by Verelst et al. (2016). In addition, a review by Wang et al. (2016) focused in mathematical epidemiology of vaccination includes a large section on behavioral models, and a review by Wang et al. (2015) presents models of epidemic spread through contact networks accounting for changes in the individual behaviors.

From the modeling perspective, the issue of voluntary prevention and its impact on the epidemic has been addressed using hybrid models that combine mathematical models describing the disease transmission at the population level, with models describing the individual’s adoption of preventive methods to avoid being infected (Verelst et al., 2016). The infectious disease transmission has been modeled using mostly deterministic compartmental models³ and individual-based models (which allow to consider stochasticity and high heterogeneity between individuals). The adoption of prevention has been modeled, for instance, by a change in the individual’s susceptibility to the infection (such as being immunized), a change in the model parameters (such as reducing disease transmissibility) or a change in the contact structure (such as reducing the number of contacts with other individuals, which is known as *social distancing*); see (Verelst et al., 2016). Traditionally, hybrid models studying social distancing use the individual-based models for the disease transmission, while those studying vaccination use compartmental models (Verelst et al., 2016).

In behavioral epidemiology, individuals are assumed to translate the information about epidemic dynamics into behavioral changes; i.e., acknowledging their risk of infection and making informed decisions. The information about the epidemic has been previously modeled as epidemiological indicators —assumed to be provided to individuals by public health authorities—, as well as subjective perceptions and/or rumors (Verelst et al., 2016). The interaction between the information about the epidemic and the change in behavior has been modeled, for instance, as a threshold that triggers the prevention adoption, as a dynamic parameter which affects and is affected by prevention adoption or as a transfer between compartments explicitly representing the awareness level of the individual (Verelst et al., 2016). Other models based in networked populations have used multiple layers to couple the epidemic-spreading network to a ‘virtual’ information-spreading network (Wang et al., 2016). Some models have used the risk of infection

³As opposed to stochastic models (that can also be compartmental), which can be particularly useful to model disease transmission among small populations.

perceived by individuals to explicitly address the prevention versus treatment dilemma (see section 1.3.3). Only a few hybrid models have been validated using available data (Verelst et al., 2016).

1.3.1 Modeling disease transmission using deterministic compartmental models

Deterministic compartmental models have been widely used to model disease progression and transmission among large populations since 1900 (Brauer, 2017). These models can be expressed as a system of ordinary differential equations (ODE), whose state variables represent the number or proportion of individuals in each compartment, and whose parameters represent the rates of transition from one compartment to another (Hethcote, 2000); for instance, from susceptible to infected, then to infectious or contagious, to recovered, susceptible again, or dead, and so on. The transition of individuals from being susceptible to being infected, is often modeled by the rate of infection, also called *force of infection*. The force of infection may be defined by a constant rate or by a function, depending explicitly on the disease transmission mechanisms, such as the contacts between uninfected and infectious individuals, and their probabilities to occur.

Classical compartmental models are usually named by acronyms obtained from merging the initials of the compartment variables. For instance, a model considering only susceptible, infected and recovered individuals is called an *SIR* model. The Bernoulli's paper mentioned in the previous section can be represented by an *SI* model (Dietz and Heesterbeek, 2002). Figure 1.1 depicts a paradigm example of a classical compartmental model accounting for newborns immunization. Susceptible individuals (S) get infected (I) and then, recover (R). Considering an imperfect preventive method allows to model waining immunity and individuals getting infected despite having been previously immunized⁴. To keep track of immunized individuals, a compartment representing the proportion of newborns who are immunized (M) may be added to the model. The classical *SIR* thus becomes an *MSIR* model.

⁴On the contrary, in the case where perfect immunity is considered, immunized individuals are directly removed from the population — to the Recovered compartment.

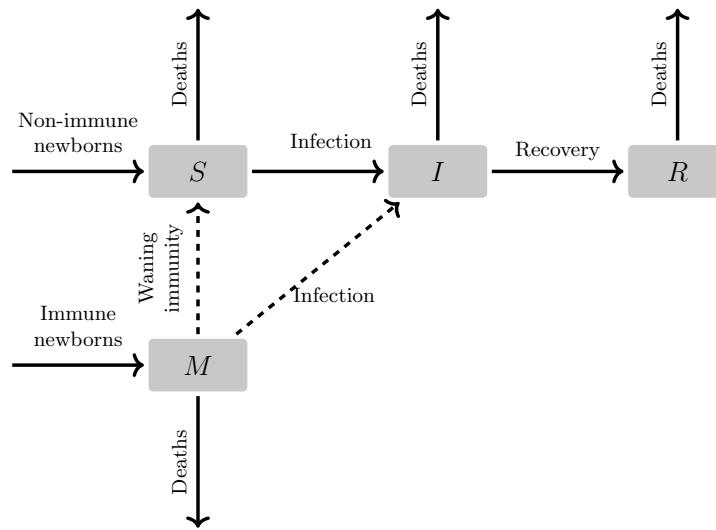


Figure 1.1 – Conceptual compartmental model with prevention

Flow diagram of a classical *SIR*-type compartmental model, describing the transmission of an infectious agent and disease progression, among a population by modeling individuals' transitions through different states, during their lifetime. Some of the newborns may be immunized (*M*) against the infectious disease or not. Susceptible (*S*) individuals get infected (*I*) and then recover (*R*). Depending on the level of protection offered by the preventive method, immunized individuals may get infected nevertheless, and/or immunity may wane with time (dashed arrows).

More complex compartmental models can include population stratification by disease progression (e.g., acute infection, chronic or asymptomatic period), case resolutions (e.g., removal, recovery, death), demographics (e.g., age, sex), exposure to the disease (e.g., risk of infection, number of contacts), use of preventive and/or therapeutic tools, etc.; see ([Hethcote, 2000](#)).

1.3.2 The basic and the effective reproduction numbers

The *basic reproduction number*, noted R_0 , is defined as the expected number of secondary cases produced by a single infectious individual, during the entire infectious period, in a fully susceptible population ([Anderson and May, 1991](#); [Heesterbeek, 2002](#)). The *effective reproduction number*—also called the replacement number—is defined as the expected number of secondary cases produced by an infectious individual, at a given time or in a given context; for instance, once the population is subject to interventions such as prevention and treatment ([Ridenhour et al., 2018](#); [van den Driessche and Watmough, 2008, 2002](#); [Hethcote, 2000](#)).

The basic and the effective reproduction numbers reflect epidemic severity, and thus are useful to study the impact of preventive methods on epidemic dynamics: a large basic reproduction number may be interpreted as a fast epidemic spread among the susceptible population exposed to the infectious disease; a decrease in the effective reproduction number reflects epidemic mitigation.

The basic and the effective reproduction numbers can be estimated using mathematical models ([Ridenhour et al., 2018](#)). In particular, they can be computed from deterministic compartmental models, and thus be expressed as functions of the ODE system parameters ([Heffernan et al., 2005](#)). Notably, there exists a relation between the reproduction numbers and the behavior of the ODE system at the equilibrium ([van den Driessche and Watmough, 2002, 2008](#)). ODE systems defining classical compartmental models for disease transmission, similar to the model depicted in [fig. 1.1](#), often have two equilibria: a disease-free state (DFS), where there are no new infections, and an endemic state (ES), where the epidemic persists ([Hethcote, 2000; van den Driessche and Watmough, 2002](#)). A reproduction number is a threshold parameter for the ODE system equilibria: there is a transcritical bifurcation (that is, an exchange in the stability between the equilibria) for the ODE system when the reproduction number equals to 1. When the reproduction number is lower than 1, the ODE system reaches the DFS and thus the epidemic is eliminated in the long run; otherwise, the ODE system will reach the ES ([Hethcote, 2000; van den Driessche and Watmough, 2002](#)). See [fig. 1.2](#) for a conceptual visualization of the transcritical bifurcation.

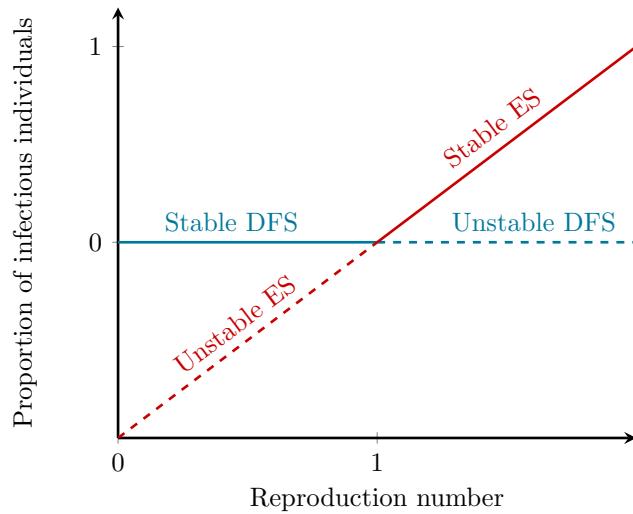


Figure 1.2 – Conceptual diagram of a bifurcation in the ODE system

Classical ODE systems describing disease transmission usually have two equilibria: the disease-free state (DFS, depicted in blue), where there are no new infections, and the endemic state (ES, depicted in red), where the epidemic persists. A change in the stability of the equilibria occurs when the reproduction number equals to 1 (depicted by the transition from a solid to a dashed line). Note that negative populations (red, dashed line), while corresponding to the solutions of the ODE system, have no biological interpretation.

Using the reproduction numbers to determine the herd immunity threshold

Prevention-induced *herd* or *community immunity* refers to the situation in which susceptible individuals are indirectly protected against infection, due to a sufficiently large prevention coverage (i.e., the proportion of the population adopting the preventive method against the pathogen) (Porta, 2013). As a result, disease transmission is greatly reduced and the population is said to be immune as a group; the epidemic is expected to be eliminated in the long run (i.e., the DFS is reached); see (Fine et al., 2011).

From the modeling perspective, the prevention coverage required for the community to reach herd immunity may be obtained by identifying the prevention coverage yielding an effective reproduction number⁵ lower than 1. The larger the basic reproduction number, the larger the prevention coverage required to eliminate the epidemic.

⁵The effective reproduction number depends (implicitly or explicitly, depending on the modeling choices) on the preventive coverage.

Public health authorities usually set the target for prevention interventions depending on the prevention coverage threshold that results in herd immunity. However, as discussed in [section 1.2](#), different public sentiments and strategies towards the prevention versus treatment dilemma may yield a sub-optimal prevention coverage (i.e., lower than the prevention coverage threshold), despite public health recommendations. Hence, to know whether the level of prevention coverage required for herd immunity can be reached voluntarily is key for the implementation of public health interventions.

1.3.3 Modeling the decision-making about prevention adoption using a game-theoretical approach

Among the epidemiological models accounting for behavioral change, game-theoretic approaches have been used to address the individual's decision-making through the study of the prevention versus treatment dilemma; see an early example in ([Bauch et al., 2013](#)), the two previously mentioned reviews about behavioral epidemiology [Verelst et al. \(2016\)](#); [Wang et al. \(2016\)](#) and a recent review, concerning specifically game-theoretic models by [Chang et al. \(2020\)](#). Game theory is a mathematical discipline that allows to model rational decision-making and individual's selection of strategies through the assessment of risk and payoff. The individuals' decisions are modeled by finding the equilibrium set of strategies; that is, the strategies that individuals benefit the most from, in the long run ([Manfredi and D'Onofrio, 2013](#)). Game theory postulates that the rational resolution of the prevention versus treatment dilemma can be mathematically modeled by maximizing the individual's expected *utility*.

Utility thus becomes the fundamental tool for modeling decision-making. In the framework of infectious disease prevention, individuals assess their risk of getting infected, and the expected utility for adopting or not prevention. Since the prevention versus treatment dilemma resolution is rather considered to be costly for a uninfected individual, the individuals' expected utility may be established from the perspective of the total *cost*: maximizing the expected utility is equivalent to minimizing the total expected cost. The total expected cost balances the individual's perception of the cost for adopting the strategy of using prevention versus that of adopting the strategy of being treated in the case of infection. A simplified definition of the total expected

cost takes the following form:

$$\begin{aligned} \text{Total cost} = & \left(\begin{array}{c} \text{Probability of} \\ \text{using prevention} \end{array} \times \begin{array}{c} \text{Cost of} \\ \text{prevention} \end{array} \right) \\ & + \left(\begin{array}{c} \text{Probability of} \\ \text{getting infected} \end{array} \times \begin{array}{c} \text{Cost of infection} \\ \text{and treatment} \end{array} \right). \end{aligned}$$

Identifying the probability of using prevention that minimizes the total cost yields the voluntary prevention coverage reached voluntarily.

Modeling studies using a game-theoretic approach for the individual decision-making have typically used deterministic compartmental models to describe the epidemic dynamics at the population level (Bauch et al., 2003; Bauch and Earn, 2004; Breban et al., 2006; D’Onofrio et al., 2007; Vardavas et al., 2007; Galvani et al., 2007; Breban, 2011; Liu et al., 2012). Applications of compartmental models include vaccination facing a biochemical attack (Bauch et al., 2003), voluntary vaccination during a public scare of vaccination against childhood infectious disease (Bauch and Earn, 2004) and recurrent decision-making on preventing seasonal infections such as influenza (Breban et al., 2006; Galvani et al., 2007), among others. The risk of infection perceived by individuals has been defined, for instance, by a free parameter taking different values (Bauch and Earn, 2004), by epidemiological indicators reflecting the current epidemiological situation (Bauch et al., 2003; D’Onofrio et al., 2007; Breban, 2011; Liu et al., 2012) or considering the past experience of individuals facing the epidemic (Breban et al., 2006; Vardavas et al., 2007; D’Onofrio et al., 2007). Prevention has been considered to offer perfect immunity (Bauch et al., 2003; Bauch and Earn, 2004; D’Onofrio et al., 2007) or short-term immunity, including recurrent decision-making (Breban et al., 2006).

Most of the above-mentioned modeling studies have concluded that the level of prevention coverage achieved through selfish individual-level decisions (i.e., decisions motivated by the individual’s own interest) may differ from the level of prevention coverage needed to achieve herd immunity (Bauch et al., 2003; Bauch and Earn, 2004; Breban et al., 2006; Galvani et al., 2007; Breban, 2011), unless incentives are offered (Vardavas et al., 2007; Liu et al., 2012) and thus, prevention programs may fail to achieve disease elimination. However, as discussed in section 1.1, mass vaccination has resulted in epidemic elimination, globally, regionally or at least temporarily, owing to vaccination campaigns facilitating vaccine adoption on nation-wide scales. Therefore, the impact of voluntary prevention on epidemic dynamics, and whether it can eliminate epidemics

or not, remains to be studied and discussed.

1.4 General objectives of my doctoral research

The main objective of my doctoral research project was to build mathematical models for infectious disease transmission at the population-level, accounting for the individual-level decision-making on whether or not to adopt available preventive methods to avoid the infection, in a context where effective treatment exists. We aimed to evaluate the impact of the voluntary adoption of prevention on the epidemic dynamics. In particular, our purpose was to determine whether and under what conditions could voluntary prevention eliminate epidemics.

Two applications were explored. The first part of my doctoral research focuses on voluntary vaccination against treatable childhood infectious diseases; see [chapter 2](#). The project was designed for analytical understanding of the results. We intended to apply our methods and findings to the epidemiology of an infectious disease preventable by vaccination allowing to assess epidemic elimination; we thus discussed our results in the context of the measles epidemiology. The second part of my thesis focuses on the voluntary use of pre-exposure prophylaxis by men who have sex with men and who are at high risk of infection, in the current context of the HIV epidemic, where highly effective antiretroviral therapies are available; see [chapter 3](#). A more complex model for the HIV transmission was built, so the model was studied using numerical methods.

1.5 General description of our methods

1.5.1 Conceptual framework

We study the interplay between individual behavior and infectious diseases' epidemic dynamics, in the context where effective treatment and imperfect preventive methods are available. We consider the adoption of prevention to be voluntary (that is, not a product of mandatory health policies), whereas treatment is assumed to be immediately adopted after disease diagnosis. That is, we do not study the individual's decision-making regarding the adoption of treatment.

Three hypotheses are key to this research project:

- i) **Individuals' decision maximizes their own benefit.** We assume that individuals are rational, in the sense that they do not act randomly, but rather choose a strategy after assessing their personal situation. In particular, we assume that individuals' decision-making is driven by weighing the perceived pros and cons of prevention versus treatment, as well as their perception of the risk of infection, and choose the strategy that benefits them the most from, in the long run.
- ii) **The costs perceived by individuals concern monetary and/or non-monetary factors.** We assume that individuals' decision-making is driven by the weighing of the perceived benefits and inconveniences of the preventive method versus those of treatment, which include monetary and non monetary aspects, such as price, undesired secondary effects, difficulties in access, disease morbidity, etc.
- iii) **Voluntary prevention coverage may differ from the estimated coverage for epidemic control, recommended by public health authorities.** Since the the risk of infection and the prevention-related barriers perceived by individuals may be biased, the prevention coverage recommended by public health authorities, and allowing to reach herd immunity, may not be achieved. In addition, these perceptions may be susceptible to external factors; for instance, available information and rumors may shape the individuals' attitudes towards the available preventive and therapeutic tools.

1.5.2 The mathematical model

We coupled two components to build a mathematical model describing the interplay between epidemic dynamics and voluntary prevention: one for the infectious disease transmission at the population level and one for the decision-making on whether or not to use prevention, at the individual level. When facing an ongoing epidemic, individuals address the prevention versus treatment dilemma by evaluating their risk of infection, its consequences, the availability of both preventive and therapeutic tools, and the related benefits and constraints. Therefore, the individuals' decision on whether or not to adopt a prevention method to avoid the infection may be biased, yet closely related to the course of the epidemic. Indeed, the risk of infection depends on the epidemic dynamics, which in turn depends on the efficacy and coverage of the preventive and

therapeutic methods. Hence, each individual's decision may be indirectly influenced by others' decisions, since the sum of all decisions determines the voluntary prevention coverage, which impacts the course of the epidemic; see [fig. 1.3](#) for an illustration of our hybrid model.

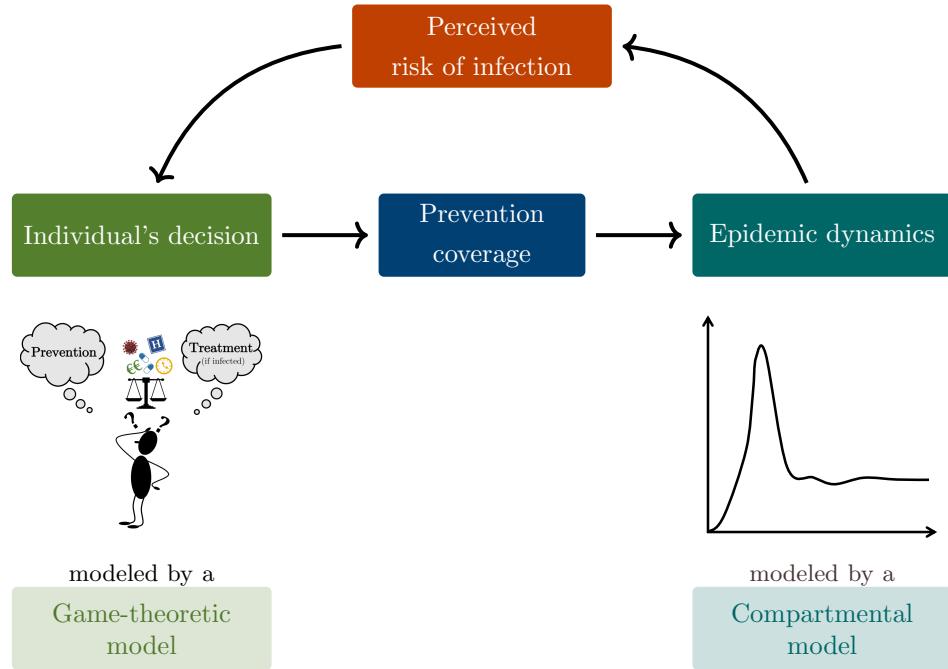


Figure 1.3 – Diagram of our hybrid model

When facing an ongoing epidemic, individuals address the prevention versus treatment dilemma by evaluating the benefits and constraints of both preventive and therapeutic tools, as well as evaluating the risk of getting infected. The risk of infection perceived by individuals depends on the epidemic dynamics, which in turn depends on the efficacy and coverage of the preventive and therapeutic methods. Hence, each individual's decision may be indirectly influenced by others' decisions, since the sum of all decisions determines the voluntary prevention coverage, which impacts the course of the epidemic.

Modeling disease transmission at the population level

To describe disease transmission within a population, we use a deterministic compartmental model, defined by a system of ODEs. We consider additional compartments representing individuals adopting prevention. As stated above, we do not consider that prevention is 100% effective and thus, individuals adopting prevention can nevertheless get infected. Therefore, our model explicitly accounts for two parameters regarding prevention: coverage and effectiveness.

We use the ODE system to compute epidemiological indicators such as the incidence rate, the disease prevalence, the number of diagnoses, etc., which can be expressed explicitly as functions of the prevention parameters. By computing these epidemiological indicators at the endemic state of the system⁶, we observe the behavior of the epidemic in the long run, which is used for the decision-making component of the model (see below).

We compute the effective reproduction number from the ODE system, following the methods developed by [van den Driessche and Watmough \(2002\)](#) and express it as a function of the prevention parameters (namely, the prevention coverage and effectiveness). As mentioned in [section 1.3.2](#), we use the effective reproduction number to study the impact of the preventive methods on the epidemic. We say that the epidemic is *eliminated* or *averted* by the prevention method if the effective reproduction number —a function of the prevention parameters— is below 1. In the case where the effective reproduction decreases with prevention adoption⁷, we say that the epidemic is mitigated or *controlled* by the preventive method, since a reduction in the effective reproduction number is reflected in a reduction in the epidemic's incidence.

We first use the effective reproduction number to determine the conditions under which disease elimination or disease persistence occur, in the long run. In particular, a threshold for the prevention coverage leading to epidemic elimination can be determined. Then, the introduction of the decision-making component allows to study whether and under what conditions this theoretical threshold for epidemic elimination could be reached voluntarily. In addition, we use the effective reproduction number resulting from voluntary prevention coverage to identify a threshold for epidemic control, by finding the conditions under which individuals are motivated to adopt prevention.

Modeling decision-making at the individual level

To describe the individual's decision-making, we rely on a game-theoretical approach: a non-cooperative single-player game, where an individual is assumed to act in his own interest. We assume that individuals address the prevention versus treatment dilemma by evaluating their risk

⁶The existence of the endemic and the disease-free equilibria is studied in detail by [Hethcote \(2000\)](#) for the vaccination model and by [Jacquez et al. \(1988\)](#) for the PrEP model.

⁷In the case of infectious diseases where no other preventive method is available, epidemic control induced by prevention may be characterized by the effective reproduction number being lower than the basic reproduction number.

of infection and by weighing the benefits and inconveniences of the preventive method versus those of treatment, which include monetary and non monetary aspects, such as price, undesired secondary effects, difficulties in access, disease morbidity, etc. In a game-theoretic framework, these factors define the perceived costs. The relative cost of prevention versus treatment thus remains a rather qualitative parameter that indicates how much more beneficial prevention is perceived over treatment.

We formally define the total expected utility as a function of the endemic risk of infection and the *relative cost of prevention versus treatment*, perceived by individuals. We further assume that individuals may acknowledge their true risk of infection (through official estimations of the epidemiological indicators obtained, for instance, from the transmission model, and could be communicated to the public by health authorities, healthcare providers, scientific journalists, associations, etc.), but may also make their decision based on misperception of their risk of infection (based in personal experience, misinformation, peer pressure, etc.).

Model's main outcomes

The prevention coverage that maximizes the individual's expected utility gives the probability for an individual to voluntarily adopt prevention, as a function of the model parameters. Hence, we obtain the *voluntary prevention coverage*, the prevention coverage reached voluntarily by the individuals who perceive themselves at risk of infection. We study the voluntary prevention coverage in terms of the preventive method's parameters: effectiveness and the relative cost of prevention versus treatment. In particular, we look for the conditions for which the voluntary prevention coverage can yield epidemic control and/or elimination, through reduction in the effective reproduction number.

Chapter 2

Voluntary vaccination against treatable childhood infectious diseases

2.1 Introduction

2.1.1 Vaccines against childhood infectious diseases

Vaccines are used to stimulate the individuals' immune system to fight infectious diseases, providing individuals with acquired immunity against the disease — in contrast to naturally-acquired immunity, which occurs after infection and recovery. The development of highly-effective vaccines inducing long-lasting immunity has changed the course of many epidemics ([Global Public Health Achievements Team, 2011](#)). As a result, most countries have established vaccination programs, with vaccination schedules varying between countries and regions. Childhood immunization schedules (i.e., vaccines to be administered before the age of 5, or when children start attending school) currently recommended by the WHO and local public health authorities include vaccines against: measles, bacterial meningitis, mumps, poliomyelitis, and rubella ([Hamborsky et al., 2015](#))¹.

Some of these infectious diseases have reached — or been close to reach — elimination sta-

¹See ([Ministère des Solidarités et de la Santé, 2019](#)) for the vaccination schedule recommended in France.

tus, at least regionally, thanks to high levels of vaccine coverage; see table 2.1. For instance, vaccination made the eradication of smallpox possible in 1980 (WHO, 1980; CDC, 2001). Immunization programs reduced the number of polio cases by 99% since 1988, worldwide. Polio was declared eliminated from the Americas in 1994, from the Western Pacific region in 2000 and from the European region in 2002. As for 2019, polio remained endemic in only 3 countries (WHO, 2019c). The combined measles-mumps-rubella (MMR) vaccine was first licensed for use in the US in 1971 and was recommended worldwide once safety and high effectiveness of the three-vaccine combination were demonstrated in different settings (Strebel et al., 2013). The remarkable reduction of disease cases inspired the worldwide priority goal to eliminate rubella and measles by 2020 (Andrus et al., 2011; WHO, 2020b), which remains yet to be achieved.

As discussed in chapter 1, epidemic control requires safe, highly-effective vaccines, as well as high levels of vaccine coverage. However, despite the large evidence of vaccine-induced reduction in the number of infections and the public health authorities' recommendations about vaccination, parents still hesitate to vaccinate their children (Larson et al., 2016). Therefore, in many settings, the coverage of vaccines against childhood infectious diseases remains suboptimal (that is, below the elimination threshold, the threshold to obtain herd immunity; cf. table 2.1) and disease outbreaks still occur.

Infectious disease	R_0	Year of licence	Vaccine effectiveness	Herd immunity threshold	Vaccine coverage (year)
Diphtheria	4–5 (Anderson and May, 1991)	1930s (Hamborsky et al., 2015)	95% ^a (Hamborsky et al., 2015)	80%–85% (Anderson and May, 1990)	85% ^d (2019) (WHO, 2020a)
Measles	8–18 (Anderson and May, 1991)	1963 (Hamborsky et al., 2015)	>95% ^b (Plotkin et al., 2012)	92%–95% (Anderson and May, 1990)	64% (2016) (WHO, 2018b)
Polio	5–7 (Anderson and May, 1991)	1955 (Plotkin et al., 2012)	99% ^c (Hamborsky et al., 2015)	80%–85% (Anderson and May, 1990)	86% ^c (2019) (WHO, 2020a)
Rubella	6–16 (Anderson and May, 1991)	1969 (Hamborsky et al., 2015)	~100% (Plotkin et al., 2012)	85%–87% (Anderson and May, 1990)	71% (2019) (WHO, 2020a)
Smallpox	3–10 (Plotkin et al., 2012)	1796 (WHO, 2016b)	95% (CDC, 2015a)	66%–70% (Plotkin et al., 2012)	*

Table 2.1 – Key data on vaccination against some preventable childhood infectious diseases, worldwide.

Basic reproduction number (R_0), year of vaccine development (or year of first use as preventive method), vaccine effectiveness, vaccine coverage required to reach herd immunity and vaccine coverage reached worldwide.

^aAfter four spaced doses between 2 and 18 months old.

^bAfter two shortly separated doses.

^cAfter three doses of inactivated poliovirus vaccine.

^dCorresponding to three doses.

*Eradication declared in 1980 (WHO, 1980). Smallpox eradication was reached through massive inoculation programs, initially aiming to reach at least 80% in 1966, then aiming to reach a 100% coverage (Plotkin et al., 2012).

2.1.2 Vaccine hesitancy

The WHO (2014) defines vaccine hesitancy as the “delay in acceptance or refusal of vaccines despite availability of vaccine services”. In 2019, vaccine hesitancy was listed among the ten threats to global health by the WHO (2019). The underlying causes for vaccine hesitancy vary widely, from misinformation, to undesired effects, safety concerns, healthcare system mistrust, social pressure, religious convictions, etc. (Brown et al., 2010; Dubé et al., 2013; Larson et al., 2014; Dubé et al., 2018; Quinn et al., 2019).

A large-scale survey on confidence in immunization conducted in 2015 found that, while the state of vaccine confidence is overall high worldwide, there are regions where vaccine hesitancy remains a public health challenge (Larson et al., 2016). Seven of the ten least confident countries were identified in the European region. Among the 67 countries included in the survey, France was identified as the country having the lowest confidence in vaccine safety: 45.2% of French respondents reported mistrust in vaccine safety (of note, the global average was 13%) (Larson et al., 2016); see fig. 2.1.

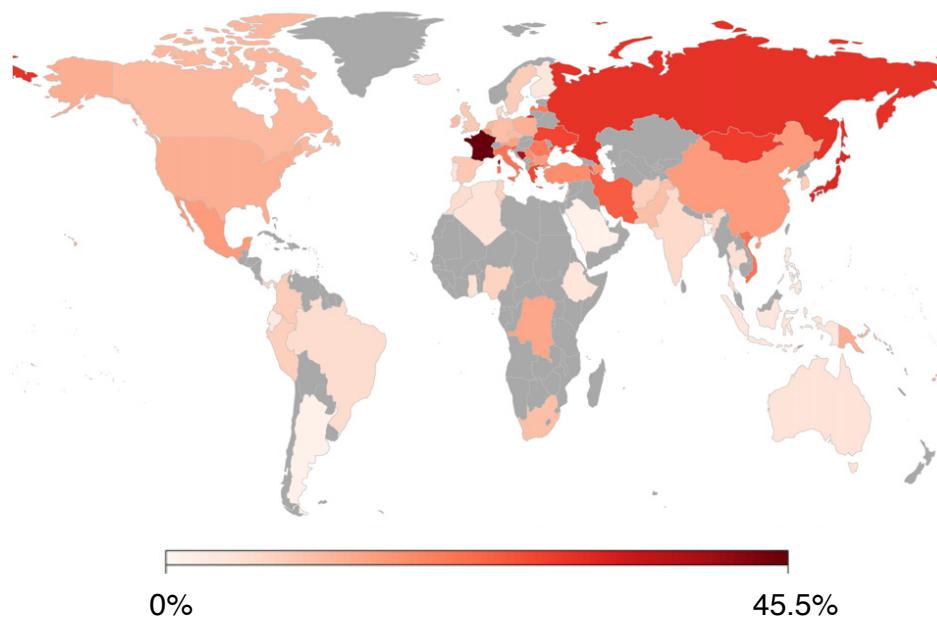


Figure 2.1 – Immunization mistrust, worldwide

World map of the proportion of negative responses (“tend to disagree” or “strongly agree”) to the survey the statement “Overall I think vaccines are safe”. Figure extracted from (Larson et al., 2016).

Childhood-vaccine hesitancy may result in a decline in vaccination coverage, which may reach sub-optimal levels and lead to outbreaks of infectious diseases otherwise controlled, such as measles (Strebel et al., 2013). Indeed, as of 2017, twelve countries of the European Union (EU) had reported a decrease in the MMR vaccine coverage (Larson et al., 2018). Parents declining MMR vaccination for their children have declared to mistrust vaccines' safety and effectiveness, as well as believing that the diseases they prevent are mild and uncommon (Brown et al., 2010). Hence, measles vaccination coverage and incidence are considered as tracers of the strength of immunization programs for the 2030 SDG (WHO, 2019).

2.1.3 The measles epidemic: its place on the path towards elimination

Measles infection, treatment and prevention

Measles is a highly contagious airborne disease. Its clinical course goes as follows. The median incubation period varies from 10 to 13 days after exposure (CDC, 2015b; Strebel et al., 2013), after which symptoms appear. A rash appears around 14 days after exposure, spreading from the head to the rest of the body in a few days. Other symptoms include high fever, conjunctivitis and coughing. Individuals infected with measles are considered to be infectious from 4 days before to 4 days after the rash onset. After infection, individuals acquire lifelong immunity. Newborns may be passively immunized through maternal antibodies, which protects them during the first months of life (Strebel et al., 2013).

In high-income settings, the most common complications of measles infection include: otitis (7%–9%), pneumonia (1%–6%, mostly among children younger than 5 years), encephalitis (1 per 1 000–2 000 measles cases, mostly among adults older than 20 years) and death (1–3 per 1 000 measles cases, where 60% of fatalities are caused by pneumonia) (Strebel et al., 2013).

Treatments for measles do not cure the disease, but may help reducing the symptoms, the disease duration and the probability of developing complications. Treatments include the administration of vitamin A (recommended for children with acute measles), dehydration treatment, and the prescription of Ribavirin and Interferon, which are antivirals mostly recommended to treat cases with complications or immunocompromised individuals (Strebel et al., 2013).

The first vaccine against measles², consisting of the attenuated virus, was licensed in the US in 1963. Around 19 million doses were administrated in the US from 1963 to 1975. Other attenuated vaccines have been developed and are currently used around the world (Strebel et al., 2013). The measles vaccine is currently administered through the MMR vaccine, by subcutaneous injections. The MMR vaccine provides immunity similar to that of natural infection; that is, lifelong immunity.

MMR vaccine is currently recommended to be administrated in two doses. As of 2018, all countries included the first dose of MMR or other measles-containing vaccines (MCV) to the vaccine schedule, whereas only 89% included the second dose (Peck et al., 2017). In most countries, the first dose is to be administered at 12 to 15 months old, and the second dose at the age of 4 to 6, before entering school. Studies have found that a high proportion of the individuals who have not had an immune response to the first dose, will respond to the second dose. Hence, the second dose is not considered a booster, but rather a way to ensure immunological response among a greater proportion of the population. MMR vaccine effectiveness has been estimated at more than 95% (Strebel et al., 2013).

Adverse effects induced by the MMR vaccine are mild. During the 6 to 12 days following vaccination, some vaccinees may experience fever (5% to 15% of the vaccinees) and rash (5% of the vaccinees). These adverse effects are more common after the first dose, rather than after the second dose, since most vaccinees do have an immune response following the first MMR administration (Strebel et al., 2013).

The measles epidemiology

Before the introduction of the measles vaccines, virtually everybody got infected, mostly before the age of 10 (Strebel et al., 2013). The effective reproduction number for measles has been estimated to be as high as 18 (Anderson, 1992), but estimations may vary by context and estimation method (Guerra et al., 2017). Around 2.6 million deaths were caused by measles each year, worldwide (WHO, 2019b). The proportion of the population that needs to be vaccinated in order to reach herd immunity has been estimated at 92% to 95% (Strebel et al., 2013).

The success of smallpox eradication had raised hopes of eliminating measles in the 80s

²Called the *Edmonston B* vaccine.

(Hopkins et al., 1982). In 1997, the WHO, the Pan American Health Organization (PAHO) and the Centers of Disease Control (CDC) established the goal of eradicating measles from the Pan American region by 2010 (Services, 1997). Intensive two-dose vaccination campaigns lead to measles no longer being endemic in the region in 2002, since transmission was interrupted in many countries (Sever et al., 2011; De Quadros, 2004). Single-dose vaccinations have demonstrated to be effective, as well, especially when mass vaccination campaigns are successfully implemented (Sever et al., 2011). Some countries tried to establish a single-dose administration of measles vaccine, but outbreaks persisted and the two-doses program was reestablished to ensure high levels of immunity at the population level (Strebel et al., 2013).

Despite these successes, measles reemerged in the American region in 2003, with some reported cases that were attributed to virus reintroduction and failure in implementing the recommendations on vaccination strategies (Services, 1997; De Quadros, 2004; Andrus et al., 2011). Still, measles epidemic remained relatively controlled in the region, which raised expectations to eliminate measles globally by 2015 (De Quadros, 2004).

Measles has reemerged in many countries, worldwide, including high-income countries, mostly due to a decrease in MCV vaccine coverage. Large outbreaks have been reported during the period 2008–2012 in countries like Italy, France and the UK (Amendola et al., 2015; Antona et al., 2013; Keenan et al., 2017; Bechini et al., 2019). As of 2018, the coverage level of the first dose of MCV was 86%, whereas for the second dose it was 69%, worldwide (Peck et al., 2017) — way below the 95% threshold for measles vaccine coverage to yield epidemic elimination. In the European region, the coverage was of 95% and 91%, respectively (Peck et al., 2017). By the end of the first half of 2019, the European region had reported the highest number of measles cases in the last decade (WHO, 2019; ECDC, April 2019). In particular, around 2600 cases were reported in France alone (WHO, 2020); see fig. 2.2 for a visualization of the measles epidemiology and MMR vaccine coverage in France, during the last decade. French coverage of MMR vaccination remained below the recommended thresholds, which provoked the reemergence of measles outbreaks in the French territory.

Measles epidemics have thus shown to be on a path towards epidemic elimination (Graham et al., 2019), at least in some regions and at a given time, but levels of vaccine coverage failing to reach the herd-immunity threshold keep yielding measles outbreaks around the world, including high-income settings.

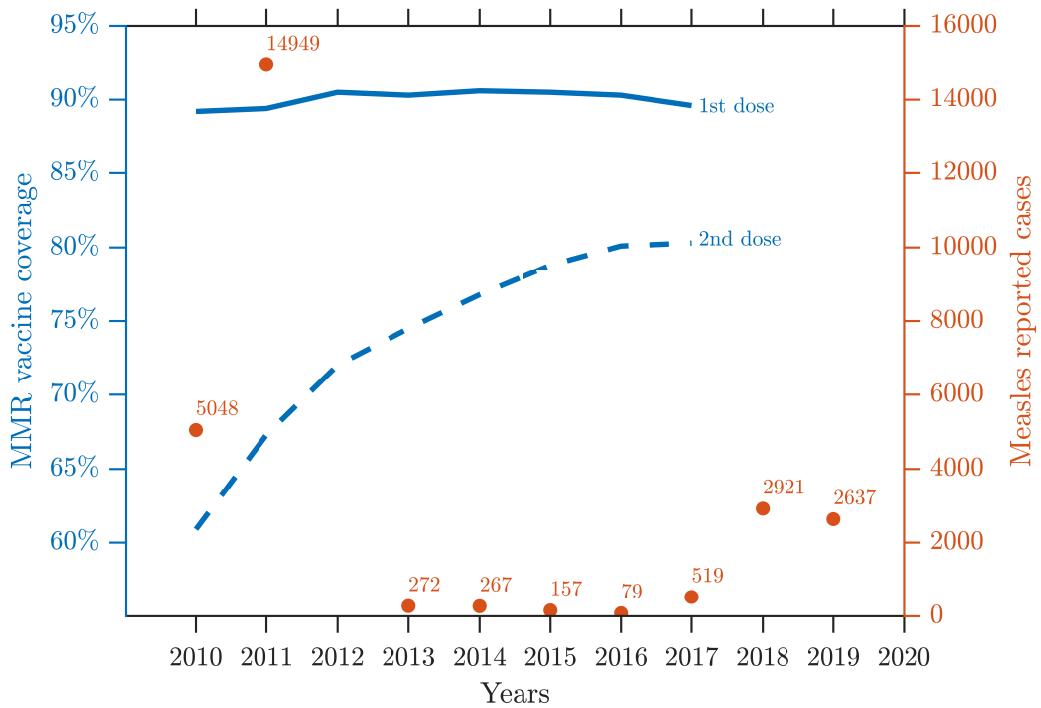


Figure 2.2 – MMR vaccine coverage and measles cases in France

In blue, the coverage for the first (solid line) and the second recommended doses (dashed line) of MMR vaccine, among 2-year-old children, for the period 2010–2017 (France, 2019). In red, the reported cases of measles in France, for the period 2010–2019 (WHO, 2020); N.B. no data was reported to the WHO in 2012. The coverage of the first recommended dose of MMR has been stable, around 89%, while the coverage of the second dose increases, but remains below 80%. These low vaccine coverages do not allow epidemic elimination. Indeed, large outbreaks occurred during the period 2010–2011, and again from 2018 on (WHO, 2020).

2.2 Publication

A scientific article titled “Prevention of treatable infectious diseases: a game-theoretic approach” (Jijón et al., 2017) was published in the journal *Vaccine*.

2.2.1 Description of the article

A brief overview of the literature regarding the modeling of infectious diseases and voluntary vaccination is found in the introduction. We propose a model combining game theory with an

infectious disease transmission model, in order to study the epidemic dynamics as a result of the individual-level decision-making on whether or not to adopt vaccination against childhood infectious diseases. A flow chart representing the compartmental model for the disease transmission at the population level is depicted in [fig. 2.5](#) of [section 2.3](#). We present in detail the methods used to compute the voluntary vaccination coverage and to determine the conditions ensuring epidemic elimination. An application of the model to the epidemiology of measles is provided. The paper includes a discussion on public policies that may be implemented in high-income settings in order to increase vaccine adoption.

2.2.2 Results statements

Adding the decision-making model to the classical disease-transmission model provides an estimate of the vaccination coverage that can be reached voluntarily, as a function of the relative cost of vaccination versus treatment, perceived by individuals. Therefore, the relative cost becomes the parameter to be tuned to increase vaccination coverage.

According to our findings, voluntary-vaccination programs can successfully avert epidemics if vaccines are highly efficient, the vaccine-induced immunity is long-lasting and they are delivered at low perceived cost. However, epidemic elimination may only be temporary (cf. [fig. 2.6](#) in [section 2.3](#)) and active efforts from public health authorities are needed to maintain the perceived cost of vaccination low.

In addition, our model provides lower bound estimates for the vaccine efficacy and the duration of vaccine-induced immunity, as well an upper bound for the relative cost of vaccine versus treatment, in the context of epidemics controlled by vaccination. These parameters are expressed as functions of the basic reproduction number, i.e., the epidemic severity before the introduction of preventive methods.

Application to measles

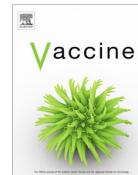
We applied our methods to the epidemiology of measles. Our findings are in accord with regional measles elimination, which was possible thanks to the very long-lasting immunity induced by the MMR vaccine, as well as to the relative cost of vaccination versus treatment which was certainly

perceived as low during the mass-vaccination programs of the 90's.

However, a decrease in vaccine coverage has been observed in several high-income countries. We conclude that reducing the cost of vaccination perceived by individuals in the current context, where measles disease and its sequelae have been less witnessed, may help reaching epidemic elimination through voluntary vaccination, and maintaining elimination status in the long run. For instance, by maintaining the population informed about measles epidemiology in the pre-vaccination era, the disease burden and measles-vaccine high-performance.

2.2.3 Article

The article in its published form is attached from the next page.



Prevention of treatable infectious diseases: A game-theoretic approach



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ARTICLE INFO

Article history:

Received 11 May 2017

Received in revised form 16 August 2017

Accepted 17 August 2017

Available online 31 August 2017

Keywords:

Prevention versus treatment

Childhood infectious diseases

Imperfect vaccine

SEIR model

Game theory

ABSTRACT

We model outcomes of voluntary prevention using an imperfect vaccine, which confers protection only to a fraction of vaccines for a limited duration. Our mathematical model combines a single-player game for the individual-level decision to get vaccinated, and a compartmental model for the epidemic dynamics. Mathematical analysis yields a characterization for the effective vaccination coverage, as a function of the relative cost of prevention versus treatment; note that cost may involve monetary as well as non-monetary aspects. Three behaviors are possible. First, the relative cost may be too high, so individuals do not get vaccinated. Second, the relative cost may be moderate, such that some individuals get vaccinated and voluntary vaccination alleviates the epidemic. In this case, the vaccination coverage grows steadily with decreasing relative cost of vaccination versus treatment. Unlike previous studies, we find a third case where relative cost is sufficiently low so epidemics may be averted through the use of prevention, even for an imperfect vaccine. However, we also found that disease elimination is only temporary—as no equilibrium exists for the individual strategy in this third case—and, with increasing perceived cost of vaccination versus treatment, the situation may be reversed toward the epidemic edge, where the effective reproductive number is 1. Thus, maintaining relative cost sufficiently low will be the main challenge to maintain disease elimination. Furthermore, our model offers insight on vaccine parameters, which are otherwise difficult to estimate. We apply our findings to the epidemiology of measles.

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1. Introduction

The 20th century has witnessed tremendous achievements in infectious disease prevention, especially with the development of effective preventive vaccines [1], often far less costly than treatment [2]. Still, the preference between prevention and treatment remains a dilemma. Some studies found no preference [3–5], others a preference for prevention [6,7], or a preference for treatment [8,9], or that preference for prevention versus treatment depends on the circumstances [10,11].

The prevention of treatable infectious diseases still poses challenges for public health authorities [12]. Faced with infection risk, individuals may decide to use prevention, or else get treated if they acquired infection. Whereas treatment is generally well accepted by infected individuals, prevention may have a wide range of acceptability profiles for the susceptible. Individual-level perceptions of risk, as well as weighing pros and cons of prevention ver-

sus treatment, may differ from the recommendations of the public health authority [13], for a variety of reasons [14,15].

The decision to use voluntary vaccination and its impact on disease transmission has been theoretically studied using mathematical models with two components: one describing the population-level epidemiology and another describing the strategy by which an individual makes his choice of whether or not to get vaccinated [16–39]. Both compartmental models [16–18,28,33–39] and social networks [19–22] have been used as the population-level model component. For the individual-level component, imitation dynamics [22,23,39], “wait and see” strategies [38], social distancing strategies [24,25], maximization of the utility of prevention [16,26–31] and inductive reasoning [33–36] have been studied. The role of altruism for the individual-level strategy has also been considered [32]. Several modeling studies discuss the impact of public misperceptions about vaccination programs on vaccination uptake [16,23,27,28,22].

The main research direction of the modeling work has been individual and group behavior in the dilemma of whether or not to get vaccinated [16–20,22–32,37–39]. Another direction has been vaccination subsidies and incentives [21,33–36]. A review of recent literature can be found in Ref. [40].

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The purpose of the current work is to assess the performance of a voluntary prevention program, utilizing an imperfect vaccine, which confers protection only to a fraction of vaccinees for a limited duration. We show that voluntary vaccination with an imperfect vaccine may temporarily eliminate epidemics. We apply our findings to the measles epidemiology.

2. Model

We propose a mathematical model describing the interplay between voluntary vaccination and treatment during the course of an epidemic. In particular, our model addresses the setup where vaccination is available as a prevention method against childhood infectious diseases. However, we assume that the vaccine is imperfect [41,42]. We consider two aspects of vaccine failure and introduce appropriate parameters. First, the vaccine may not take for all vaccinees; the fraction of vaccinees for which the vaccine yields an immune response is called *vaccine efficacy*. This has been largely used to model voluntary vaccination [27–29,32,38,39]. In this case, the key epidemiological concept is the *effective vaccination coverage* [43,44], the fraction of the population that acquires immunity due to vaccination. Second, even if the vaccinee acquires an immune response, this may not result in lifelong immunity. That is, the vaccinee acquires a limited *duration of immunity*, a feature much less studied in the modeling of voluntary vaccination [20].

We describe epidemic dynamics using an *SEIR*-type system of ordinary differential equations. Recovery may be reached naturally or through treatment, which may be either symptomatic or therapeutic. Furthermore, we involve an individual-level model of decision-making about whether or not to get vaccinated. We assume that individuals make their decisions by judging pros and cons for vaccination versus treatment, and have a sense of the imminence of getting infected and then treated. According to game theory, such a decision-making process may be modeled as a *non-cooperative game*, where individuals act in their own interest to maximize the utility of vaccination versus treatment. However, an individual's decision is indirectly influenced by those of others: the sum of all individuals' decisions determines the proportion of the population that gets vaccinated, which, in turn, affects the epidemic progression and the probability of acquiring infection. The game model is intertwined with the model of epidemic dynamics. Model analyses assume that the resolution of the dilemma of vaccination versus treatment yields stable disease epidemiology.

2.1. The compartmental model

We make further assumptions for our deterministic *SEIR*-type model. The vaccination program is constantly in place, regardless of whether or not there is an epidemic. Treatment is available in unlimited supply, and no decision-making is involved about when to start treatment. Complete recovery is possible, with the benefit of lifelong immunity. These assumptions lead to the following ordinary differential equations of *SEIR* type:

$$\begin{aligned} \frac{dV}{dt} &= \epsilon p \pi - (\rho + \mu)V, \\ \frac{dS}{dt} &= (1 - \epsilon p) \pi + \rho V - \frac{\beta I}{N} S - \mu S, \\ \frac{dE}{dt} &= \frac{\beta I}{N} S - (v + \mu)E, \\ \frac{dI}{dt} &= vE - (\sigma + \gamma + \mu)I, \\ \frac{dR}{dt} &= (1 - \xi) \sigma I + \gamma I - \mu R, \\ \frac{dT}{dt} &= \xi \sigma I - \mu T. \end{aligned} \quad (1)$$

Newborns can remain susceptible (*S*) or acquire vaccine-induced immunity (*V*), in which case they may become susceptible thereafter, as vaccine-induced immunity wanes. Recently infected individuals (*E*) pass through a latent stage of infection. Then, they

become infectious (*I*) and can recover either naturally (*R*) or through treatment (*T*). The total population size is given by $N = V + S + E + I + R + T$.

The probability of getting vaccinated is denoted by p and the vaccine parameters are ϵ , the vaccine efficacy, and ρ , the rate of waning of vaccine-induced immunity. The parameter π stands for the inflow of newborns, μ is the disease-unrelated death rate, β stands for the disease transmissibility, v for the progression through the latency stage, σ is the rate at which individuals start treatment, ξ represents the treatment efficacy and γ is the natural recovery rate. All variables and parameters are positively defined.

The model has two equilibria: a disease-free state (DFS) where

$$V_{\text{DFS}} = \frac{\epsilon p \pi}{\rho + \mu}, \quad S_{\text{DFS}} = \frac{\rho \epsilon p \pi}{\mu(\rho + \mu)} + \frac{(1 - \epsilon p) \pi}{\mu}, \quad (2)$$

and $E_{\text{DFS}} = I_{\text{DFS}} = R_{\text{DFS}} = T_{\text{DFS}} = 0$, and an endemic state (ES) where all the equilibrium components are non-zero

$$\begin{aligned} V_{\text{ES}} &= \frac{\epsilon p \pi}{\rho + \mu}, \quad S_{\text{ES}} = \frac{\pi}{\mu R_0}, \quad I_{\text{ES}} = \frac{\pi}{\beta}(R^* - 1), \\ E_{\text{ES}} &= \frac{\sigma + \gamma + \mu}{v} I_{\text{ES}}, \quad R_{\text{ES}} = \frac{(1 - \xi)\sigma + \gamma}{\mu} I_{\text{ES}}, \quad T_{\text{ES}} = \frac{\xi\sigma}{\mu} I_{\text{ES}}, \end{aligned} \quad (3)$$

where

$$R^* = \left(1 - \frac{\epsilon p \mu}{\rho + \mu}\right) R_0, \quad (4)$$

and

$$R_0 = \frac{\beta v}{(v + \mu)(\sigma + \gamma + \mu)}. \quad (5)$$

R^* is called the *effective reproduction number*, representing the expected number of secondary cases produced by a single infectious individual within a disease-naive population. It is important to note that, in a population undergoing disease prevention, R^* depends on the level of disease susceptibility. In our case, R^* is a function of p , the probability of getting vaccinated. The *SEIR*-type model (1) undergoes a transcritical bifurcation [45] at $R^* = 1$. If $R^* > 1$, then ES will be reached; otherwise, $R^* \leq 1$ and DFS will be reached. R_0 is the *basic reproduction number* [46,47,45], obtained from the model in the absence of prevention (i.e., $p = 0$). To quantify the impact of vaccination on epidemics, we analyze $R^*(p)$ given that there is an epidemic in absence of vaccination; i.e., $R_0 > 1$.

Using Eqs. (2) and (3), the *endemic prevalence* of the infectious disease can be written as

$$\Pi(p) = \begin{cases} \Pi_{\text{DFS}}(p), & \text{if } R^* \leq 1, \\ \Pi_{\text{ES}}(p), & \text{if } R^* > 1; \end{cases} \quad (6)$$

where

$$\Pi_{\text{DFS}}(p) = \frac{I_{\text{DFS}} + E_{\text{DFS}}}{N_{\text{DFS}}} = 0, \quad (7)$$

and

$$\Pi_{\text{ES}}(p) = \frac{I_{\text{ES}} + E_{\text{ES}}}{N_{\text{ES}}} = \frac{\mu}{\beta} \left(1 + \frac{\sigma + \gamma + \mu}{v}\right) (R^*(p) - 1). \quad (8)$$

A critical vaccination coverage, p_c , may be defined using $R^*(p_c) = 1$ or, equivalently, $\Pi_{\text{ES}}(p_c) = 0$, and verifies

$$\epsilon p_c = \left(1 + \frac{\rho}{\mu}\right) \left(1 - \frac{1}{R_0}\right). \quad (9)$$

A similar formula is provided in Ref. [41, Eq. (8)]. In the case of a perfect vaccine (i.e., $\rho = 0$ and $\epsilon = 1$), Eq. (9) recovers a well-known result; see Refs. [46, p. 87] and [47, ch. 6].

A diagram of disease prevalence at the equilibria of the *SEIR*-type model (1), as a function of p , is shown in Fig. 1. ES is always

stable (attracting), while DFS is unstable (repelling) for $p < p_c$ and stable for $p > p_c$. It is important to note that, in the general case where the vaccination coverage is a function of time, disease-free dynamics, where $E = I = R = T = 0$, is possible for all values of R_0 .

2.2. The single-player game

We assume vaccination to be voluntary. The pros and cons of vaccination versus treatment perceived by a typical individual may be biased and involve monetary and/or non-monetary aspects [15] such as: price, undesired vaccine effects, accessibility of vaccination, vaccination schedule, time spent to get vaccinated, disease morbidity, secondary effects induced by (symptomatic or/and therapeutic) treatment, etc. In game theory, they are generally expressed as cost. A utility function is employed to make the balance of all the cost with respect to vaccination versus treatment, as described below. Game theory postulates that the individual-level decision of whether or not to get vaccinated maximizes the utility of vaccination. Mathematically, this is expressed by maximizing the utility function. As a result, we obtain the probability that a typical individual gets vaccinated, depending on cost and vaccine and epidemiological parameters. In turn, this yields the voluntary vaccination coverage. Hence, the addition of game theory to the SEIR-type model (1) makes explicit that the vaccination coverage is not a parameter of the model that may be easily tuned. Rather, the relative cost of vaccination versus recovery is a more tunable parameter, as we will see below.

We assume that individuals address the matter of vaccination as long as they acknowledge an epidemic threat in the absence of vaccination (i.e., $R_0 > 1$). Otherwise, individuals do not get vaccinated. We also assume that individuals have a sense of the probability of acquiring infection when there is an epidemic threat. We express this probability using the endemic prevalence of the infectious disease, Π , defined by Eqs. (6)–(8).

The balance of cost is as follows. To prevent getting infected under epidemic threat, an individual would pay the cost of vaccination, c_p , with probability p of getting vaccinated, and the cost of recovery, c_r , with probability $(1 - \epsilon p)\Pi(p)$ of getting infected. A similar account of costs may be found in Ref. [23, Eqs. (2.1) and (2.2)]. The utility function of vaccination versus treatment when $R_0 > 1$ becomes:

$$U(p; c_p, c_r) = -p c_p - (1 - \epsilon p) c_r \Pi(p), \quad (10)$$

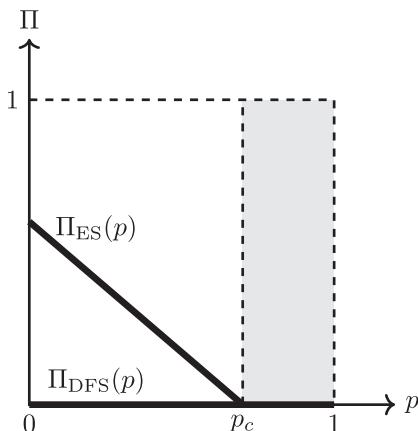


Fig. 1. The endemic prevalence, Π , as a function of the vaccine coverage, p . If $R^* \leq 1$ ($p > p_c$), the system reaches the disease-free state (DFS) where $\Pi_{DFS} = 0$. On the other hand, if $R^* > 1$ ($p < p_c$), the system reaches the endemic state (ES) with endemic prevalence Π_{ES} . We note that DFS still exists for $p < p_c$, but it is unstable.

where c_p and c_r are positive. Introducing the relative cost of vaccination versus recovery $r = c_p/c_r$ and rescaling the utility function $U(p; r)$ by c_r , we obtain

$$U(p; r) = -pr - (1 - \epsilon p)\Pi(p). \quad (11)$$

3. Results

By maximizing the utility function $U(p; r)$ for the individual player, we obtain an expression of the probability for an individual to get vaccinated as a function of the relative cost of vaccination versus recovery. We denote this probability by $\hat{p}(r)$.

Case 1: $R^* > 1$. The probability $\hat{p}(r)$ is a solution of $\partial U(p; r)/\partial p = 0$ and verifies

$$\epsilon \hat{p}(r) = \begin{cases} \frac{r_b - r}{r}, & \text{if } r_a < r < r_b, \\ 0, & \text{if } r \geq r_b, \end{cases} \quad (12)$$

where

$$\tilde{r} = \frac{2\epsilon\mu^2}{(\nu + \mu)(\rho + \mu)} \left(1 + \frac{\nu}{\sigma + \gamma + \mu} \right), \quad (13)$$

and

$$r_b = \tilde{r} \left[1 - \frac{1}{2R_0} + \frac{\rho}{2\mu} \left(1 - \frac{1}{R_0} \right) \right]. \quad (14)$$

The restriction $R^*(\hat{p}) > 1$ yields $r > r_a$, where

$$r_a = \tilde{r} \left[\frac{1}{2R_0} - \frac{\rho}{2\mu} \left(1 - \frac{1}{R_0} \right) \right]. \quad (15)$$

Eqs. (14) and (15) yield $r_a < r_b$ whenever $R_0 > 1$. A threshold for the probability for an individual to be effectively vaccinated is immediately obtained

$$\epsilon \hat{p}(r_a) = \left(1 + \frac{\rho}{\mu} \right) \left(1 - \frac{1}{R_0} \right), \quad (16)$$

retrieving Eq. (9) for p_c .

Case 2: $R^* \leq 1$. In this case, $0 \leq r \leq r_a$ and the endemic prevalence is zero; cf. Eq. (7). Utility reaches the maximum value of zero at $\hat{p}(r) = 0$; cf. Eq. (11). Along with Eq. (4), this implies $R^* = R_0 > 1$ and leads to contradiction. We conclude that the game theoretic assumption of an equilibrium resolution of the vaccination-versus-treatment dilemma is not tenable. There exists no equilibrium coverage for voluntary vaccination once the epidemic has been averted; $\hat{p}(r)$ does not have a stable equilibrium when $R^* \leq 1$.

The results on voluntary vaccination coverage are summarized in Fig. 2. Given the vaccine efficacy, ϵ , the domain of the function $\epsilon \hat{p}(r)$, representing the probability of effective vaccination, is divided into three regions. Region (c) corresponds to $r \geq r_b$, where individuals find the relative cost of vaccination versus treatment too high and do not get vaccinated; i.e., $R^* = R_0 > 1$. Region (b) corresponds to $r_a < r < r_b$, where some individuals adopt prevention and the epidemic is alleviated; i.e., $R_0 > R^* > 1$. Region (a) corresponds to $0 \leq r \leq r_a$ and $R^* \leq 1$. Individuals will get vaccinated in sufficient numbers to avert the epidemic, as long as they have the motivation to do so. However, according to our model, a long-term motivation based on disease prevalence does not exist.

This situation may be reversed if an incentive is used and individuals perceive a net gain from being vaccinated (i.e., r is allowed to take negative values) when $R^* \leq 1$. Straightforward calculations show that, in this case, $\hat{p}(r) = 1$ maximizes the utility of vaccination, independently of the perceived gain.

Fig. 1, intended for the SEIR-type model (1), remains illustrative for the two-component model using game theory, as well. Just as before, ES exists for the region $0 \leq p < \hat{p}(r_a) = p_c$ (i.e., $R^* > 1$) and

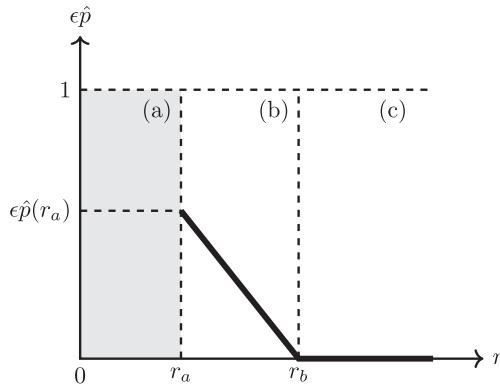


Fig. 2. The probability that individuals get effectively vaccinated, $\hat{e}\hat{p}(\epsilon, r)$, as a function of the relative cost of vaccination versus treatment, r . The domain is divided into three regions. In region (c), individuals do not get vaccinated due to the high cost of vaccination versus treatment. Region (b) corresponds to the case where lower cost encourages some individuals to adopt vaccination and, as a result, the epidemic is alleviated. For region (a), the relative cost is significantly reduced. However, the interplay between vaccination and treatment there does not lead to steady disease epidemiology.

is stable. However, DFS exists only for $p = 0$ and is unstable, as we assumed $R_0 > 1$.

The equilibrium structures uncovered in Figs. 1 and 2 invite to a discussion about vaccine parameters. From the point of view of public health, the first and key desideratum is the ability to prevent epidemics; i.e., $p_c \leq 1$. This yields (cf. Eq. (9))

$$\frac{\epsilon}{1 + \rho/\mu} \geq 1 - \frac{1}{R_0}, \quad (17)$$

and guarantees the existence of region (a) in Fig. 2, where epidemics may be temporarily prevented. From Eq. (15), we obtain that $r_a > 0$ if and only if

$$\frac{R_0 - 1}{\mu} < \frac{1}{\rho}. \quad (18)$$

That is, region (a) exists if and only if the duration of vaccine-induced immunity, $1/\rho$, is larger than $(R_0 - 1)$ expected lifetimes, $1/\mu$.

The second desideratum is that region (a) be as large as possible in terms of the relative cost of vaccination versus treatment, to leave room for ample variation in cost. It can be shown that

$$0 \leq r_a \leq \frac{\mu}{R_0(\mu + \nu)} \left(1 + \frac{\nu}{\sigma + \gamma + \mu} \right). \quad (19)$$

Furthermore, we have $\partial r_a / \partial \epsilon > 0$ and $\partial r_a / \partial \rho^{-1} > 0$; i.e., r_a increases with improving the efficacy and induced duration of immunity of the imperfect vaccine.

3.1. Application to measles

Measles is a very contagious infectious disease, for which only symptomatic treatment and treatment to improve disease outcomes (e.g., vitamin A) are available [48–50]. Recovery from infection is believed to lead to lifelong immunity [50]. However, measles can be prevented through vaccination, which induces long-term protection [51,52]. Before the vaccine was developed, infection with measles virus was nearly universal during childhood [50]. The average number of secondary infections generated by index cases in fully susceptible populations was estimated at $R_0 = 5–18$ [46, p. 70] or 12.5–18 [42].

Mass vaccination campaigns ran in many countries once the vaccine was licensed in the 60's, and were continued by national programs for the vaccination of children. Measles vaccine schedules varied across time and countries [51]. Initially, the recommendation was to administer one dose at 8–9 months of age. Then, the recommended age for vaccination was raised to 12–15 months in some countries, mainly high-income countries, to overcome the inhibitory effect of maternal antibodies on vaccine efficacy [51]. Among children initially vaccinated after 12 months of age, vaccine efficacy is at least 95%, while it can be lower for children vaccinated before 12 months of age [51]. Starting with the 1980s, most countries introduced a routine second dose of measles vaccine to further reduce the number of children left susceptible after primary vaccination and increase vaccine efficacy. Hence, the second dose is not considered as a booster [51]. The age for the second dose varies across countries: the second dose is either administrated few months apart from the first dose (e.g., France, Austria, Germany, Brazil, Australia) or a few years apart (e.g., USA, UK, Italy, Sweden, Finland), around the age of school enrollment [51,53,54]. The implementation of measles vaccination programs has led in many settings to the elimination of endemic transmission of measles, at least temporarily [51,55,56], even before adopting routine two-dose schedules [57].

We apply our modeling results to the epidemiology of measles vaccination. Because we assume that vaccination occurs shortly after birth, our results apply best for countries where the time interval between measles vaccine doses is relatively short. We propose that measles elimination for current vaccination programs is ongoing as described for region (a) in our model; see Fig. 2. Reaching this region was possible because, when vaccination programs were implemented, the relative cost of vaccination versus treatment (i.e., r) for measles was most certainly perceived as low by individuals, for the following main reasons: measles was endemic, parents witnessed measles-related morbidity and mortality, public health authorities would make vaccines freely available or subsidized them, and decline of measles incidence would provide direct evidence of vaccination success. However, our results also show that there is no stable equilibrium in region (a). This implies that measles epidemiology is evolving toward the border between regions (a) and (b). The transition may, however, take a long time because national vaccination programs only induce small changes in vaccination coverage, compared to mass vaccination campaigns. This transition occurs because, as high levels of coverage are achieved, individuals may perceive a larger cost of vaccination versus treatment (i.e., higher r) and lose motivation to vaccinate their children. Indeed, when measles is not endemic, most parents do not witness measles-related morbidity and mortality. Furthermore, vaccine rumors/controversies [13] may lead to vaccine hesitation [15] and lower vaccination coverage. A decrease below the critical coverage, $\hat{p}(r_a)$, may lead to epidemic resurgence [50,58], and thus to a transition from region (a) to region (b), where the disease is endemic and individuals will find, once more, the motivation to vaccinate.

Our theoretical findings offer insight on vaccine parameters when the epidemic was eliminated at least temporarily through voluntary vaccination. We consider countries where measles vaccination programs have led to the elimination of measles using a one-dose routine vaccination schedule (e.g., some countries in the Americas [57]) or two doses administered in a relatively short period of time (e.g., Australia [56]). In this case, according to Eq. (18), measles vaccination provides immunity for at least $(R_0 - 1)$ expected lifetimes. The current value of R_0 is not known, but we may assume that R_0 remains in the range of 5–18, as before the vaccination campaigns. We may thus conclude that measles vaccine provides immunity for a duration much longer than the

expected lifetime (4–17 times the expected lifetime). The duration of immunity of current measles vaccines is difficult to determine directly, as it requires long-term studies. A 15-year observational study in China [59] reported that the negative conversion rate of measles vaccinated individuals was 8.1–20.0% over 14 years, which leads to an estimated 63–166 years for the duration of vaccine-induced measles immunity. This is in qualitative agreement with our modeling results.

4. Discussion

In this paper, we used game theory and ordinary differential equations to address the dilemma of prevention versus treatment. In particular, we focused on a classic SEIR-type model for childhood infectious diseases subject to both vaccine prevention and treatment.

We found that voluntary vaccination may lead toward epidemic elimination if two conditions are met. First, the duration of vaccine-induced immunity should be sufficiently long; we derived a mathematical formula for this duration, depending on the basic reproduction number of the epidemic, R_0 . Second, the relative cost of prevention versus treatment must be sufficiently low; we found a threshold cost, r_a . Disease elimination may occur when a high-performance vaccine is made available, at low cost, in an endemic setting where individuals witness disease-related morbidity and mortality, as well as the benefits of vaccination, as disease incidence declines. All together, this yields a low relative cost of prevention versus treatment (i.e., lower than r_a), resulting in a vaccination coverage high enough to avert the epidemic. However, our modeling results show that disease epidemic elimination is only temporary; this is captured by the absence of an equilibrium for the effective coverage when $R^* < 1$. Indeed, as vaccination coverage increases, leading to less epidemic adversity, individuals may also lose their initial motivation to vaccinate. Hence, with epidemic elimination, the perception of cost in the dilemma of prevention versus treatment may change and increase up to r_a . In turn, this causes a decrease in vaccination coverage and reverses disease elimination to the situation where $R^* = 1$. Previous results consider this to be the maximum long-term impact of voluntary vaccination [16,18,60]. However, it is very important to note that, once the epidemic is averted (in region (a)), the dynamics toward the situation where $R^* = 1$ may be slowed down significantly, owing to continuous effort from the public health authority to maintain a low cost for vaccination.

These findings have implications for prevention and public health programs. For the condition on vaccine quality to be met, it is essential to develop one-shot highly effective vaccines that provide long-lasting immunity. For the condition on the relative cost of prevention versus treatment, we have to distinguish two epidemiological phases: the initial phase, when the vaccine is made available in presence of endemic disease, and the elimination phase, when vaccination continues after reaching high coverage. The cost for a highly effective vaccine introduced when the disease is endemic may be easily perceived as low. However, once the epidemic is eliminated, maintaining a low perceived cost for vaccination may become a complex issue, which will depend on the setting [15]. Witnessing almost no epidemic adversity, individuals may lose motivation to vaccinate. In addition, with the increased vaccination coverage, they may be particularly aware of adverse effects [61] and susceptible to vaccine rumors/controversies [13]. In this case, maintaining a low relative cost of prevention versus treatment may be a difficult and long-running task, requiring multi-scale actions.

Costs associated with vaccine accessibility and uptake, encountered by both individuals and health professionals, may act as

important barriers [15] and should be reduced. They include monetary cost of the vaccines, as well as time spent on accessing vaccination, communicating about the safety profile, and administrative burden. Furthermore, vaccination incentives could be implemented [62–64]. For instance, modest non-monetary incentives [63,65] and conditional cash transfers [62,64] have been used to increase the vaccination coverage. However, this type of incentives proved effective only for low-and-middle-income settings [66,62]. In addition, dialogue-based interventions (e.g., social mobilization, communication through mass and social media, etc.) and reminders (e.g., telephone calls or letters) have been used to encourage vaccination [65].

We propose three additional interventions to maintain a low cost for vaccination. First, vaccination in high-income settings might be encouraged using health insurance policies. For instance, the health insurance provider may offer a progressive reduction of the insurance premium (and/or increase of benefits) along with the completion of the vaccination schedule. Second, the public health authority should acknowledge in the media the participation and success of prevention programs in search for continuous public support. Involving civil society representatives and other relevant stakeholders as full participants in vaccine recommendation and policy, as it was recently done in France [67], may help improving mutual understanding and trust around vaccination. Third, recalling information about disease sequelae, and their statistics, using epidemiological data on childhood diseases from countries where vaccine coverage are low, may help individuals to perceive better the aim of prevention, and maintain a fair perception of prevention cost. This also requires providing clear information about vaccine adverse effects, based, for example, on statistics elaborated from the notification of adverse effects by health professionals and parents.

In addition, using the basic reproduction number, our model provides a lower bound estimate for the duration of vaccine-induced immunity against epidemic diseases controlled through vaccination. This may be a particularly important result, since the duration of vaccine-induced immunity is not precisely known for most vaccines [42]. Measuring long-standing vaccine-induced immunity (years) requires long-term follow-up of large numbers of vaccinated individuals (e.g., [59]). Nonetheless, a precise estimation of the duration of vaccine-induced immunity is key to optimize immunization schedules, guide vaccination policy and enhance public trust in vaccines. Along with traditional epidemiology methods, mathematical modeling may offer valuable insight in estimating this vaccine parameter.

In conclusion, we used a game-theoretic model to discuss the dilemma of prevention versus treatment. We demonstrated the circumstances under which non-cooperative, self-interested individuals arrive to alleviate, and potentially eliminate, an epidemic through the use of an imperfect vaccine. Maintaining a low relative cost of prevention versus treatment will be the main challenge to maintain disease elimination unless incentives are considered.

Acknowledgements

The authors thank Dominique Costagliola for helpful comments on the manuscript. S.J. was supported by a Ph.D. fellowship from the French Ministry of Higher Education and Research, and the Public Health Doctoral Network coordinated by the EHESP.

Declaration of interest

The authors declare no conflict of interest.

Author contributions

R.B. conceived the model. S.J. and R.B. conducted the calculations. All authors wrote the main manuscript text, analyzed the results and have approved the final version of the article.

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2.3 Additional material

2.3.1 Additional figures

Disease transmission flow diagram

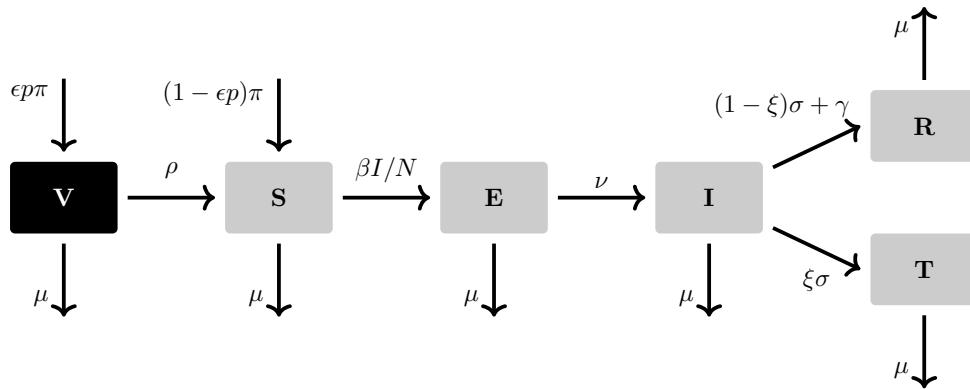


Figure 2.5 – Flow diagram for the compartmental model of vaccination against childhood infectious diseases

This flowchart depicts to the ODE system (1) of section 2.2. Newborns can get vaccinated (V) or remain susceptible (S). Recently infected individuals (E) pass through a latent stage of infection. Then, they become infectious (I) and can recover naturally (R) or get on treatment (T). N denotes the total population. We use p for vaccine coverage, ϵ for vaccine efficacy and ρ for the rate of vaccine-induced immunity waning. The parameter π stands for the inflow of newborns, μ for the disease-unrelated death rate, β for disease transmissibility, ν for the progression through the latent stage, σ is the rate at which individuals start treatment and γ is the natural recovery rate. Treatment efficacy is noted ξ .

Bifurcation diagram

Fig. 2.6 is a variation of fig. 1 of section 2.2, allowing to visualize the stability of the ODE system equilibria and the loss of stability of the DFS when the decision model is coupled to the transmission model.

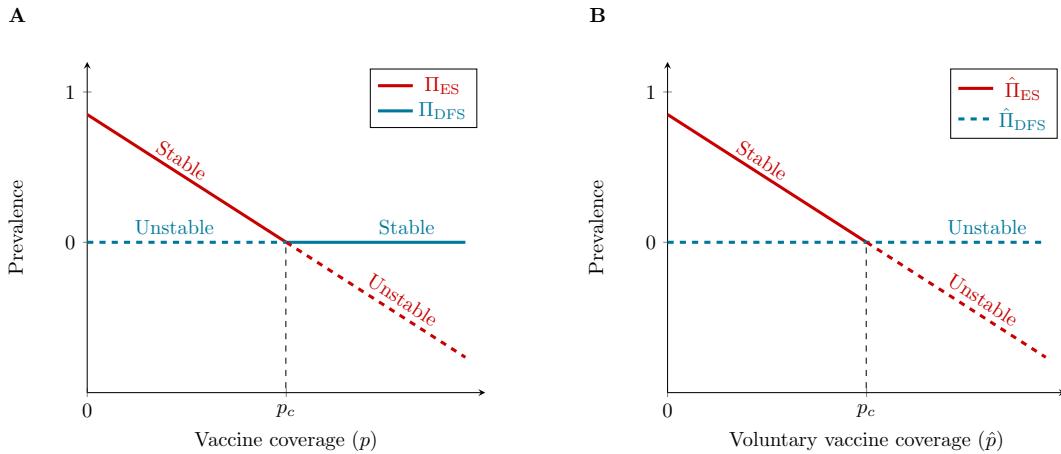


Figure 2.6 – Bifurcation diagram for the endemic prevalence

The disease-free state (DFS) and the endemic state (ES) are depicted in blue and red, respectively. A change in the stability of the system's equilibria occurs when the vaccine coverage (p) reaches the critical value p_c (i.e., when the effective reproduction number equals to 1), which is depicted by the transition from a solid to a dashed line.

(A) The bifurcation diagram for prevalence, Π , for the model without the individual-level decision-making component. (B) The bifurcation diagram for prevalence induced by voluntary prevention, $\hat{\Pi} \equiv \Pi(\hat{p})$. The stability of the DFS for $\hat{p} \geq p_c$ is lost when the game is coupled to the compartmental model: there exists no equilibrium coverage for voluntary vaccination once the epidemic has been averted. Individuals may not get vaccinated if the disease is eliminated.

2.4 Further discussion

2.4.1 A note on mandatory vaccination

Here, we discuss briefly the results of implementing mandatory vaccination, as an alternative to allowing individuals to decide whether or not to adopt recommended immunization programs.

Some countries have witnessed infectious diseases reemergence and have established manda-

tory vaccination as a result. As of 2018, vaccination against measles was mandatory in 9 European countries. In 2019, France had added 8 mandatory vaccines to a list of 3, and Italy had established 10 mandatory vaccines (Bechini et al., 2019). The most common strategies to enforce vaccination have been implementing monetary fines to parents who do not vaccinate their children, excluding unvaccinated children from school (Drew, 2019; Bechini et al., 2019) and withholding public financial child support (Drew, 2019; Australian Government Department of Health, 2015).

Italy, France and Australia have witnessed an increase in MMR vaccine coverage following mandate establishment. However, it is not clear whether this coverage level will last in the future. In addition, mandatory vaccination may not always accomplish the objective of increasing vaccination coverage. For instance, in California, in the US, the number of unvaccinated children that were home-schooled quadrupled between September 2016 and August 2019 (Drew, 2019).

Hence, mandatory vaccination may not solve the issues that lead to non-vaccination and may increase health disparities between individuals. Experts thus believe that mandatory vaccination should be a temporary measure only (Bechini et al., 2019). Instead of mandates enforcing vaccination, increasing vaccination coverage through the voluntary participation of individuals would require allocating resources towards facilitating access to vaccination and information campaigns to address vaccine hesitancy (Drew, 2019; Bechini et al., 2019). These arguments highlight the importance of addressing the individuals' voluntary participation on vaccination and the pertinence of our results.

Chapter 3

Voluntary use of pre-exposure prophylaxis to prevent HIV infection among men who have sex with men

3.1 Introduction

3.1.1 The HIV epidemic

HIV infection, diagnosis and treatment

Human immunodeficiency virus (HIV) is a retrovirus that attacks the human immune system, by targeting the CD4+ T immune cells (or simply CD4 cells), which are white cells that help killer cells by signaling the presence of the infectious pathogen. HIV uses CD4 cells to replicate itself, destroying them in the process. HIV is a sexually transmitted infection (STI), which may spread through seminal, rectal and vaginal fluids as well as through blood and breast milk ([CDC, 2020](#)).

The natural stages of the HIV infection (i.e., when the infection is not treated) go as follows. A recently infected individual goes through an acute stage of infection, where the virus replicates at a high rate, and the individual may experience flu-like symptoms. The acute stage of infection

lasts a few weeks. Then, for several years, the chronic¹, often asymptomatic, stage of infection takes place. During the chronic stage of infection, both CD4 cells count and viral load are relatively stable. The last stage of the HIV infection is the acquired immune deficiency syndrome (AIDS), where the count of CD4 cells rapidly decreases along with rapid increment of the viral load. In the AIDS stage, the individual's immune system is severely compromised and thus, opportunistic infections (such as tuberculosis, pneumonia, etc.) occur and lead to AIDS-related death. AIDS may last a few years (CDC, 2020). Fig. 3.1 depicts the natural dynamics of CD4 cells count and viral load, during the HIV stages.

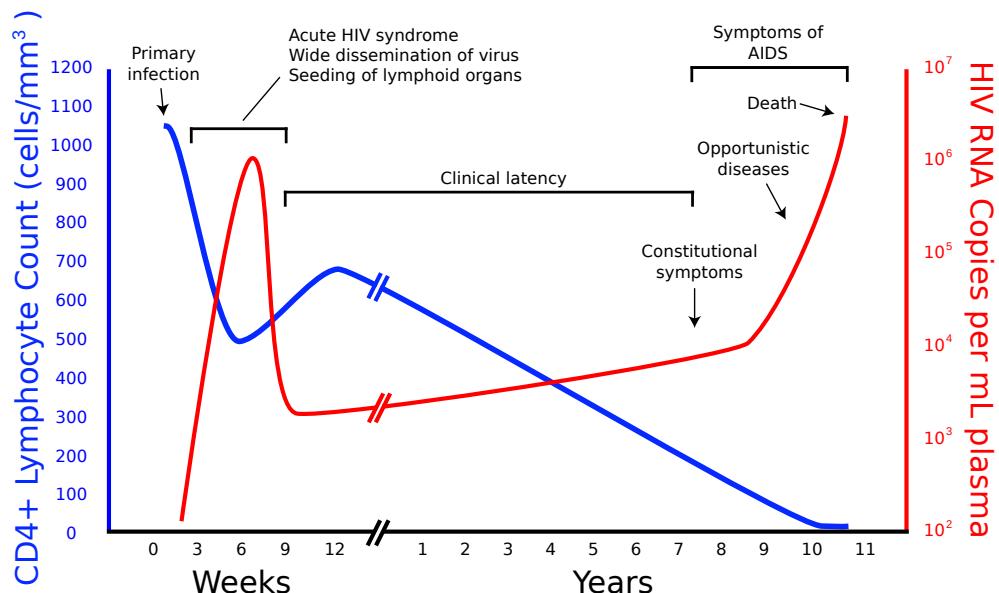


Figure 3.1 – The HIV infection progression

Average CD4+ T cell count (blue) and HIV viral load (red) during the course of an untreated HIV infection. Image source: (Sigve, 2011).

HIV infection may be diagnosed 10 to 90 days after exposure to HIV, depending on the testing method used (CDC, 2020). To date, there is no cure for HIV. However, effective antiretroviral therapy (ART) inhibiting viral replication has been developed to treat HIV infection, stopping its progression. Multiple types of ART disrupting different stages of the HIV life cycle are currently available. This has allowed to combine two or three different HIV drugs, which is called combination ART, to prevent the emergence of drug resistance, which may result from the rapid mutation capacity of HIV (WHO, 2016a).

The WHO (2016a) currently recommends HIV infected individuals to start ART immediately

¹Also referred to as the *latent* phase.

after diagnosis, and to take ART for life. An infected individual successfully undergoing ART is able to decrease the viral load until being undetectable to HIV tests, which is called *viral suppression*. It has been shown in clinical trials that an individual with undetectable viral load does not transmit HIV (AJ et al., 2016). Moreover, the life expectancy for infected individuals taking ART can be almost the same as the life expectancy of uninfected individuals, especially in high-income settings (Trickey et al., 2017). Thanks to effective ART, the number of infections, AIDS-related diseases and deaths has been greatly reduced globally (WHO, 2016a).

The HIV epidemiology, worldwide

The first patients with —what would later be known as— AIDS were observed in 1981 (Barré-Sinoussi et al., 2013). HIV was first isolated in 1983, and identified as its causal pathogen in 1984 (Gallo and Montagnier, 2003). The peak of the epidemic was observed in the late 90's. Nowadays, despite great efforts to prevent and treat HIV infection, the epidemic continues to spread globally (UNAIDS, 2018; Roser and Ritchie, 2020); see fig. 3.2. As of 2019, about 38 million people around the globe were living with HIV, and 32 million have died from AIDS-related illnesses since the start of the epidemic (UNAIDS, 2019b).

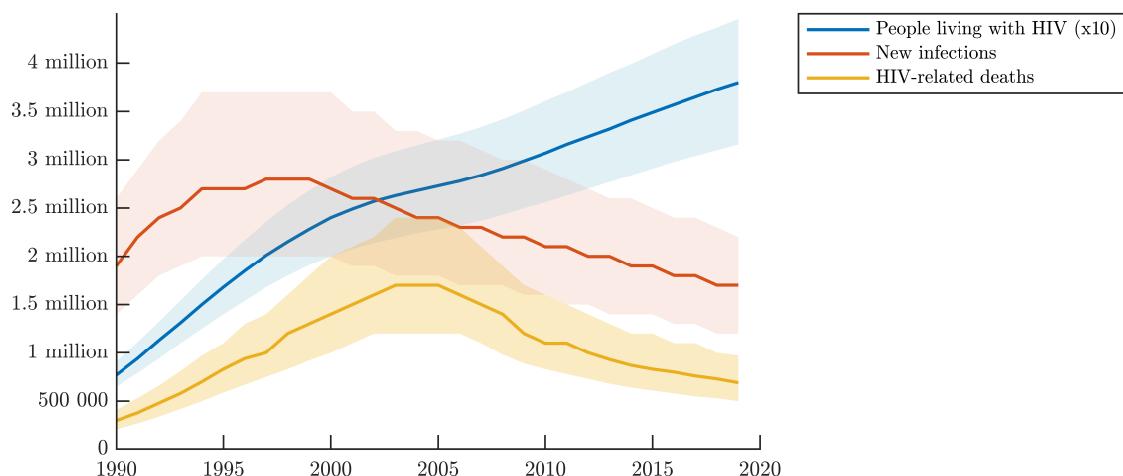


Figure 3.2 – HIV/AIDS epidemiological indicators, worldwide

Total number of people living with HIV (the data was divided by 10 to fit the same figure with the other measures; i.e., in 2019, there were ~ 38 million people living with HIV), number of new HIV infections and number of HIV-related deaths, from 1990 to 2019, worldwide. Source: UNAIDS HIV estimates (UNAIDS, 2020).

In most high-income settings, the population of men who have sex with men (MSM) is one

of the most affected by the HIV epidemic ([UNAIDS, 2018](#); [WHO, 2016b](#); [Beyrer et al., 2012](#)). The high transmission of HIV among MSM may be explained by biological factors, such as the high probability of HIV transmission through receptive anal intercourse, as well as by risky behavioral factors, such as unprotected sexual intercourses, large number of casual partners and using recreational drugs ([Beyrer et al., 2012](#)).

The prevention of HIV infection

Prevention interventions have proven to be successful to reach risk reduction among MSM, by sharing information on HIV/AIDS risk, promoting safer sex and changes in social behavior, etc. ([Johnson et al., 2002](#)). The prevention methods against HIV include, among others: abstinence, condom use ([Chen et al., 2017](#)), seroadaptation² (practices aiming to reduce contamination among serodiscordant sexual partners, such as seropositioning and serosorting) ([McFarland et al., 2011](#); [Velter et al., 2015](#)) and, more recently, the use of ART to prevent infection (in the form of pre- and post-exposure prophylaxis) ([WHO, 2016a](#)).

3.1.2 Pre-exposure prophylaxis uptake among MSM

Pre-exposure prophylaxis (PrEP) consists of the use of ART by uninfected individuals before possible exposure to HIV. The first commercialized version of PrEP consists of the combination of two antiretrovirals, Emtricitabine (FTC) and Tenofovir disoproxil fumarate (TDC), sold under the registered name Truvada®, and currently available in generic form. FTC/TDC pills may be taken continuously (i.e., taken every day) or *on demand* (i.e., taken right before and after possible exposure to HIV) ([Desai et al., 2018](#); [Siguier and Molina, 2018](#)).

As of June 2018, only 35 countries had at least one public policy implemented regarding PrEP rollout; most of them (15 countries) in the European region ([Hodges-Mameletzis et al., 2018](#)). Global efforts thus remain far from the [WHO \(2016b\)](#) recommendations to scale up PrEP programs among high-risk populations.

²The term *seroadaptation* refers to the adaptation of sexual behaviors due to serological status awareness. Similarly, *seropositive* (respectively, *seronegative*) refers to an individual infected (respectively, uninfected) with HIV.

Efficacy of PrEP

The first randomized, double blind, clinical trial conducted among MSM to study the efficacy of PrEP was the *iPrev* study, which showed a moderate relative risk reduction of 44%, through daily use of TDF-FTC (versus placebo) (Siguier and Molina, 2018; Grant et al., 2010). However, the results suggested that compliance was a major factor for efficacy: the risk reduction increased to 92% when considering only the subgroup of individuals with detectable TDF-FTC concentrations (Grant et al., 2010).

The efficacy of daily oral PrEP was also studied among serodiscordant heterosexual couples in the *Partners* study, which found a TDF-FTC PrEP efficacy of 84% for men and 66% for women, and in the *TDF-2* study, which found the efficacy of 62.2% (Siguier and Molina, 2018). Among heterosexual women, two studies found no efficacy of PrEP, due to the low compliance of the participants (Siguier and Molina, 2018). An efficacy of 49% was estimated in a study among injecting drug users (Siguier and Molina, 2018).

Two recent trials conducted on high-risk MSM showed that PrEP has an effectiveness of 86%: *PROUD*, a study comparing daily PrEP uptake versus the deferred (by 1 year) adoption of daily PrEP (McCormack et al., 2016), and *Ipergay* (Molina and Earn, 2015), a randomized double blind trial comparing on-demand PrEP uptake versus placebo. Both the placebo arm of *Ipergay* and the deferred arm of *PROUD* were discontinued anticipatedly, in light of the high efficacy of PrEP (Siguier and Molina, 2018). The open-label follow-up of the participants of the *Ipergay* trial showed a 97% reduction in the incidence (Siguier and Molina, 2018; Molina et al., 2017). In addition, two cohort studies observed no HIV infections among MSM taking PrEP under good compliance (Siguier and Molina, 2018; Desai et al., 2018). These results place PrEP, next to condom use, among the most effective HIV prevention methods for MSM.

Therefore, the WHO (2015, 2016b,a) currently recommends PrEP as a prevention method for MSM at high risk of HIV of infection. Individual-level PrEP eligibility criteria for MSM include, for instance, having unprotected anal intercourses with casual partners and/or partners with positive or unknown serostatus (WHO, 2015). PrEP uptake recommendations include providing PrEP together with other HIV prevention options (notably, condom use), performing HIV tests every 3 months, regularly testing for other STIs and monitoring renal functions (WHO, 2016a)

Price of PrEP and cost-effectiveness analyses

The price payed by PrEP users varies widely between countries where PrEP is available. In the US, the price of PrEP may be about 1 400€ to 1 800€ per month, while in countries like France and Sweden, PrEP is offered for free to individuals, since it is completely covered or reimbursed by the social security system. In addition, the availability of generic TDF/FTC molecules has led to a reduction in the price of PrEP paid by individuals in countries like Germany, Ireland, Switzerland and Poland ([Salzman, 2019](#)).

Cost-effectiveness analyses have shown that a PrEP rollout among MSM at high risk of infection is cost-effective in comparison to other interventions ([Durand-Zaleski et al., 2018](#); [Revill and Dwyer, 2017](#); [Cambiano et al., 2017](#); [Nichols et al., 2016](#); [Ouellet et al., 2015](#); [Desai et al., 2008](#)), but may remain costly nevertheless ([Juusola et al., 2013](#); [Gomez et al., 2012](#)). Moreover, cost-effectiveness analyses have shown to be highly sensitive to the price of PrEP ([Coleman and Prins, 2017](#)). This exhibits the need of reducing the price of PrEP, which remains a key barrier to broadly provide PrEP through public health programs ([ECDC, 2016](#)).

PrEP acceptability among MSM

As with other prevention methods, PrEP effectiveness is associated with persistence and adherence, which highlights the importance of MSM accepting to adopt and keep using PrEP as long as their risk of HIV infection remains high, and use it correctly. It is thus important for individuals to have a fair perception of their risk of HIV infection, the consequences of acquiring HIV infection and all the implications of a PrEP uptake to make informed decisions on whether or not to adopt PrEP as a prevention method against HIV infection.

On one hand, the MSM community has shown to be highly aware about HIV risk of infection, which has resulted in the practice of risk-reduction strategies ([McFarland et al., 2011](#); [Velter et al., 2015](#)). Paradoxically, these preventive practices may mislead individuals into believing their sexual behaviors are not risky enough ([Golub, 2014](#)), so additional prevention measures, such as PrEP, may no longer be adopted ([Young et al., 2014](#)). On the other hand, MSM have also shown to be highly aware of PrEP ([Frankis et al., 2016](#); [Grov et al., 2016](#)) and PrEP has shown to be well-accepted (if available) among MSM who identify themselves at high risk of infection ([Frankis et al., 2016](#); [Ferrer et al., 2016](#); [Taylor et al., 2014](#); [Aghaizu et al., 2013](#)).

Still, PrEP acceptability among MSM has been recently estimated at a moderate level of about 58% (Peng et al., 2018). Acceptability may be affected not only by the price of the molecule, but also by other non-monetary barriers, all the extra efforts and discomfort that the individuals on PrEP may confront; for instance: difficulties regarding PrEP uptake and accessibility, pill burden, difficulties in managing adherence, fear of acquiring other sexually transmitted infections due to drop in condom use (Young et al., 2014; Taylor et al., 2014; Pérez-Figueroa et al., 2015; Holt et al., 2018; Desai et al., 2018; Sidebottom et al., 2018), difficulties understanding PrEP effectiveness (Underhill et al., 2016), lack of tolerability (Siguier and Molina, 2018), alcohol-PrEP interactive toxicity beliefs (Kalichman and Eaton, 2017) and social stigma and discrimination (Young et al., 2014; Pérez-Figueroa et al., 2015; Arnold and Steward, 2016).

3.1.3 The HIV epidemiology and PrEP rollout among the MSM population in France

In France, like in most high-income settings, the number of new HIV infections remains remarkably high in some subpopulations. Between 6 000 and 7 000 new HIV infections are estimated to occur each year at the national level (Marty et al., 2018). These numbers have remained rather stable since 2011 (Siguier and Molina, 2018; Santé Publique France, 2019). More than 40% of the new HIV infections occur among people living in Île-de-France (ÎdF)—the Paris region, while only 19% of the French population lives in this region (Marty et al., 2018).

About 43% of the new HIV infections occur among MSM (Siguier and Molina, 2018), while MSM represent less than 2% of the general population (Bajos and Bozon, 2008)—1.6% when defining MSM as men who had at least one sexual intercourse with another man in the past twelve months and 4% when defining MSM as men who had at least one sexual intercourse with another man in their lifetimes (Marty et al., 2018). By far, MSM are the most affected by HIV in France, with HIV incidence rates ($\sim 1\%$) more than 60-fold higher than the national level (Marty et al., 2018). The incidence rate among high-risk MSM living in ÎdF has been estimated as high as 9% in the *Ipergay* trial (Molina et al., 2018).

The PrEP rollout in France

PrEP was authorized by French health authorities in 2016 ([Siguier and Molina, 2018](#)) and is currently recommended for MSM at high risk of HIV infection ([ANRS, 2015; EPI-PHARE, 2020; Siguier and Molina, 2018; Haute Autorité de Santé](#)). MSM need to meet at least one of the following criteria, to be prescribed PrEP: i) To have had unprotected, i.e., condomless sexual intercourses with at least 2 different partners in the last 6 months; ii) To have had STI events in the last 12 months; iii) To have had at least one post-exposure treatment for HIV in the last 12 months; iv) Drug use during sexual intercourse.

The recommendation to use PrEP in its registered form (Truvada®) was made in November 2015. Full PrEP reimbursement (both for Truvada and generics) by the French Social Security system was implemented in January 2016 ([EPI-PHARE, 2020](#)). PrEP has also shown to be cost saving in the French context ([Durand-Zaleski et al., 2018](#)).

About 13 900 MSM initiated PrEP in ÎdF between January 2016 and June 2020 ([EPI-PHARE, 2020](#)), with a marked growing trend; cf. [fig. 3.3](#). Still, there remains a gap between PrEP eligibility and PrEP adoption. A recent study found that there is a high number of cases of MSM recently diagnosed with HIV that would have been eligible for PrEP prescription ([Lions et al., 2019](#)). Among on-PrEP MSM in the Paris region, some evidence of drop in condom use has been observed ([Molina et al., 2018](#)). Also, a 30-month dropout rate of ~ 32% ([Costagliola et al., 2019](#)) from PrEP program was observed, which reveals the need of understanding and addressing PrEP persistence.

3.1.4 Worldwide efforts to end AIDS and the path towards ending the HIV epidemic

Specific strategies and objectives to end AIDS globally have been set by the [UNAIDS \(2011, 2014\)](#) during the past decade. Nowadays, the initiative to end AIDS as a public health threat by 2030 is part of the WHO Sustainable Development Goals. One essential direction adopted towards ending AIDS is through the scaling up of diagnosis, treatment and care. The UNAIDS 90–90–90 initiative was launched in 2015, aiming for 90% of infected individuals to be aware

³Scientific group of the French Agency of Medicine and Health Products Safety (ANSM) analyzing the data collected by the French System of Health Data (SNDS).

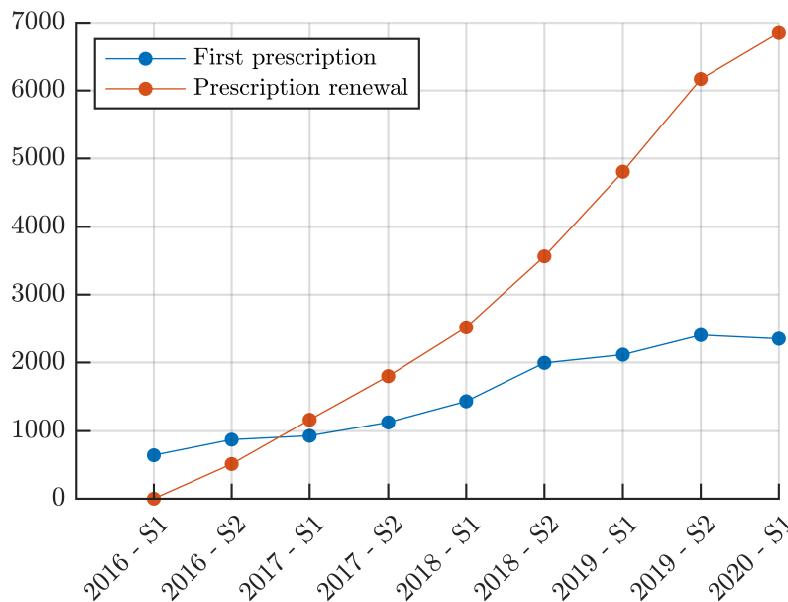


Figure 3.3 – PrEP users in Île-de-France, by semester and year

Number of first PrEP prescriptions (i.e., people starting PrEP; in blue) and PrEP prescription renewals (in red) in the Paris region, by semester (S1 and S2) from January 1st, 2016 to June 30th, 2020. The data suggests that the great majority of PrEP users in the region were MSM. The total number of first prescriptions since PrEP rollout in the region was $\sim 13\,900$ while only $\sim 6\,850$ prescription renewals were established the first semester of 2020. On average, 85% of PrEP users got a prescription renewal the following year. Source: [EPI-PHARE \(2019, 2020\)](#)³.

of their serostatus, 90% of diagnosed individuals to receive sustained ART and 90% of treated individuals to reach viral suppression, by 2020 ([UNAIDS, 2017](#)). In 2014, the objectives were extended to 95%–95%–95% by 2030, targeting to achieve a 90% reduction in HIV incidence compared with 2010 levels ([UNAIDS, 2014](#)).

Another strategy to end AIDS has been to implement HIV prevention interventions, through the combination of behavioral and biomedical approaches ([UNAIDS, 2011, 2014](#)). In particular, the WHO has published recommendations targeting the populations most at risk of HIV infection⁴, which include MSM ([WHO, 2016b](#)). Hopes are that the use of PrEP may curb the HIV epidemic among MSM, towards epidemic elimination. Recent studies have estimated a reduction in the number of new HIV infections at the population level after PrEP rollout among high-risk MSM that may place some settings in the path towards HIV epidemic elimination ([Palk et al.,](#)

⁴Also called *key populations*, among which an HIV incidence greater than 3 per 100 person-years has been observed ([WHO, 2015](#)).

2018; Grulich et al., 2018; Brown et al., 2018).

3.1.5 Mathematical modeling of the HIV epidemic and PrEP uptake among MSM

Mathematical modeling has been extensively used to describe the HIV epidemic dynamics (Jacquez et al., 1988; Castillo-Chavez, 1989). In particular, it has been used to describe HIV transmission among MSM and to evaluate the impact of preventive interventions on the epidemic's dynamics (Gumel et al., 2006; Gomez et al., 2012; Punyacharoensin et al., 2011; Eaton et al., 2012; Cremin et al., 2013; Punyacharoensin et al., 2016; Kim et al., 2014; Robineau et al., 2017; Palk et al., 2018; LeVasseur et al., 2018). For instance, deterministic approaches using compartmental models have been implemented to describe the HIV transmission at the population level (Supervie et al., 2010; Punyacharoensin et al., 2011; Gomez et al., 2012; Juusola et al., 2013; Kim et al., 2014; Punyacharoensin et al., 2016; Palk et al., 2018; Rozhnova et al., 2018).

The heterogeneity of the risk of HIV infection among MSM has been modeled by considering structured mixing, where the population is stratified by risk of infection and the probabilities of sexual contacts between individuals are assumed to be non-random (Jacquez et al., 1988, 1989; Gupta et al., 1989; Sattenspiel et al., 1990). The risk categories have been defined according to the individuals sexual behavior: by explicitly defining the probabilities of HIV transmission in terms of the number of sexual contacts the individuals may sustain, the probability of having sexual contacts with individuals in other risk-categories and the inherent probability of HIV-transmission.⁵ Hence, an individual at high-risk (respectively, low-risk) of infection would be assumed to have a high (respectively, low) number of sexual contacts.

There are two main kinds of non-random structured mixing that have been used to model HIV-transmission dynamics: i) *proportional mixing*, where sexual contacts are assumed to be proportional to the number of individuals in each risk-category; and ii) *preferred mixing*,⁶ where a fraction of the individuals is assumed to mix preferentially with other individuals in the same risk-category, and the rest of the contacts are proportional (Jacquez et al., 1988). The higher the heterogeneity, the lower the prevalence at the endemic state (where there are no changes in the

⁵Sexual behavior is also referred to in the literature as *sexual activity*. Sexual contacts may be defined, for instance, by sex acts or sexual partnerships (Jacquez et al., 1988).

⁶Also referred to as *assortative mixing*.

epidemic dynamics) and, in the case that extremely risky behaviors are considered, two peaks may be observed in the epidemic dynamics ([Punyacharoen et al., 2011](#)).

Modeling studies have evaluated the impact of a PrEP rollout on the HIV epidemic among MSM, predicting a remarkable reduction in the number of new HIV infections ([Gomez et al., 2012](#); [Kim et al., 2014](#); [Punyacharoen et al., 2016](#); [Jenness et al., 2016](#); [Robineau et al., 2017](#); [Rozhnova et al., 2018](#); [Palk et al., 2018](#); [Rozhnova et al., 2019](#)). In particular, recent mathematical models have studied HIV epidemic elimination through PrEP rollouts among MSM ([Rozhnova et al., 2018](#); [Scott et al., 2018](#); [Hansson et al., 2020](#)). In these models, different levels of PrEP coverage are considered ([Gomez et al., 2012](#); [Punyacharoen et al., 2016](#); [Robineau et al., 2017](#); [Rozhnova et al., 2018](#)), including full coverage ([Kim et al., 2014](#)). However, high levels of PrEP coverage, which are required to substantially impact or eliminate HIV epidemics, may not be granted in the real world. Therefore, it remains to know whether and how PrEP coverage levels can be reached and maintained, in the long term.

The subject of HIV elimination through healthcare interventions has also been addressed by modeling studies. For instance, by defining HIV elimination as the effective reproduction number being below 1, along with an incidence under 1 yearly case by 1000 individuals, a 2009 study found that testing the whole population yearly and treating immediately all seropositive individuals may result in epidemic elimination within 10 years ([Granich et al., 2009](#)). Another study found that, to reach less than 1 yearly case by 1000 among MSM in the UK, would require a 90% of recently infected individuals to be diagnosed and treated in the year following infection ([Phillips et al., 2013](#)). A more recent study estimated that, reaching the 95–95–95 target, along with high adoption of preventive methods like PrEP and condom coverage among MSM, would only ensure an 80% reduction in incidence by 2030 ([Scott et al., 2018](#)). Regarding PrEP interventions, a recent study found that HIV elimination would require 82% PrEP coverage among high-risk MSM during 5 years to reach HIV elimination ([Rozhnova et al., 2018](#)).

To the best of our knowledge, no modeling study has addressed the individual-level decision-making on whether or not to adopt a prevention method—namely, PrEP—to avoid HIV infection and thus evaluated the impact of voluntary adoption of PrEP on the HIV epidemic.

3.2 Article submitted for publication

A scientific article presenting our findings, titled “Can HIV epidemics among men who have sex with men be eliminated through participation to PrEP rollouts?” ([Jijón et al., 2021](#)), was submitted for publication to the *AIDS* journal in January 2021, and is currently under review.

The preprint of the main text is included below, along with the supplementary material, where the mathematics of our model is presented in detail. The computations and proofs of the analytical results presented in the article’s supplementary material are available in [section 3.3](#) of this chapter. Additional figures are also found in [section 3.3](#). The implementation of HIV prevention programs are further discussed in [section 3.4](#), as well as the limitations and perspectives of our modeling choices.

3.2.1 Description of the article

We propose a mathematical model describing the interplay between the HIV epidemic among MSM and the individual-level decision-making on whether or not to adopt PrEP as a prevention method against HIV infection, in the current therapeutic context, where universal ART is in place. In particular, we address this issue for one of the most at risk populations in mainland France: MSM in ÎdF (the Paris region).

3.2.2 Results statements

We obtained a mathematical characterization of the probability that a typical individual adopts PrEP on his own, which would yield the voluntary PrEP coverage at the population level. We thus obtained the PrEP coverage reached voluntarily by high-risk MSM, as a function of the risk of HIV infection, the PrEP parameters and the HIV epidemic’s intrinsic parameters. In particular, we study the PrEP coverage in terms of the PrEP effectiveness and the relative cost of PrEP versus ART perceived by individuals.

We evaluated the impact of PrEP on the HIV epidemic among MSM, when PrEP is taken voluntarily by those who find themselves most at risk. Moreover, we identified the conditions for which epidemic control (i.e., reduction in HIV incidence) or elimination (i.e., reduction of HIV

incidence to zero) are possible owing to voluntary adoption of PrEP by MSM at high risk of HIV infection in a typical urban setting of a high-income country (e.g., the Paris region).

According to our findings, the reduction in condom use with PrEP adoption (risk compensation) may not play an essential role against epidemic elimination because PrEP is highly effective. However, several conditions regarding the relative cost of PrEP versus ART and risk perception need to be fulfilled to reach elimination. Specifically, the relative cost must be perceived by eligible MSM as sufficiently low, and the perception of the risk of acquiring HIV infection should be fair; if risk is underestimated, an even lower cost of PrEP is required for elimination. In addition, we found that lower testing rates among PrEP users require PrEP effectiveness to be high, in order to ensure epidemic elimination through a voluntary PrEP coverage below 100%. Importantly, and similarly to our previous work on voluntary vaccination ([Jijón et al., 2017](#)), we found that epidemic elimination is temporary unless active maintenance of the PrEP rollout is in place.

We conclude that current PrEP rollout protocols, including that of the Paris region, may not reduce enough the cost of PrEP to achieve epidemic elimination. Active efforts are thus needed to increase PrEP demand by easing PrEP access, identifying MSM at high risk of infection, and communicating HIV risk information to the target population. If these efforts lead to HIV elimination, the next challenge will be to maintain, in a context of less epidemic adversity, a fair perception for the HIV risk and the cost of PrEP perceived as low.

3.2.3 Article

The article in its published form is attached from the next page.

Can HIV epidemics among men who have sex with men be eliminated through participation to PrEP rollouts?

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Word count:

Abstract: 243/250

Main text: 3471/3500

ABSTRACT

Objectives: To study the conditions under which PrEP coverage can eliminate HIV among men who have sex with men (MSM) in the Paris region.

Design: Mathematical modeling.

Methods: We propose an innovative approach, combining a transmission model with a game-theoretic model, for decision-making about PrEP use. Individuals at high risk of HIV infection decide to use PrEP, depending on their perceived risk of infection and the relative cost of using PrEP versus antiretroviral treatment (ART), which includes monetary and/or non-monetary aspects, such as price and access model of PrEP, consequences of being infected and lifelong ART.

Results: If individuals perceive fairly their infection risk, and the cost of using PrEP is sufficiently low, the PrEP coverage can lead to elimination. Specifically, assuming 86% PrEP effectiveness, as observed in two clinical trials, a minimum PrEP coverage of 55% (95% CI:43%–64%) among high-risk MSM would achieve elimination in the Paris region. A complete condom drop by PrEP users slightly increases the minimum PrEP coverage by \sim 1%, while underestimation of their own HIV infection risk would demand PrEP programs to reduce the cost of using PrEP by a factor \sim 2 to achieve elimination.

Conclusions: Elimination conditions are not yet met in the Paris region, where at most 47% of high-risk MSM were using PrEP as of mid-2019. Further lowering the cost of PrEP and promoting a fair perception of HIV risk are required and should be maintained in the long run, to maintain elimination status.

Keywords: Pre-exposure prophylaxis; HIV; men who have sex with men; behavioral epidemiology; game theory; prevention coverage.

INTRODUCTION

In many settings, men who have sex with men (MSM) are most affected by HIV [1]. Pre-exposure prophylaxis (PrEP) is a highly effective prevention method recommended by the WHO for individuals at high risk of infection with HIV [2]. Both IPERGAY and PROUD clinical trials showed that PrEP can reduce HIV incidence among MSM by 86% [3,4]. Modeling studies, elaborating on these results, suggested that PrEP has the potential to curtail, and even eliminate HIV epidemics, notably among MSM [5–8]. For instance, in the Netherlands, elimination would require 82% PrEP coverage in the highest-risk group [6].

The question of whether it is possible to achieve a certain PrEP coverage in a population has not been addressed; modeling studies only assume that the coverage reaches certain values, which may not be granted in public health practice. It is therefore unclear whether, and under what conditions, target PrEP coverage levels, required to eliminate HIV epidemics, can be reached voluntarily and maintained in the long run. Currently, PrEP remains underutilized in many settings [12]. For instance, in the United States, 220,000–225,000 individuals were on PrEP as of April 2020 [9], still short of the CDC estimate that 1.2 million persons have indications for considering PrEP use [10]. Furthermore, a recent study shows that only two in five individuals keep using PrEP for >2 years [11].

Mathematical tools for modeling individual-level decision-making are offered by game theory [13–15]. We propose an innovative approach, combining an epidemic model at the population level, and a game-theoretic model for decision-making about PrEP at the individual level. We model PrEP adoption in a population at high risk of HIV infection to determine whether and under what conditions certain PrEP coverage levels can be reached voluntarily. Particularly, we study the potential impact of PrEP among MSM in the Paris region of France, where universal antiretroviral treatment (ART) is in place, and PrEP is available for eligible individuals.

METHODS

We built an HIV epidemic model (Figures S1 and S2) to describe the epidemiological context of an MSM community where eligible individuals make informed decisions about adopting PrEP. The decision making is modeled as a non-cooperative game, where individuals act to maximize the utility of adopting PrEP, or, in other words, minimize the cost of using PrEP to avoid acquiring HIV and lifelong ART. Individual's decision is, however, indirectly influenced by that of others. The sum of all individuals' decisions determines the PrEP coverage, which, consequently, affects epidemic progression and the risk of acquiring HIV. The decision-making game model is thus intertwined with the epidemic model. Below, we describe the main features of our two-component model; see the Supplementary Material (SM) for further details.

The epidemic model

The epidemic model stratifies the MSM population into two risk groups (low and high), to account for heterogeneity in the infection risk. The majority of partnerships occur within the same risk group and individuals at high risk of infection drive the epidemic. The model also stratifies over HIV status, disease progression, diagnosis and the use of PrEP or ART. Once diagnosed, individuals immediately begin ART, no longer transmitting HIV. We varied PrEP effectiveness, denoted ε , from 0 to 100% to study sub-optimal PrEP adherence. The PrEP coverage, p , was not fixed; rather, it was obtained through the decision-making game model (see below).

We computed the effective reproduction number for the epidemic model, R , defined as the expected number of secondary cases caused by one infected individual, during his entire infectious period, in an uninfected population subject to control interventions [20,21]. PrEP use may change individuals' preference for other prevention tools, turning R into a function of PrEP parameters. $R(p, \varepsilon) > 1$ indicates epidemic persistence, meaning that an endemic

state will be reached. Elimination requires $R(p, \varepsilon) < 1$, such that the disease-free state will be reached. Elimination implies that incidence is reduced to zero in the studied population, but HIV can re-emerge in absence of control interventions, as it does not imply eradication. We say the epidemic is controlled using PrEP if $R(p, \varepsilon)$ decreases with the PrEP parameters, although the decrease is not below 1. Our model shows that epidemic control and elimination can occur through PrEP, provided that two thresholds in PrEP effectiveness are exceeded; $\varepsilon \geq \varepsilon_C$ is required for epidemic control and $\varepsilon \geq \varepsilon_E$ for epidemic elimination (see SM section 1.2.3). These thresholds are called the epidemic control and the epidemic elimination thresholds, respectively.

The decision-making game model

During an epidemic, individuals may adopt PrEP according to their perceived HIV risk [18], price [19] and access model of PrEP [20], adverse effects [21], social stigma [22], consequences of being infected, lifelong ART, and other pros and cons. These factors, summarizing monetary and/or non-monetary aspects, are expressed in our decision-making model as costs perceived by the individual.

We assume that individuals choose between two mutually-exclusive strategies. If an individual decides not to use PrEP, then in the case of acquiring HIV he will start ART upon positive HIV diagnosis, and pay the cost of ART for the rest of his life; we use the notation $C_{\text{No-PrEP}}$ for the lifetime cost of this strategy. Otherwise, the individual decides to adopt PrEP prevention. Thus, he takes and pays the cost of PrEP and, in the case of acquiring HIV despite PrEP uptake, being diagnosed and starting ART, pays the cost of ART for the rest of his life. We use the notation C_{PrEP} for the lifetime cost of the second strategy. The total cost explicitly depends on the yearly costs of ART and PrEP, the PrEP parameters, and, implicitly, the yearly risk of acquiring HIV. Introducing r , the relative cost of PrEP versus ART, the balance of cost, when the probability to adopt PrEP is p , becomes

$$C(p, \varepsilon, r) = pC_{\text{PrEP}}(p, \varepsilon, r) + (1 - p)C_{\text{No-PrEP}}(p, \varepsilon),$$

where all functions and parameters, other than p , are given in our mathematical modeling. The value of p that minimizes $C(p, \varepsilon, r)$, denoted $\hat{p}(\varepsilon, r)$, estimates the probability that a typical high-risk individual adopts PrEP, and also represents the voluntary PrEP coverage among high-risk MSM. The solution of the game represents an endemic state where individuals make decisions to adopt PrEP in stationary epidemiological context. We thus assumed that, for the long run, individuals stand by their decisions about adopting PrEP.

Application to the HIV epidemic among MSM in the Paris region

We calibrated the epidemic model to represent the epidemiological context before the introduction of PrEP [23,24], and obtained many HIV parameter sets, to reveal uncertainty in the model output (SM section 2 and Tables S1-S4). In our baseline scenario, we assumed that MSM on PrEP get tested for HIV quarterly, according to the French recommendations [25]. The testing frequency on PrEP was thus much higher than that observed off PrEP, as data shows 3.1 years for the median time from HIV infection to diagnosis among MSM before the introduction of PrEP (personal communication with VS). We further assumed that individuals have a fair perception of their infection risk when making decisions about PrEP use; the infection risk was determined by the force of HIV infection of the epidemic model. Furthermore, MSM were assumed to drop condom use from 30% to 20% when adopting PrEP [3], and the condom effectiveness was 58%–80% [26]. Sensitivity scenarios were explored assuming that i) MSM misperceived their risk of acquiring HIV, ii) MSM adopting PrEP completely dropped condom use [27], or iii) MSM did not change their HIV testing behavior upon adopting PrEP (SM Section 3).

RESULTS

About 500 parameter sets calibrated our epidemic model to the HIV epidemiology among MSM in the Paris region, before the introduction of PrEP: total yearly mean incidence was 1.3%, prevalence was 17%, and 17% of MSM living with HIV were undiagnosed (Table S3).

The mean number of MSM was $\sim 111,000$, of which 13% (i.e., $\sim 14,200$) were at high risk of infection and eligible for PrEP. Yearly incidence for high-risk MSM was 7%. The model parameters implied that the PrEP rollout had two effects: first, it offered the prevention benefits of the regimen, and, second, it behaved as a test-and-treat strategy [28,29], imposing a major change in HIV testing practice (SM Section 3.1 and Figure S3).

The voluntary PrEP coverage if individuals perceived correctly HIV infection risk

We first investigated a typical parameter set calibrating our model; Table S2. The PrEP coverage starts at zero, before introducing PrEP, and then reaches an equilibrium value where the expected cost of adopting PrEP is minimum. The final value reached depends on HIV parameters of the epidemic before the introduction of PrEP, the PrEP effectiveness, ε , and the perceived relative cost of PrEP versus ART, r . Figure 1A shows the voluntary PrEP coverage reached among high-risk MSM, $\hat{p}(\varepsilon, r)$. Figure 1B shows the corresponding relative reduction in HIV incidence in the MSM community. Each of these two figures shows three regions:

- Region III, where no high-risk MSM adopts PrEP, because the perceived relative cost of PrEP versus ART is too high. Therefore, HIV remains endemic, unaffected by the introduction of PrEP (i.e., no reduction in incidence);
- Region II, where some, but not enough, high-risk MSM adopt PrEP, since the relative cost remains high. The epidemic is controlled and incidence decreases, but not enough for elimination (i.e., $R(\hat{p}, \varepsilon) > 1$);
- Region I, where PrEP is offered at low relative cost. This allows reaching high levels of PrEP coverage ($\sim 54\text{--}75\%$) and the epidemic can be eliminated; for Region I, $R(\hat{p}, \varepsilon) < 1$. HIV elimination for low PrEP effectiveness (bottom part of Figure 1A) occurs as a consequence of the test-and-treat effect of the PrEP rollout; consequently, $\varepsilon_C = \varepsilon_E = 0\%$. In this case, MSM taking PrEP are poorly protected against HIV. However, they are diagnosed and treated very early in the course of infection, because they get tested for HIV every three months. Early diagnosis and treatment prevent further HIV transmission. In contrast, when PrEP

effectiveness is high (top part of Figure 1A), most on-PrEP MSM do not acquire HIV, so the test-and-treat benefit of the PrEP rollout is marginal. It is PrEP, particularly its high effectiveness, that contributes decisively to epidemic elimination. If $\varepsilon = 86\%$, as observed in the IPERGAY and PROUD trials, a minimum PrEP coverage of 56% should be reached among high-risk MSM, to eliminate HIV; Figure S4.

It is important to note that elimination is temporary, as the disease-free state is unstable. Indeed, once the epidemic is eliminated, individuals perceive HIV risk as being low and may reevaluate PrEP-induced advantages and disadvantages; this may severely increase the relative cost of PrEP versus ART, since the epidemic is considered to be eliminated. As fewer individuals consider PrEP use, the PrEP coverage decreases and the HIV epidemic dynamics in Region I can enter Region II, where the epidemic reemerges and becomes again of public health concern.

We generated the outputs in Figure 1 using each of the ~ 500 parameter sets obtained through calibration, to estimate uncertainty intervals for our results (SM Section 2). Figure 2A shows the probability that HIV is eliminated, as a function of ε and r . The probability is high on the left, where Region I is found, and declines severely toward Region II. In Figure 2B, we illustrate the boundaries between Regions I and II (continuous line), and between Regions II and III (dashed line); the three-region structure appears robust to parameter uncertainties. Additionally, when $\varepsilon = 86\%$, we found that the 95% confidence interval (CI) of the minimum PrEP coverage needed for elimination (i.e., 55%) is 43%–64%.

Sensitivity scenarios

We assumed that individuals could misperceive their HIV risk when deciding to adopt PrEP, and repeated our analyses. Specifically, rather than having a fair sense of HIV risk, based on the force of infection, high-risk MSM could get a sense of HIV risk from, for instance, the proportion of their high-risk MSM peers being diagnosed each year with HIV (SM Section

3.3.1). The voluntary PrEP coverage computed for this scenario is illustrated in Figure 3A and reveals a qualitatively similar structure to that in Figure 1. However, when high-risk MSM misinterpret and underestimate their HIV risk, Region I is smaller, implying that the relative cost of PrEP versus ART must be lower to achieve epidemic elimination. In particular, when $\varepsilon = 86\%$, the relative cost needed for epidemic elimination decreases by a factor of ~ 2 , making Region I harder to reach in practice of public health.

We performed two other sensitivity analyses. First, we analyzed PrEP-driven condom drop. In our baseline scenario, MSM dropped condom use from 30% to 20% when adopting PrEP. Similar results were obtained assuming that PrEP users stopped using condoms completely (SM Section 3.3.2 and Figure S5). We thus concluded that condom drop is not a major factor against HIV elimination when PrEP effectiveness is high. Specifically, epidemic elimination where $\varepsilon = 86\%$ requires a coverage of $>57\%$, rather than $>56\%$ in the baseline scenario.

Second, we analyzed a scenario where PrEP uptake does not require higher rates of HIV testing and MSM do not change their HIV testing behavior when adopting PrEP; Figure 3B and SM Section 3.3.3. In this case, HIV elimination is entirely due to PrEP and can only be reached if $\varepsilon \geq \varepsilon_E = 58\%$. For high PrEP effectiveness, the results are very close to those of the baseline scenario, as very few MSM fail PrEP and the testing frequency on PrEP does not impact many MSM. For instance, epidemic elimination when $\varepsilon = 86\%$ requires a coverage of $>58\%$, rather than $>56\%$ in the baseline scenario. For low PrEP effectiveness, Figure 3B shows a fourth region, where low relative cost encourages all high-risk MSM to adopt PrEP ($\hat{p} = 100\%$) and PrEP effectiveness is above the epidemic control threshold ($\varepsilon_C = 8\%$), but below the epidemic elimination threshold ($\varepsilon_E = 58\%$). Therefore, the epidemic is controlled, but not eliminated, and a new HIV endemic state is reached; $R(\hat{p}, \varepsilon) > 1$.

Perspectives on the PrEP rollout in the Paris region

In 2016, a PrEP rollout started in the Paris region, offering fully subsidized PrEP to eligible individuals. As aforementioned, under the baseline scenario, for 86% PrEP effectiveness, we found that at least 55% (95%CI: 43%–64%) of the high-risk MSM would need to take PrEP for the HIV epidemic to be eliminated. Since, according to our calibration, the estimated number of PrEP-eligible MSM in the Paris region is 14,200 (95%CI: 9,200–23,000), this means that 7,700 (95%CI: 5,800–10,100) high-risk MSM should be on PrEP. This is an objective to be reached. As of mid-2019, ~6,700 men were on PrEP in the Paris region [30], with a marked growing trend; the 30-month dropout rate was ~32% [31]. The PrEP coverage among high-risk MSM was then estimated to be at most 47% (95%CI: 30%–73%), assuming that all men on PrEP were indeed high-risk MSM. If all these MSM maintained using PrEP in the long term, our model predicted epidemic control (i.e., Region II), with a reduction of 90% (95%CI: 81%–100%) in HIV incidence at the new endemic state.

DISCUSSION

We addressed the role of individual-level decision-making in the potential impact of PrEP on the HIV epidemic, identified the conditions for epidemic control or elimination, and estimated PrEP coverage levels which can be reached voluntarily. We obtained four major findings for PrEP rollouts. First, HIV epidemics can be eliminated provided that the relative cost of using PrEP versus ART is sufficiently low. Second, frequent HIV testing while taking PrEP can compensate for poor PrEP adherence and act as a test-and-treat intervention. Third, HIV risk perception may play a major role for elimination, while drop in condom use among PrEP users may not. Fourth, epidemic elimination may be only temporary.

We applied our model to the Paris region. Assuming a PrEP effectiveness of 86%, as reported in two major clinical trials, we found that at least 55% (95%CI: 43%–64%) of the high-risk MSM would need to be on PrEP to achieve HIV elimination. As of mid-2019, at most 47% high-risk MSM were on PrEP in the Paris region, meaning that the PrEP-rollout protocol

did not reduce enough the cost of PrEP for epidemic elimination, so far. Still, a recent update on new HIV diagnoses in Paris [32] shows that the numbers among French-born MSM decreased by 28%, between 2015 and 2018, with no significant decrease for other MSM. This decrease could be partly due to the PrEP rollout starting in 2016, and, according to our modeling, should continue in the near future. In two other settings, a moderate-high PrEP coverage has been quickly reached. The region of New South Wales witnessed a rapid PrEP rollout ($\sim 9,000$ MSM on PrEP within 2 years) during an implementation study providing PrEP for free at several sites, including public HIV and sexual health services, and private general practices with expertise in ART prescription [33]. About 41% of the high-risk MSM in Australia were on PrEP in 2017 [34]. Since April 2018, PrEP is subsidized by the Australian government and can be prescribed by any practitioner [35]. In San Francisco, a citywide-coordinated PrEP rollout, within the Getting to Zero program, strongly promoted PrEP use and allowed many people to access PrEP for free or at low monetary cost, through insurance benefits or patient assistance programs. Close to 50% of the eligible MSM were on PrEP in 2017 in San Francisco [36]. Although these levels of PrEP coverage contributed to decreasing HIV transmission [33,36,37], HIV elimination has not been reported.

Moving toward epidemic elimination will require further decreasing the cost of PrEP, which may involve reducing monetary and non-monetary barriers to PrEP uptake, such as difficulties in accessing PrEP, pill burden, tolerability of the molecules, social stigma and discrimination, and the acquisition of other sexually transmitted infections in case of dropping condom use [20–22]. Online tools [38], home-based programs [39], long-lasting injectable versions of PrEP [40], rather than daily or on-demand pills, allowing trained general practitioners to prescribe PrEP and interventions that increase awareness, motivations and behavioral skills about risk reduction [41] may also help reduce the perceived cost of PrEP and decrease the drop-out rate. It is important to note that, in practice, estimating the cost of PrEP relative to that of ART can be complex, but not strictly needed, as reducing this cost may be intuitive and places the PrEP rollout in the right direction. Instead, the PrEP

coverage and HIV incidence can serve as indicators for how far the PrEP rollout is from achieving elimination.

Moving toward epidemic elimination will also require reaching MSM who may not perceive themselves at high risk, and thus require a lower cost for adopting PrEP, in order to join the prevention effort. Recent studies found that high-risk individuals can underestimate their HIV risk [42] and there are many missed opportunities for PrEP uptake [43]. Specifically, in France, >90% of the recently infected individuals were eligible for PrEP [43]. Therefore, assessing and communicating individual-level risk for acquiring HIV remains a key objective for achieving elimination. Promoting a fair perception of HIV risk can be achieved through, not only advertising and marketing PrEP [44], but also through using electronic health records for identifying high-risk MSM [45].

Importantly, if HIV is eliminated, interventions will be needed so individuals keep perceiving a low cost for PrEP and fair perception of HIV risk, to maintain a high PrEP coverage. Otherwise, HIV can reemerge and reach again an endemic state of concern for public health. The situation is similar to that of vaccination prevention, which requires continuous vaccine coverage even though the disease is nearly eliminated [46].

Our study has some limitations. First, we assumed that individuals act out of self-interest and do not cooperate to avoid getting infected by HIV. Modeling PrEP adoption through other theories of health behavior, considering for instance interactions between individuals [15], remains a subject to be studied in further work. Second, we assumed that MSM are homogeneous regarding risk perception. In reality, the MSM population is certainly heterogeneous, fair perception co-existing with misperception. Nevertheless, our baseline and alternative scenarios can be regarded as optimistic and pessimistic scenarios, respectively. Third, we did not account for migration or travel [47], nor for condom drop among non-PrEP users [48], which could influence elimination efforts. Fourth, our estimates of the number of

high-risk individuals, who should be on PrEP for HIV elimination, depend on the size of the MSM community, which is a metric difficult to estimate. Also, the number of high-risk MSM on PrEP currently reported, and hence the PrEP coverage, may represent an overestimate because establishing PrEP eligibility relies on self-reported behavior, which is difficult to appraise by practitioners.

Conclusion

Perception of the cost of PrEP and of HIV risk are two important levers to increase voluntary use of PrEP, reach coverage levels necessary to eliminate HIV, and maintain elimination in the context of less epidemic adversity. Current PrEP rollouts should aim at lowering the perceived cost of using PrEP and promoting a fair perception of the risk of acquiring HIV, to realize the full potential of PrEP prevention.

Authors' contributions

SJ, VS an RB conceived the model. SJ conducted the numerical simulations. All authors participated to the writing of the manuscript, analysis and interpretation of the results. All authors read and approved the final manuscript.

Acknowledgements

SJ was supported by an ANRS fellowship and a PhD fellowship from the French Ministry of Higher Education and Research, obtained via the Public Health Doctoral Network coordinated by the EHESP. The sponsors had no role in the study.

List of abbreviations

ART: Antiretroviral treatment; MSM: Men who have sex with men; PrEP: Pre-exposure prophylaxis; CI: confidence interval.

Supplemental Digital Content

Supplementary Material (pdf document containing the model description, model calibration and supplementary results).

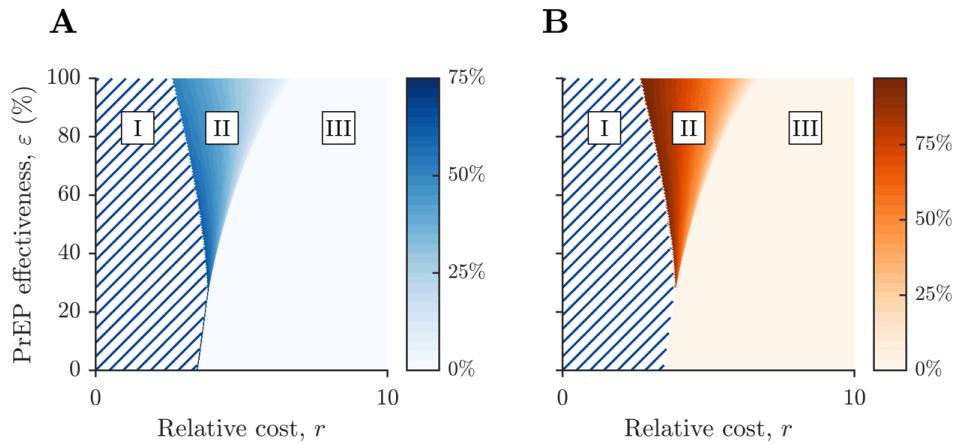
FIGURES

Figure 1. The voluntary PrEP coverage and its impact on HIV incidence, assuming fair risk perception

Color maps of **(A)** the voluntary PrEP coverage among high-risk men who have sex with men (MSM), \hat{p} , and **(B)** the corresponding reduction in the overall endemic HIV incidence rate, as functions of ϵ and r , assuming that individuals have a fair perception of HIV risk. The model outputs were obtained for one typical parameter set calibrating our model. Three regions were identified, depending on \hat{p} : Region III, where r is high and no MSM uses PrEP ($\hat{p} = 0\%$), so HIV incidence is not reduced; Region II, where some, but not enough MSM use PrEP, since r remains high, and thus the epidemic is controlled; and Region I (marked by blue stripes), where epidemic elimination is possible.

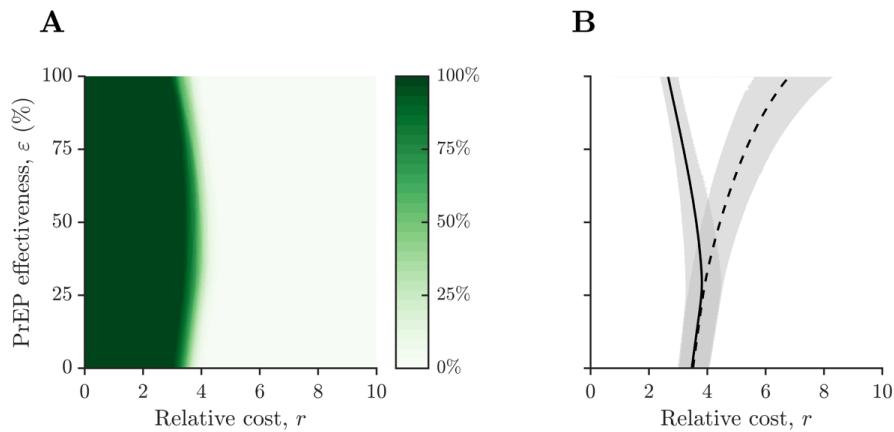


Figure 2. The probability of HIV elimination and boundary uncertainty for the three-region structure

(A) The probability of HIV epidemic elimination due to voluntary PrEP coverage, obtained from the ~500 calibrated parameter sets. **(B)** The boundaries (the mean is represented as a line and the 95% confidence interval as grey area) between Regions I and II (continuous line), and between Regions II and III (dashed line).

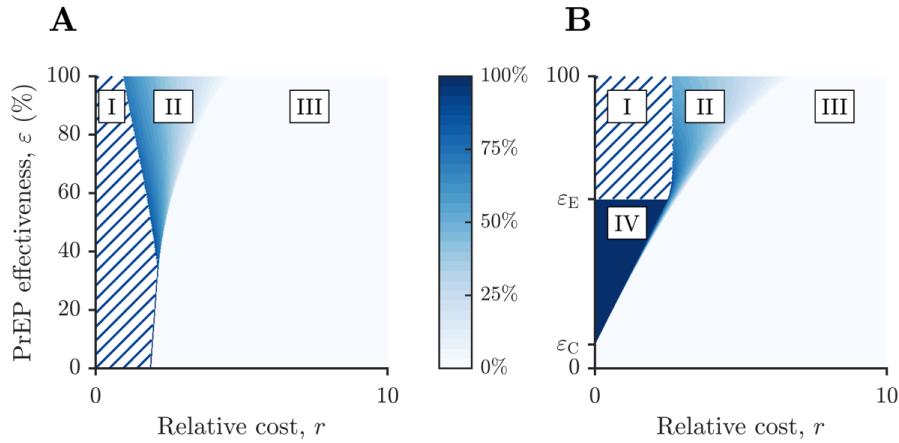


Figure 3. Sensitivity analyses for the baseline scenario

(A) Decision-making based on misperceived risk of acquiring HIV can significantly reduce the size of Region I, where epidemic elimination is possible (blue stripes), despite high levels of PrEP effectiveness. (B) By assuming fair perception of HIV risk but no change in HIV testing behavior among PrEP users (i.e., the time from infection to diagnosis remains at 3.1 years), the PrEP effectiveness thresholds required to reach epidemic control and epidemic elimination become $\varepsilon_C = 8\%$ and $\varepsilon_E = 58\%$, respectively. In turn, this yields a fourth region, denoted Region IV, where all individuals adopt PrEP but $\varepsilon_C \leq \varepsilon < \varepsilon_E$, so the epidemic is controlled, yet not eliminated. Regions II and III in both panels depict some and no PrEP adoption, respectively, similarly to Figure 1A.

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Supplementary Material

Can HIV epidemics among men who have sex with men be eliminated through participation to PrEP rollouts?

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S1 Model description

We propose a hybrid mathematical model describing the interplay between the HIV epidemic among men who have sex with men (MSM), and individual-level decision-making on whether or not to adopt pre-exposure prophylaxis (PrEP) against HIV infection, in the current therapeutic context, where efficient antiretroviral treatment (ART) is available. We used a deterministic compartmental model to describe HIV transmission among MSM and a game-theoretical approach to model individual's decision-making about PrEP adoption.

S1.1 Modeling the population-level spread of an HIV epidemic

S1.1.1 Compartmental model without PrEP

We stratified the MSM population into two risk groups (low and high) to account for heterogeneity in sexual activity and risk of acquiring HIV;¹ we used the subscript $i \in \{h, \ell\}$ (h stands for high and ℓ stands for low) to denote these two populations. Furthermore, we assumed that individuals at high risk of infection drive the epidemic, and thus there would be no epidemic if all individuals would be at low risk of HIV infection.

The flow diagram of the HIV epidemic model is shown in figure S1. Uninfected MSM join the sexually-mixing population at a rate π_i . Susceptible individuals, S_i , get infected with HIV at a rate Λ_i , which represents the per-capita force of infection; see section S1.1.3 for the definition. Once infected, individuals enter the acute stage of infection and progress to the chronic stage of infection at a rate σ . We used the superscript $k \in \{a, c\}$ (a stands for acute and c stands for chronic) to distinguish between the stages of infection. Infected individuals, I_i^k , are diagnosed at a rate θ , in any stage of infection, and immediately start ART, no longer transmitting HIV.² That is, only infected individuals unaware of their status transmit HIV. MSM on ART, T_i , remain stratified by risk group. Susceptible and undiagnosed MSM spend $1/\mu$ years selecting new sexual partners, while MSM on ART leave the sexually-mixing population at a higher rate, $\mu_T > \mu$.

The system of ordinary differential equations (ODE) for the HIV epidemic model is the following

$$\begin{aligned} dS_i/dt &= \pi_i - (\Lambda_i + \mu) S_i, \\ dI_i^a/dt &= \Lambda_i S_i - (\sigma + \theta + \mu) I_i^a, \\ dI_i^c/dt &= \sigma I_i^a - (\theta + \mu) I_i^c, \\ dT_i/dt &= \theta (I_i^a + I_i^c) - \mu_T T_i, \end{aligned} \tag{S1}$$

where $i \in \{h, \ell\}$. All the variables and parameters are positively defined. The total number of individuals in each risk group is $N_i = S_i + I_i^a + I_i^c + T_i$, and the total population is $N = \sum_i N_i$.

S1.1.2 Structured mixing

We consider that individuals do not mix uniformly random (i.e., according to the law of mass action), rather that most partnerships occur within the same risk group (i.e., non-random mixing).^{1,3–5} We used ρ_{ij} to denote the probability for an i -risk individual to start a sexual partnership with an j -risk individual. The matrix

$$\rho = \begin{pmatrix} \rho_{hh} & \rho_{h\ell} \\ \rho_{\ell h} & \rho_{\ell\ell} \end{pmatrix} \tag{S2}$$

is called *mixing matrix*, and its elements verify $0 < \rho_{ij} < 1$ and $\sum_j \rho_{ij} = 1$. Since we assumed that individuals mix preferentially within the same risk group, we have $\rho_{ii} > 1/2$.

We further consider that i -risk individuals have c_i new sexual partners per year, and that the number of partners for high-risk individuals was higher than that for low-risk individuals ($c_h > c_\ell$). The total number of partnerships that i -risk individuals have with j -risk individuals

per unit of time is given by $\rho_{ij}c_iN_i$. To balance the total number of partnerships,¹ we require $\rho_{ij}c_iN_i = \rho_{ji}c_jN_j$, which yields

$$\rho_{\ell h} = (1 - \rho_{hh}) \frac{c_h N_h}{c_\ell N_\ell}. \quad (\text{S3})$$

Furthermore, $\rho_{ii} > 1/2$ yields

$$c_h < \frac{c_\ell N_\ell}{2(1 - \rho_{hh})N_h}, \quad (\text{S4})$$

which is an important constraint for the model calibration; see section S2. In simulations, we assumed that the elements of the mixing matrix remain constant, taking the values obtained through calibration.

S1.1.3 The force of infection

We use β_j^k to denote the per-partnership probability of HIV transmission from a j -risk infected individual in stage of infection k . We reasonably assume that individuals in the acute stage of infection are more likely to transmit HIV than individuals in the chronic stage,⁶ and therefore set $\beta_j^a = w\beta_j^c$, with $w > 1$.

The rate at which i -risk susceptibles acquire HIV by forming sexual partnerships with infected individuals is called the *force of infection*³ and is given by

$$\Lambda_i \equiv \sum_{\substack{j \in \{h, \ell\} \\ k \in \{a, c\}}} \frac{c_i \rho_{ij} \beta_j^k I_j^k}{N_j}. \quad (\text{S5})$$

S1.2 Accounting for the uptake of PrEP

S1.2.1 Including PrEP epidemiology into the HIV epidemic model

We adapt the HIV epidemic model (S1) for the context where PrEP is available as an HIV prevention method. We suppose that only susceptible individuals having high risk of acquiring HIV are eligible to adopt PrEP. We do not consider that individuals go on and off PrEP, rather that they rigorously follow the PrEP regimen for the entire duration of their sexually mixing period. This modeling choice is further discussed in section S1.3, as it matches other modeling choices for the decision-making game model for the adoption of PrEP. We use p and ε to denote, respectively, the PrEP coverage and the PrEP effectiveness. Of note, the PrEP coverage parameter is not imposed, rather, it is obtained by solving the decision-making model; see section S1.3.1. We assume that individuals on PrEP (P) can get infected at a rate $(1 - \varepsilon)\Lambda_P$, defined in section S1.2.2, and get tested for HIV at a rate θ_P . The ODE system of the HIV epidemic model becomes

$$\begin{aligned} dP/dt &= p\pi_h - ((1 - \varepsilon)\Lambda_P + \mu)P, \\ dS_h/dt &= (1 - p)\pi_h - (\Lambda_h + \mu)S_h, \\ dS_\ell/dt &= \pi_\ell - (\Lambda_\ell + \mu)S_\ell, \\ dI_P^a/dt &= (1 - \varepsilon)\Lambda_P P - (\sigma + \theta_P + \mu)I_P^a, \\ dI_h^a/dt &= \Lambda_h S_h - (\sigma + \theta + \mu)I_h^a, \\ dI_\ell^a/dt &= \Lambda_\ell S_\ell - (\sigma + \theta + \mu)I_\ell^a, \\ dI_P^c/dt &= \sigma I_P^a - (\theta_P + \mu)I_P^c, \\ dI_h^c/dt &= \sigma I_h^a - (\theta + \mu)I_h^c, \\ dI_\ell^c/dt &= \sigma I_\ell^a - (\theta + \mu)I_\ell^c, \\ dT_h/dt &= \theta_P (I_P^a + I_P^c) + \theta(I_h^a + I_h^c) - \mu_T T_h, \\ dT_\ell/dt &= \theta(I_\ell^a + I_\ell^c) - \mu_T T_\ell, \end{aligned} \quad (\text{S6})$$

illustrated by the flow diagram in figure S2. The ODE system (S6) has two equilibria: an endemic state (ES) where all the population compartments are non-empty, and a disease-free state (DFS) with no infected individuals

$$I_i^{k,\text{DFS}} = 0, \quad T_i^{\text{DFS}} = 0, \quad \text{for all } i \in \{P, h, \ell\}, k \in \{a, c\}, \quad (\text{S7})$$

only uninfected individuals, whether or not on PrEP

$$P^{\text{DFS}} \neq 0, \quad S_i^{\text{DFS}} \neq 0, \quad \text{for all } i \in \{h, \ell\}. \quad (\text{S8})$$

We further assume that the per-partnership probability for acquiring HIV from an infected, high-risk MSM is the same, whether or not the MSM is taking PrEP. Hence, the force of infection for the population at i -risk of infection, not taking PrEP, becomes

$$\Lambda_i = c_i \left(\frac{\rho_{ih}\beta_h^a(I_P^a + I_h^a) + \rho_{ih}\beta_h^c(I_P^c + I_h^c)}{N_h} + \frac{\rho_{i\ell}\beta_\ell^a I_\ell^a + \rho_{i\ell}\beta_\ell^c I_\ell^c}{N_\ell} \right), \quad \text{for } i \in \{h, \ell\}, \quad (\text{S9})$$

where

$$N_h = P + S_h + I_P^a + I_P^c + I_h^a + I_h^c + T_h, \quad (\text{S10})$$

and

$$N_\ell = S_\ell + I_\ell^a + I_\ell^c + T_\ell. \quad (\text{S11})$$

S1.2.2 PrEP-induced risk compensation

The PREVENIR study reported that MSM using PrEP may use condoms less often;⁷ we call this the phenomenon of *risk compensation*. We model risk compensation among susceptibles on PrEP explicitly, showing how the force of infection for high-risk susceptibles on PrEP depends on condom effectiveness and condom use among high-risk susceptibles.

We denote by β_{jh}^k the per-partnership probability of HIV transmission from a j -risk individual in k stage of infection toward high-risk susceptibles. This can be written as

$$\beta_{jh}^k \equiv \beta_{j0}^k(1 - \xi\eta_h) = \beta_j^k, \quad (\text{S12})$$

where β_{j0}^k is the baseline (i.e., without condom) per-partnership probability, ξ denotes condom effectiveness and η_h is the probability of using condoms for high-risk susceptibles before the introduction of PrEP.

We assumed that, once PrEP becomes available, high-risk susceptibles, who do not adopt PrEP, continue to use condoms with probability η_h , while high-risk susceptibles who adopt PrEP use condoms with probability $\eta_P < \eta_h$; i.e., they are less likely to use condoms. We thus obtained that the per-partnership probability of HIV transmission to high-risk susceptibles on PrEP is given by $\beta_j^k(1 - \xi\eta_P)/(1 - \xi\eta_h)$. In sum, the force of infection on high-risk susceptibles taking PrEP is given by

$$(1 - \varepsilon)\Lambda_P = (1 - \varepsilon) \left(\frac{1 - \xi\eta_P}{1 - \xi\eta_h} \right) \Lambda_h. \quad (\text{S13})$$

S1.2.3 The effective reproduction number

We computed the *effective reproduction number* for the ODE system (S6), the expected number of secondary cases produced by a single infected individual, during his entire infectious period, in an uninfected population subject to control interventions,^{8,9} and we expressed it as a function of the PrEP coverage and effectiveness

$$R(p, \varepsilon) = A \left[H(p, \varepsilon) + M + \sqrt{(H(p, \varepsilon) - M)^2 + 4BH(p, \varepsilon)M} \right], \quad (\text{S14})$$

where

$$A^{-1} \equiv 2(\theta + \mu)(\theta_P + \mu)(\sigma + \theta + \mu)(\sigma + \theta_P + \mu), \quad (\text{S15})$$

$$B \equiv \left(\frac{1}{\rho_{hh}} - 1 \right) \left(\frac{1}{\rho_{\ell\ell}} - 1 \right), \quad (\text{S16})$$

$$M \equiv (\theta_P + \mu)(\sigma + \theta_P + \mu) \left[(\theta + \mu)c_\ell\rho_{\ell\ell}\beta_\ell^a + \sigma c_\ell\rho_{\ell\ell}\beta_\ell^c \right], \quad (\text{S17})$$

are independent of the PrEP parameters. In contrast, $H(p, \varepsilon)$ is the following function of p and ε

$$H(p, \varepsilon) \equiv (1-p)H_h + p(1-\varepsilon) \left(\frac{1-\xi\eta_P}{1-\xi\eta_h} \right) H_P, \quad (\text{S18})$$

where

$$H_h \equiv (\theta_P + \mu)(\sigma + \theta_P + \mu) \left[(\theta + \mu)c_h\rho_{hh}\beta_h^a + \sigma c_h\rho_{hh}\beta_h^c \right], \quad (\text{S19})$$

and

$$H_P \equiv (\theta + \mu)(\sigma + \theta + \mu) \left[(\theta_P + \mu)c_h\rho_{hh}\beta_h^a + \sigma c_h\rho_{hh}\beta_h^c \right], \quad (\text{S20})$$

do not depend on PrEP parameters

We used the effective reproduction number to quantify the impact of PrEP on the HIV epidemic. We refer to the epidemic as being *controlled by PrEP* if the effective reproduction number after the introduction of PrEP is lower than that in the absence of PrEP; i.e., if $R(p, \varepsilon) < R(0, \varepsilon)$. A transcritical bifurcation occurs for the ODE system (S6) when $R(p, \varepsilon) = 1$.^{3,9} If $R(p, \varepsilon) > 1$, then the endemic state will be reached; if $R(p, \varepsilon) < 1$ then the disease-free state will be reached. We say the epidemic among MSM is *eliminated by PrEP* if $R(p, \varepsilon) \leq 1$.

It is important to note that the introduction of PrEP does not lead unconditionally to control of the HIV epidemic, especially that the introduction of PrEP can cause less condom use. In the following of this manuscript, we determine the conditions for which PrEP prevention can induce control and elimination of the HIV epidemic.

The epidemic control threshold. For the epidemic to be controlled, certain conditions for PrEP uptake, HIV testing and condom use parameters must be satisfied. In particular, we found a threshold value for the PrEP effectiveness, denoted ε_C , ensuring $R(p, \varepsilon) < R(0, \varepsilon)$ if and only if $\varepsilon \geq \varepsilon_C$, where

$$\varepsilon_C \equiv 1 - \left(\frac{1-\xi\eta_h}{1-\xi\eta_P} \right) \left(\frac{H_h}{H_P} \right). \quad (\text{S21})$$

The epidemic elimination threshold. In our model, epidemic elimination (i.e., $R(p, \varepsilon) \leq 1$) is possible if and only if the *effective PrEP coverage*, $\varphi(\varepsilon)p$, is equal to or larger than K , where

$$\varphi(\varepsilon) \equiv H_h - (1-\varepsilon) \left(\frac{1-\xi\eta_P}{1-\xi\eta_h} \right) H_P. \quad (\text{S22})$$

and K is a constant independent of the PrEP parameters defined by

$$K \equiv H_h - \left(M - \frac{1}{2A} \right) \left(\frac{1}{2AM(1-B)-1} \right). \quad (\text{S23})$$

The lowest value for the PrEP effectiveness allowing for the HIV epidemic elimination is obtained assuming full PrEP coverage: $R(p=1, \varepsilon) \leq 1$ if and only if $\varepsilon \geq \varepsilon_E$, where

$$\varepsilon_E \equiv 1 - \left(1 - \frac{K}{H_h} \right) (1 - \varepsilon_C). \quad (\text{S24})$$

Hence, the epidemic elimination condition $R(p, \varepsilon) \leq 1$ is met when $\varphi(\varepsilon)p \geq K$, for $\varepsilon \geq \varepsilon_E$ and $0 \leq p \leq 1$.

S1.3 Modeling individual-level decision-making on PrEP adoption

S1.3.1 Decision model

We propose a mathematical model for the individual-level decision-making on whether or not to adopt PrEP for HIV prevention. As mentioned in section S1.2.1, we assume that only uninfected individuals at high risk of infection are proposed to adopt PrEP.

We use a game-theoretical approach, where individuals act alone and in their own interest. Individuals are considered to weigh their perceived pros and cons of using PrEP, versus getting infected and the consequent lifelong ART. These pros and cons consist of monetary and/or non-monetary aspects such as: undesired secondary effects, price, reimbursement policies, accessibility, social stigma, disease morbidity, etc.¹⁰⁻¹³ Pros and cons are expressed as *costs* perceived by the individual and they are balanced in a *utility function*. Then, the individual-level decision-making on whether or not to adopt PrEP is modeled by the maximization of the utility, which is equivalent to the minimization of the total expected cost by the individual MSM.

The solution of the game model is an equilibrium situation for the HIV epidemiology, where a fraction of the individuals adopt PrEP in stationary epidemic conditions; i.e. there are no longer changes in prevention behavior. We therefore assumed that, in the long term, the individuals are pleased with their decision regarding PrEP adoption, which they maintain for the duration of their sexually mixing period. That is, we do not model changes of decision and recurrent decision-making. In addition, we consider no formal difference between PrEP regimens (daily or event-driven PrEP approach).

S1.3.2 Utility of PrEP for the individual-level decision-making

An individual at high risk of infection can adopt one of the two mutually exclusive strategies: not to use PrEP, at a perceived cost $C_{\text{No-PrEP}} > 0$ or to use PrEP for HIV prevention, at a perceived cost $C_{\text{PrEP}} > 0$. For a probability p to adopt PrEP, the expected utility $U(p)$ for the individual is given by

$$U(p) = -p C_{\text{PrEP}} - (1 - p) C_{\text{No-PrEP}} \equiv -C(p), \quad (\text{S25})$$

where $C(p)$ stands for the total expected cost.

The cost of adopting the strategy of not using PrEP. In the case where an individual decides not to use PrEP, he may get infected, starts treatment upon positive HIV diagnosis, and eventually pays the cost of ART for the rest of his life. We thus assumed that an individual who decides not to use PrEP pays, once he becomes HIV infected during his sexually-mixing period, the cost of ART. After leaving the sexually-mixing population, if infected with HIV, the individual continues to pay the cost of ART for the rest of his life. An individual who decides not to use PrEP and does not get infected with HIV pays no cost. Mathematically, the cost of adopting the strategy of not using PrEP can be written as

$$C_{\text{No-PrEP}}(p, \varepsilon) \equiv \int_0^L \left(1 - e^{-\lambda(p, \varepsilon)t}\right) c_T dt + \int_L^{L+L_T} \left(1 - e^{-\lambda(p, \varepsilon)L}\right) c_T dt, \quad (\text{S26})$$

where c_T is the per-year perceived cost of ART, L is the number of years that an infected individual stays sexually mixing, L_T is the number of life years remaining after leaving the sexually-mixing population for individuals on ART, λ is the rate of getting infected with HIV; see section S1.3.3.

The cost of adopting the strategy of using PrEP to avoid HIV infection. Similarly, in the case where an individual decides to adopt PrEP, he would take and pay the cost of PrEP and, in the case of acquiring HIV despite PrEP uptake, being diagnosed and starting ART, he

would pay the cost of treatment for the rest of his life. This is summarized mathematically as follows

$$C_{\text{PrEP}}(p, \varepsilon) \equiv \int_0^L e^{-\lambda_P(p, \varepsilon)t} c_P dt + \int_0^L \left(1 - e^{-\lambda_P(p, \varepsilon)t}\right) c_T dt + \int_L^{L+L_T} \left(1 - e^{-\lambda_P(p, \varepsilon)L}\right) c_T dt, \quad (\text{S27})$$

where c_P is the per-year perceived cost of PrEP and λ_P is the rate of getting infected with HIV despite taking PrEP; see section S1.3.3.

We introduce the *relative cost of prevention versus treatment* (i.e., PrEP versus ART), $r = c_P/c_T > 0$. Rescaling equations (S26) and (S27) by c_T and maintaining the notation (namely, keeping the symbols $C_{\text{No-PrEP}}$, C_{PrEP} and U for the rescaled quantities), we rewrite the utility function as follows:

$$U(p; \varepsilon, r) = -p C_{\text{PrEP}}(p; \varepsilon, r) - (1-p) C_{\text{No-PrEP}}(p; \varepsilon) \equiv -C(p; \varepsilon, r). \quad (\text{S28})$$

The PrEP coverage that maximizes $U(p; \varepsilon, r)$ or, equivalently, minimizes the expected cost $C(p; \varepsilon, r)$ is interpreted as the probability of an MSM at high risk of infection to use PrEP, which yields the *voluntary PrEP coverage*, $\hat{p}(\varepsilon, r)$, as a function of PrEP effectiveness, ε , and the relative cost of PrEP versus ART, r .

S1.3.3 Risk of HIV infection perceived by high-risk individuals

In the baseline scenario, we assumed that individuals have a fair sense of their own risk to acquire HIV. Thus, in the absence of an HIV epidemic, individuals (whether or not on PrEP) acknowledge zero risk; that is,

$$\Lambda_h^{\text{DFS}} = \Lambda_P^{\text{DFS}} = 0. \quad (\text{S29})$$

In the case of adopting the No-PrEP strategy, individuals acknowledge a risk of infection given by the force of infection for high-risk individuals not on PrEP, at the endemic state,

$$\Lambda_h^{\text{ES}}(p, \varepsilon) = c_h \left(\frac{\rho_{ih}\beta_h^a(I_P^{a,\text{ES}} + I_h^{a,\text{ES}}) + \rho_{ih}\beta_h^c(I_P^{c,\text{ES}} + I_h^{c,\text{ES}})}{N_h^{\text{ES}}} + \frac{\rho_{i\ell}\beta_\ell^a I_\ell^{a,\text{ES}} + \rho_{i\ell}\beta_\ell^c I_\ell^{c,\text{ES}}}{N_\ell^{\text{ES}}} \right), \quad (\text{S30})$$

where the population variables $I_j^{k,\text{ES}}$, for $j \in \{P, h, \ell\}$, $k \in \{a, c\}$ and N_j^{ES} , for $i \in \{h, \ell\}$ depend implicitly on p and ε . In the case of adopting PrEP, individuals acknowledge a risk of infection given by the force of infection for high-risk individuals on PrEP at the endemic state

$$(1 - \varepsilon)\Lambda_P^{\text{ES}}(p, \varepsilon) = (1 - \varepsilon) \left(\frac{1 - \xi\eta_P}{1 - \xi\eta_h} \right) \Lambda_h^{\text{ES}}(p, \varepsilon). \quad (\text{S31})$$

Specifically, $\lambda(p, \varepsilon)$, the rate of HIV infection for individuals, who decide not to use PrEP, is given by

$$\lambda(p, \varepsilon) = \begin{cases} \Lambda_h^{\text{ES}}(p, \varepsilon), & \text{if } R(p, \varepsilon) > 1, \\ \Lambda_h^{\text{DFS}}, & \text{if } R(p, \varepsilon) \leq 1; \end{cases} \quad (\text{S32})$$

while λ_P , the rate of becoming infected despite taking PrEP for individuals who decide to use PrEP (cf. equation (S27)), is given by

$$\lambda_P(p, \varepsilon) = \begin{cases} (1 - \varepsilon)\Lambda_P^{\text{ES}}(p, \varepsilon), & \text{if } R(p, \varepsilon) > 1, \\ \Lambda_P^{\text{DFS}}, & \text{if } R(p, \varepsilon) \leq 1. \end{cases} \quad (\text{S33})$$

The quantities $\lambda(p, \varepsilon)$ and $\lambda_P(p, \varepsilon)$ are used in the definitions of $C_{\text{PrEP}}(p; \varepsilon, r)$ and $C_{\text{No-PrEP}}(p; \varepsilon)$, the perceived costs for the strategies to adopt PrEP and not to adopt PrEP, respectively; see section S1.3.2.

S2 Model calibration

The hybrid model combining the ODE system and the decision model was built in MATLAB (release 2018). We first calibrated the model (S1) to reproduce the HIV epidemiology among MSM in the Paris region, Île-de-France, assumed to be close to an endemic state in 2016.¹⁴ The initial values used for the HIV transmission parameters in the calibration process are listed in tables S1 and S2, respectively. As calibration criteria, we used estimates for MSM in Île-de-France, listed in table S3, regarding the HIV incidence rate, prevalence of undiagnosed infections,¹⁵ prevalence of HIV,¹⁶ size of the MSM population,^{17,18} we used the HIV incidence estimated by the ANRS IPERGAY study in Paris⁷ as an upper bound for the incidence among high-risk MSM. The epidemiological indicators were related to model simulations according to the formulae given in table S4.

Using the initial ranges (cf. tables S1 and S2), we generated 500 000 parameter sets through latin hypercube sampling, assuming that each parameter follows a uniform distribution. Out of these 500 000 parameter sets, 111 passed the calibration checks. Then, to refine the calibration, we generated additional 1 400 parameters sets, by sampling nearby the previously obtained parameter sets. In total, 505 parameter sets passed the calibration checks. Summary statistics for each HIV parameter yields a mean and a 95% confidence interval (CI); see table S2. Of note, that the calibration selects for $\beta_h^k > \beta_\ell^k$, which, indeed, suggests an intrinsic, riskier behavior for individuals with high sexual activity.

Using our ~ 500 calibrated parameter sets, we estimated epidemiological indicators for the HIV epidemic in the MSM community of Île-de-France. They provide our modeling perspective on the HIV epidemiology before the introduction of PrEP (cf. table S3): overall yearly mean incidence was 1.3%, mean prevalence 17%, and 17% of MSM living with HIV were unaware of their HIV status. The mean number of MSM was $\sim 111\,000$, of which $\sim 14\,200$ were at high risk of HIV infection and eligible for PrEP. Yearly mean HIV incidence for high-risk MSM was 7%. We note, however, that our estimates for the HIV epidemiological indicators, resulting from the model calibration, do not differ much from the estimates obtained through direct data analyses (cf. table S3), indicative of successful calibration. The ~ 500 calibrated parameter sets were further used for simulations regarding the introduction of PrEP and the decision model.

S3 Supplementary results

S3.1 Impact of PrEP rollouts on HIV epidemics

In France, PrEP prescriptions need to be renewed every three months.¹⁹ Meanwhile, the PrEP-eligible individual must provide proof that they tested negative for HIV infection. Consequently, on-PrEP MSM get tested for HIV every three months, which determines our parameter $1/\theta_P = 3$ months; see table S2. It is very important to note that on-PrEP MSM get tested much more frequently than MSM before the PrEP rollout, when the median time from HIV infection to diagnosis for MSM was 3.1 years.¹⁵ Due to the dramatic change in testing behavior, the PrEP rollout can act as a test-and-treat intervention, where individuals get tested very often for HIV infection, and start treatment upon positive diagnostic, no longer transmitting HIV. In principle, this can be sufficient to eliminate the HIV epidemic, even without PrEP.^{20,21}

The deterministic component of our HIV model (S6) can offer insight into the epidemic-level impact of a PrEP rollout, and the action of various parameters. Figure S3A depicts the effective reproduction number R versus ε and p , for one typical parameter set calibrating our model. According to our baseline scenario, we assumed that high-risk MSM, not taking PrEP, use condom with probability 30%, and if they take PrEP, the probability drops at 20%; condom effectiveness was considered to be 70%. The fact that a 70%-80% PrEP coverage is sufficient to eliminate HIV, even when PrEP efficacy is zero, is entirely due to the test-and-treat effect of the PrEP rollout, as explained before. In particular, this implies that the thresholds in PrEP

effectiveness, such that epidemic control and elimination are possible, are zero; i.e., $\varepsilon_E = \varepsilon_C = 0$. The test-and-treat action of the PrEP rollout is further evidenced in figure S3B, which represents R as a function of the PrEP coverage p and testing rate θ_P , assuming that the effectiveness of PrEP is zero ($\varepsilon = 0$); that is, there is no PrEP and p is the coverage of frequent testing, with the rate θ_P . Figure S3B reveals that, for HIV elimination in the absence of PrEP (i.e., or using a PrEP regimen with no efficacy), it would suffice that $\sim 80\%$ of the high-risk MSM in the Paris region got tested every three months; see figure S3 for $p = 80\%$ and $\theta_P = 4 \text{ years}^{-1}$. Still, an intervention based just on the test-and-treat strategy may be difficult to implement. The individual at risk is not directly protected from acquiring HIV, by joining a test-and-treat program. Rather, the benefits are indirect, emerging from the success of the test-and-treat intervention at the population level. It is thus expected that test-and-treat interventions have low acceptability. The French guidelines recommend, since 2009, annual HIV testing for MSM at risk, and 3-month testing since 2017. Yet, testing rate estimates are significantly lower, since the median time from HIV infection to diagnosis for MSM was estimated at 3.1 years.¹⁵

The distinct advantage of PrEP rollouts is that they offer direct protection to individuals at risk of acquiring HIV, through highly effective PrEP regimens. Hence, the individual recognizes his interest in adopting PrEP, and may join the PrEP rollout voluntarily, ensuring high acceptability for PrEP rollouts. Furthermore, as more and more individuals join the prevention effort, population-level benefits emerge, down to HIV elimination.

S3.2 Adoption of PrEP under the baseline scenario

In the baseline scenario, we assumed that individuals have a fair sense of their risk of infection and condom use drops from 30% to 20% when individuals adopt PrEP.²² The risk of HIV infection is computed using the HIV transmission model, and corresponds to the force of HIV infection (cf. section S1.3.3). In addition, we considered that on-PrEP MSM follow the recommendations of the regimen, which requires 3-month testing to renew their PrEP prescription.²² Therefore, MSM on PrEP are advised to test much more frequently than what is the current practice of MSM not taking PrEP; i.e., $\theta_P \ll \theta$ and the PrEP rollout can share the action of a test-and-treat intervention. We found that, in this case, the thresholds in PrEP effectiveness, such that epidemic control and elimination are possible, are zero; i.e., $\varepsilon_E = \varepsilon_C = 0$.

S3.2.1 Voluntary PrEP coverage

We computed the voluntary PrEP coverage among high-risk MSM, denoted \hat{p} , for one typical parameter set calibrating our model; see table S2. The PrEP coverage starts at zero, before the introduction of PrEP, and then reaches an optimal value where the expected cost of adopting PrEP is minimum. The final value reached by \hat{p} depends on HIV epidemic parameters before the introduction of PrEP, that were found by calibration, PrEP effectiveness, ε , and perceived relative cost of PrEP versus ART, r , which were varied over broad ranges.

Our previous work²³ helped identify the conditions for which our model algorithms could be reliably implemented. Indeed, if $R(\hat{p}, \varepsilon) \leq 1$, then there is no stable equilibrium for the individual strategies and numerical methods fail to compute an approximation for the voluntary PrEP coverage, $\hat{p}(\varepsilon, r)$; otherwise, numerical estimation of $\hat{p}(\varepsilon, r)$ is possible. We say that, for $R(\hat{p}, \varepsilon) \leq 1$, the game regarding the adoption of PrEP has no solution.

As a supplement to the colormaps in figure 1 of the main text, figure S4 depicts the PrEP coverage reached voluntarily among high-risk MSM, $\hat{p}(\varepsilon, r)$, and the corresponding endemic force of infection among high-risk MSM when the PrEP effectiveness is $\varepsilon = 86\%$; n.b., $\hat{\Lambda}_h^{\text{ES}}(\varepsilon, r) \equiv \Lambda_h^{\text{ES}}(\hat{p}(\varepsilon, r), \varepsilon)$. For a given value of the PrEP effectiveness, ε , we used $r_E(\varepsilon)$ and $r_C(\varepsilon)$ to denote, respectively, the elimination and control threshold values for the relative cost; n.b., $0 < r_E(\varepsilon) < r < r_C(\varepsilon)$ implies $0\% < \hat{p}(\varepsilon, r) < 100\%$. The three regions identified in figure 1 of the main text

are also present in figure S4, delimited by the thresholds in PrEP effectiveness and relative cost (n.b., $\varepsilon = 86\%$ for figure S4):

- Region III, where $r \geq r_C(\varepsilon)$. The relative cost of prevention versus treatment is perceived as being too high. Therefore, no one adopts the strategy of using PrEP to prevent HIV infection (i.e., $\hat{p}(\varepsilon, r) = 0\%$) and the endemic state of the epidemic stays unaffected (i.e., $\hat{\Lambda}_h^{\text{ES}}(\varepsilon, r) = \Lambda_h^{\text{ES}}(0, 0)$).
- Region II, where $r_E(\varepsilon) < r < r_C(\varepsilon)$. The relative cost is low enough, so a proportion of high-risk MSM adopts the strategy of using PrEP (i.e., $0\% < \hat{p}(\varepsilon, r) < 100\%$). However, not enough MSM adopt PrEP and thus, the *effective, voluntary PrEP coverage*, $\varphi(\varepsilon) \hat{p}(\varepsilon, r)$, is below the threshold K . Hence, the HIV epidemic is controlled (i.e., $\hat{\Lambda}_h^{\text{ES}}(\varepsilon, r) < \Lambda_h^{\text{ES}}(0, 0)$), but not eliminated.
- Region I, where $0 \leq r \leq r_E(\varepsilon)$. The relative cost is low, and the PrEP effectiveness is above the elimination threshold, thus the effective, voluntary PrEP coverage, $\varphi(\varepsilon) \hat{p}(\varepsilon, r)$, may reach or exceed the threshold K , so the epidemic may be averted. Hence, in region I, the reproduction number is below 1 (i.e., $R(\hat{p}(\varepsilon, r), \varepsilon) \leq 1$).

S3.2.2 Relative reduction in HIV incidence rate

The endemic HIV incidence rate reached after the introduction of PrEP (cf. model (S6)) is given by

$$\mathcal{I}^{\text{ES}}(p, \varepsilon) \equiv \frac{(1 - \varepsilon)\Lambda_h^{\text{ES}} P^{\text{ES}} + \Lambda_h^{\text{ES}} S_h^{\text{ES}} + \Lambda_\ell^{\text{ES}} S_\ell^{\text{ES}}}{P^{\text{ES}} + S_h^{\text{ES}} + S_\ell^{\text{ES}}}. \quad (\text{S34})$$

The endemic incidence rate in the absence of PrEP is $\mathcal{I}^{\text{ES}}(0, 0) = 1.3\%$. Figure 1B of the main text depicts the relative reduction in the endemic HIV incidence rate due to voluntary PrEP coverage, $[\mathcal{I}^{\text{ES}}(0, 0) - \mathcal{I}^{\text{ES}}(\hat{p}(\varepsilon, r), r)] / \mathcal{I}^{\text{ES}}(0, 0)$. Note that increasing PrEP effectiveness and reducing PrEP cost results in greater reduction of the endemic incidence rate, provided that the condition for epidemic control regarding PrEP effectiveness is met; i.e., $\varepsilon > \varepsilon_C$.

S3.3 Sensitivity analyses

S3.3.1 Risk misperception

In the baseline scenario, we assumed that high-risk MSM have a fair sense of their risk of infection when deciding whether or not to adopt PrEP; this risk of infection was computed using the HIV transmission model, and corresponds to the force of HIV infection; see section S1.3.3. However, individuals could misperceive their risk of acquiring infection.²⁴ In a sensitivity scenario, we assumed that individuals underestimate their risk of infection when deciding whether or not to adopt PrEP. Specifically, we assumed that high-risk MSM get a sense of the risk of infection from, for instance, the rate of their high-risk MSM peers being diagnosed with HIV each year, given by

$$\tilde{\Lambda}(p, \varepsilon) \equiv \frac{\theta_P \left(I_P^{a,\text{ES}} + I_P^{c,\text{ES}} \right) + \theta \left(I_h^{a,\text{ES}} + I_h^{c,\text{ES}} \right)}{P^{\text{ES}} + S_h^{\text{ES}} + I_P^{a,\text{ES}} + I_P^{c,\text{ES}} + I_h^{a,\text{ES}} + I_h^{c,\text{ES}}}. \quad (\text{S35})$$

We repeated our analyses using $\tilde{\Lambda}$ in equations (S31)–(S33) instead of Λ_h^{ES} and compared the results with those of the baseline scenario; see figure 3 of the main text. The HIV epidemiological picture regarding voluntary PrEP coverage is qualitatively similar. That is, we recover the 3-region structure and the voluntary PrEP coverage required for HIV elimination is the same. Still, the misperception of infection risk leaves less room for intervention aiming at epidemic elimination: Region I gets significantly reduced along the relative cost axis (r), compared with the baseline scenario using the force of infection for the perceived risk; see figure 3 of the main

text. In particular, for a PrEP effectiveness of 86%, the cost of PrEP relative to that of ART should be lowered by a factor of ~ 2 relative to the baseline scenario, in order to reach Region I.

S3.3.2 Condom use and risk compensation

In the baseline scenario, we assumed that there is a drop in condom use among PrEP users from $\eta_h = 30\%$ to $\eta_P = 20\%$. In a worse-case scenario for condom drop (i.e., a sensitivity scenario), we considered that individuals on PrEP stop using condoms completely (i.e., $\eta_P = 0\%$) and, redoing the analyses, we compared the results with those of the baseline scenario; see figure S5. Risk compensation among PrEP users has low impact on our results: (1) the boundary between regions II and III shifts only slightly, and (2) only slightly higher levels of PrEP coverage are required for epidemic elimination when PrEP users completely drop condom use.

S3.3.3 Unchanged rates of HIV testing for individuals on PrEP

In the baseline scenario, we assumed that on-PrEP MSM test against HIV every 3 months. Here, we considered that on-PrEP MSM do not change their behavior regarding HIV testing; that is, the PrEP program does not require a change in testing behavior, thus $\theta_P = \theta$. Therefore, we have

$$\varepsilon_C \equiv 1 - \left(\frac{1 - \xi \eta_h}{1 - \xi \eta_P} \right), \quad (\text{S36})$$

and

$$\varepsilon_E \equiv 1 - (1 - \tilde{K})(1 - \varepsilon_C), \quad (\text{S37})$$

where

$$\tilde{K} \equiv 1 - \frac{1}{\tilde{H}_h} \left(\tilde{M} - \frac{1}{2\tilde{A}} \right) \left(\frac{1}{2\tilde{A}\tilde{M}(1 - B) - 1} \right), \quad (\text{S38})$$

with

$$\tilde{A}^{-1} \equiv 2(\theta + \mu)(\sigma + \theta + \mu), \quad (\text{S39})$$

$$\tilde{M} \equiv (\theta + \mu)c_{\ell\rho\ell\ell}\beta_{\ell}^a + \sigma c_{\ell\rho\ell\ell}\beta_{\ell}^c, \quad (\text{S40})$$

$$\tilde{H}_h \equiv (\theta + \mu)c_h\rho_{hh}\beta_h^a + \sigma c_h\rho_{hh}\beta_h^c. \quad (\text{S41})$$

Epidemic elimination is reached if and only if $\varphi(\varepsilon)p \geq \tilde{K}$, where $\varphi(\varepsilon)$ becomes

$$\varphi(\varepsilon) \equiv 1 - (1 - \varepsilon) \left(\frac{1 - \xi \eta_h}{1 - \xi \eta_P} \right). \quad (\text{S42})$$

Equation (S37) simplifies to $\tilde{H}(p, \varepsilon) \equiv (1 - \varphi(\varepsilon)p)\tilde{H}_h$. Furthermore, in the case where on-PrEP MSM do not incur in risk compensation (i.e., there is no condom drop with PrEP adoption and $\eta_P = \eta_h$), the PrEP effectiveness threshold for epidemic control is zero (i.e., $\varepsilon_C = 0$) and the PrEP effectiveness threshold for epidemic elimination is \tilde{K} (i.e., $\varepsilon_E = \tilde{K}$).

Assuming that adoption of PrEP does not require changes in HIV testing behavior, and keeping all the other assumptions of the baseline scenario (i.e., high-risk MSM not on PrEP use condoms with 30% probability and MSM on PrEP use condoms with 20% probability, condom effectiveness is 70% and HIV-risk perception is fair), we found $\varepsilon_C = 8\%$ and $\varepsilon_E = 58\%$. As a consequence, an additional region emerges in the domain of the voluntary PrEP coverage when PrEP effectiveness is below 58%. In total, we identified four regions, delimited not only by the relative cost thresholds, but also by the PrEP effectiveness thresholds (see figure 3B of the main text):

- Region IV, where $0 \leq r \leq r_E(\varepsilon)$ and $\varepsilon_C \leq \varepsilon < \varepsilon_E$. The low relative cost makes all MSM willing to adopt PrEP (i.e., $\hat{p}(\varepsilon, r) = 100\%$), but its effectiveness is below the epidemic elimination threshold (i.e., we have $\varphi(\varepsilon)\hat{p}(\varepsilon, r) = \varphi(\varepsilon) < K$), so the epidemic is controlled but not eliminated.

- Region III, where either $0 \leq r \leq 1$ and $\varepsilon < \varepsilon_C$ or $r \geq r_C(\varepsilon)$ and $\varepsilon \geq \varepsilon_C$. If $r \geq 0$ and $\varepsilon < \varepsilon_C$, PrEP does not control the epidemic because the drop in condom use among PrEP users is not compensated by the uptake of PrEP, which has low effectiveness. If $r \geq r_C(\varepsilon)$ and $\varepsilon \geq \varepsilon_C$, the relative cost of prevention versus treatment is perceived as being too high. Therefore, no one adopts the strategy of using PrEP to prevent HIV infection (i.e., $\hat{p}(\varepsilon, r) = 0\%$) and the endemic state of the epidemic stays unaffected (i.e., $\hat{\Lambda}_h^{\text{ES}}(\varepsilon, r) = \Lambda_h^{\text{ES}}(0, 0)$).
- Region II, where $r_E(\varepsilon) < r < r_C(\varepsilon)$ and $\varepsilon \geq \varepsilon_C$. The relative cost is low enough, so a proportion of high-risk MSM adopts the strategy of using PrEP (i.e., $0\% < \hat{p}(\varepsilon, r) < 100\%$), and PrEP effectiveness is above the control threshold. However, not enough MSM adopt PrEP and thus, the effective, voluntary PrEP coverage, $\varphi(\varepsilon) \hat{p}(\varepsilon, r)$, is below the threshold K . Hence, the HIV epidemic is controlled (i.e., $\hat{\Lambda}_h^{\text{ES}}(\varepsilon, r) < \Lambda_h^{\text{ES}}(0, 0)$), but not eliminated.
- Region I, where $0 \leq r \leq r_E(\varepsilon)$ and $\varepsilon \geq \varepsilon_E$. The relative cost is low, and the PrEP effectiveness is above the elimination threshold, thus the effective, voluntary PrEP coverage, $\varphi(\varepsilon) \hat{p}(\varepsilon, r)$, may reach or exceed the threshold K , so the epidemic may be averted. Hence, in region I the reproduction number is below 1; i.e., $R(\hat{p}(\varepsilon, r), \varepsilon) \leq 1$.

It is interesting to note that, for high PrEP effectiveness (say $\varepsilon > 85\%$), figure 3B of the main text, displaying four regions for PrEP outcomes, is in fact very similar to figure S4, displaying three regions for PrEP outcomes. The reason why the HIV testing frequency is not determinant when PrEP regimes are highly effective rests with the fact that, in this case, very few individuals taking PrEP get infected with HIV and benefit from early diagnosis. Nevertheless, high frequency of HIV testing is needed to prevent the emergence of HIV strains resistant to the PrEP molecules, which is a phenomenon not included in our HIV model.

S4 Supplementary tables

Table S1: Initial values for several epidemiological indicators about the MSM population in the Paris region.

Epidemiological indicator	Value/range	[Ref.]
Total population	83 000–167 000	[17, 18]
HIV prevalence (%)	10–30	[16]
Fraction of susceptible individuals at high risk of infection (%)	5–50	–
Fraction of infected individuals with high risk behavior (%)	70–90	–
Fraction of infected individuals in chronic stage of infection (%)	80	–
Fraction of infected individuals on treatment (%)	80	–

Table S2: Definition, initial value and calibrated values for the model parameters

The fourth column presents initial ranges/values used for the parameters; these ranges/values were either based on published estimates or assumed. The third column presents the mean and 95% confidence interval (CI) for the parameters values obtained through the model calibration.

Param.	Description	Calibrated value Mean (CI 95%)	Initial value/range	[Ref.]
π_i	Inflow into the population at i risk of infection ^a	–	–	–
c_h	Per-year number of partners for high-risk individuals ^b	7.4 (6.2–9.0)	1–20	[25, 26]
c_l	Per-year number of partners for low-risk individuals	0.7 (0.6–0.9)	0–1	[25]
ρ_{hh}	Fraction of partnerships formed between individuals within the same risk group (%)	95 (92–97)	50–100	–
β_h^a	Per-partnership probability of HIV transmission from high-risk undiagnosed MSM, during the acute stage of infection (%)	71 (58–87)	0–100	–
β_l^a	Per-partnership probability of HIV transmission from low-risk undiagnosed MSM, during the acute stage of infection (%)	40 (16–64)	0–100	–
β_h^c	Per-partnership probability of HIV transmission from high-risk undiagnosed MSM, during the chronic stage of infection (%)	8 (7–9)	0–100	–
β_l^c	Per-partnership probability of HIV transmission from low-risk undiagnosed MSM, during the chronic stage of infection (%)	4 (2–7)	0–100	–
w	Ratio between acute and chronic stage infectivity	9.1 (8.4–9.6)	8–12	[6]
$1/\sigma$	Time spent in acute stage of infection (weeks ^c)	8.2 (6.7–9.8)	6–12	[27]
$1/\theta$	Time between infection and diagnosis (baseline scenario; years)	3.1 (2.7–3.5)	1–4	[15]
$1/\theta_P$	Time between infection and diagnosis for on-PrEP individuals (baseline scenario; months)	3	–	[28]
$1/\mu$	Time that individuals stay sexually mixing (years)	30.6 (27.2–33.7)	25–50	[25]
α	Reduction of the sexually-mixing period of time, once diagnosed with HIV	0.48 (0.41–0.54)	0–1	–
$1/\mu_T$	Time that individuals diagnosed with HIV stay sexually mixing ^d	14.7 (11.2–18.2)	–	–
ξ	Condom effectiveness (%)	–	58–80	[29]
η_h	Probability of using condoms for high-risk MSM not on PrEP (baseline scenario; %)	–	30	[22]
η_P	Probability of using condoms for high-risk MSM not on PrEP (baseline scenario; %)	–	20	[7]
L_E	Life expectancy (years)	–	79.5	[30, 31]
L_{SA}	Age at which individuals start sexual activity	–	15	[25]
L	Time spent in the sexually-mixing population for individuals on treatment	–	$1/\mu_T$	–
L_T	Number of life years remaining after leaving the sexually-mixing population	–	$L_E - L - L_{SA}$	–

^aComputed using the formula μN_i^{DFS} , where N_i^{DFS} is the number of i -risk MSM at the disease-free state (DFS).

^bSubject to condition (S4).

^cWe approximated 1 year by 52 weeks.

^dCan be estimated as α/μ .

Table S3: Calibration to the HIV epidemiology for MSM in the Paris region

The epidemiological indicators used for the model calibration are indicated by star (*). Other indicators are shown for additional information. The third column presents recently published estimates for the epidemiological indicators. The second column presents the mean and 95% confidence interval (CI) for these indicators, obtained through the model calibration.

Epidemiological indicator	Calibrated estimates Mean (CI 95%)	Published estimates Mean (CI 95%)	[Ref.]
HIV incidence rate* (%)	1.3 (1.0–1.6)	2.0 (1.0–2.6)	[15]
Per-year number of new HIV infections	1 200 (900–1 500)	1 100 (900–1 400)	[15]
HIV incidence rate among high-risk MSM* (%)	7 (4–10)	9.2	[7]
Prevalence of HIV* (%)	17 (14–20)	16 (12–20)	[16]
Proportion of undiagnosed HIV infections* (%)	17 (15–20)	18 (15–20)	[15]
Per-year number of new HIV diagnoses	1 100 (800–1 400)	1 000 (900–1 100)	[15]
Number of infected, undiagnosed MSM	3 200 (2 000–4 200)	3 400 (3 000–3 800)	[15]
Total population*	111 000 (94 000–130 000)	118 000 (83 000–167 000)	[17, 18]
Individuals eligible for PrEP ^a	14 200 (9 200–23 000)	–	–
High-risk MSM among susceptibles (%)	15 (11–23)	–	–

^aHigh-risk, susceptible MSM.

Table S4: Epidemiological indicators for the HIV transmission model at the endemic state

Subscript $i \in \{h, \ell\}$ stands for the risk group (high, low) and superscript $k \in \{a, c\}$ stands for the stage of infection (acute, chronic). Superscript ES stands for endemic state.

Epidemiological indicator	Definition	Formula
Endemic HIV incidence rate	Number of new infections among individuals at risk of HIV infection	$\sum_i \Lambda_i S_i^{\text{ES}} / \sum_i S_i^{\text{ES}}$
Endemic proportion of undiagnosed HIV infections	Fraction of infected individuals who are unaware of their infection	$\sum_{i,k} I_i^{k,\text{ES}} / (\sum_{i,k} I_i^{k,\text{ES}} + \sum_i T_i^{\text{ES}})$
Endemic prevalence of HIV	Fraction of the population who is infected with HIV	$(\sum_{i,k} I_i^{k,\text{ES}} + \sum_i T_i^{\text{ES}}) / N^{\text{ES}}$

S5 Supplementary figures

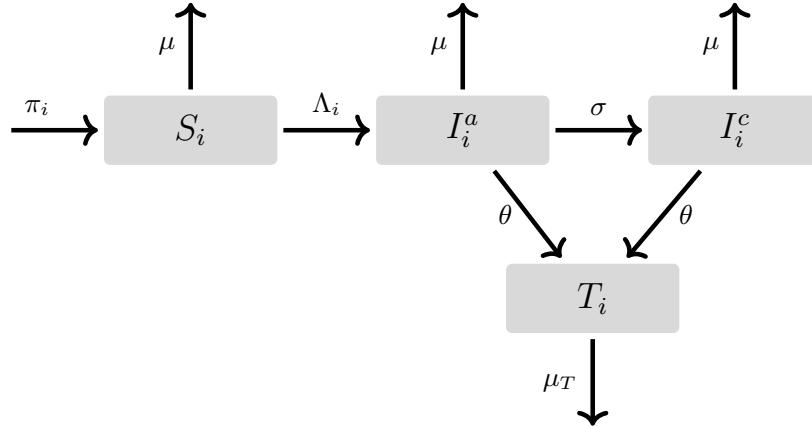


Figure S1: Flow diagram for the compartmental model of HIV transmission among MSM, when PrEP is not available as a prevention method

Sexually mixing MSM are stratified in two disjoint categories according to their risk group ($i \in \{h, \ell\}$, standing for high and low, respectively). Uninfected MSM join the i -risk-group population at a rate π_i and spend $1/\mu$ years selecting new sexual partners. Susceptible individuals, S_i , get infected with HIV at a rate Λ_i . Individuals I_i^k , where $k \in \{a, c\}$, with a standing for acute and c standing for chronic stage of infection, are infected and unaware of their infection. The progression from the acute stage of infection to the chronic stage of infection occurs at a rate σ . Infectious individuals are diagnosed at a rate θ at any stage of their infection and get immediately treated with antiretroviral therapy. Treated individuals, T_i , leave the sexually mixing population at a rate μ_T .

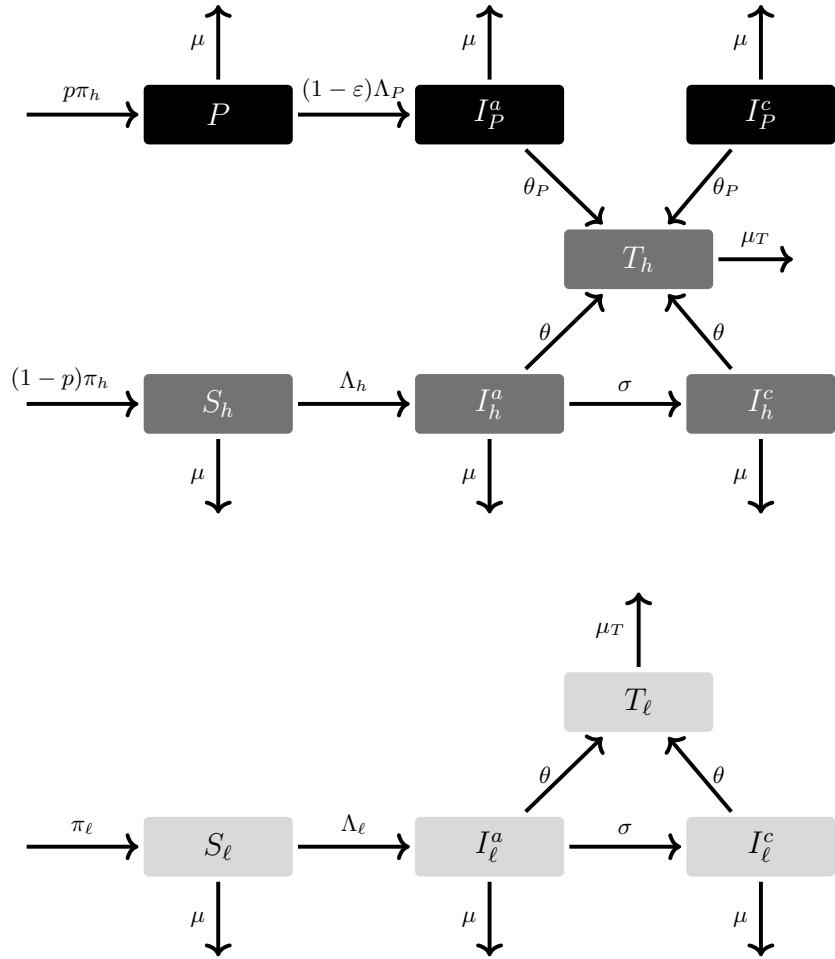


Figure S2: Flow diagram for the compartmental model of HIV transmission among MSM, when PrEP is available as a prevention method

Dark (respectively light) gray compartments depict individuals with high (respectively low) risk of HIV infection. Only uninfected individuals at high risk of infection are eligible to adopt PrEP (P). PrEP users are depicted by black compartments. PrEP coverage and PrEP effectiveness are denoted by p and ε , respectively. The HIV testing rate for on-PrEP MSM is denoted by θ_P . Individuals on PrEP get infected at a rate $(1 - \varepsilon)\Lambda_P$.

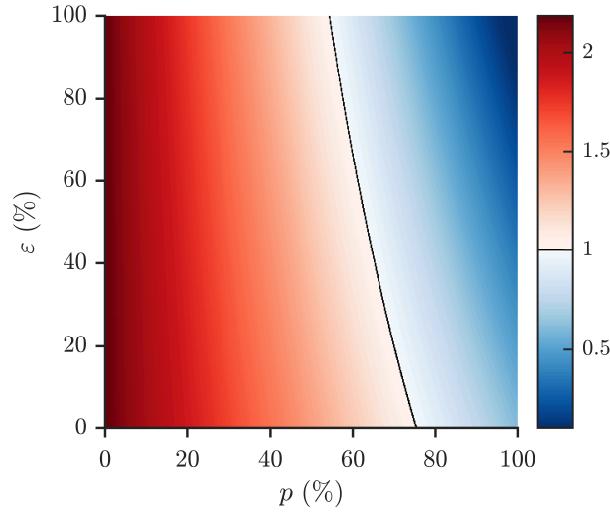


Figure S3: The effective reproduction number R as a function of the PrEP parameters

Color maps of the effective reproduction number, R , obtained for a typical parameter set calibrating our model, under the baseline scenario; i.e., high-risk MSM not on PrEP use condom with probability 30%, and if they get on PrEP, the probability drops at 20%; condom effectiveness is 70%. $R > 1$ (i.e., epidemic persistence) is shown in red shades and $R < 1$ (i.e., epidemic elimination) is shown in blue shades. The solid black line depicts $R = 1$. **A** The effective reproduction number R versus the PrEP coverage, p , and PrEP effectiveness, ε . **B** The effective reproduction number R versus the PrEP coverage, p , and the HIV testing rate while taking PrEP, θ_P , assuming that the PrEP effectiveness is zero (i.e., $\varepsilon = 0$). Note that HIV elimination is possible even when $\varepsilon = 0$. This intervention is equivalent to assuming that there is no PrEP, but a fraction p of the high-risk MSM get tested more frequently than the others, at a rate θ_P .

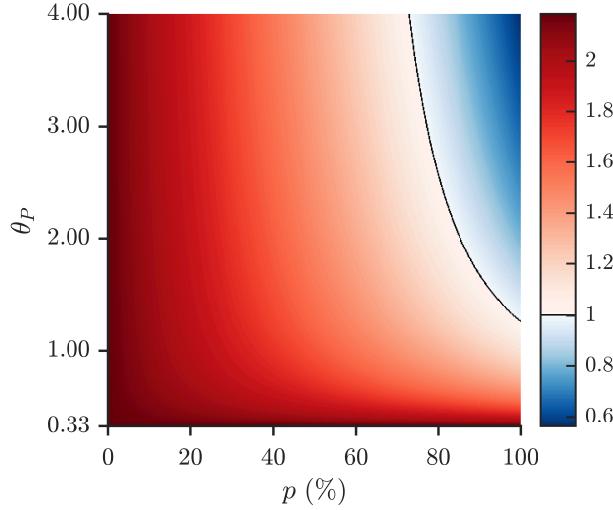


Figure S4: Impact of rollout with voluntary PrEP uptake, function of the relative cost of PrEP versus ART, when the PrEP effectiveness is 86%

We illustrate the PrEP coverage (%) reached voluntarily by high-risk MSM (left axis) and the endemic force of infection on high-risk MSM reached through voluntary PrEP use (right axis), assuming the PrEP effectiveness is $\varepsilon = 86\%$. We assumed that (i) high-risk MSM not on PrEP use condoms with 30% probability, and when they get on PrEP, the probability drops at 20%; (ii) condom effectiveness is 70%; and (iii) MSM have a fair perception of the risk of HIV infection; i.e., assumptions of the baseline scenario. The three regions correspond to the three regions identified in figure 1 of the main text. In Region III, no MSM adopts the strategy of using PrEP (i.e., $\hat{p}(\varepsilon, r) = 0$) due to high perceived cost of PrEP (i.e., $r \geq r_C(\varepsilon)$; r_C denotes the threshold cost for epidemic control). Hence, in Region III, there is no impact on the course of the epidemic: the endemic force of infection among high-risk MSM remains unchanged after the introduction of PrEP; i.e., $\hat{\Lambda}_h^{\text{ES}}(\varepsilon, r) = \Lambda_h^{\text{ES}}(0, 0) = 0.07$, where $\Lambda_h^{\text{ES}}(0, 0)$ is the endemic incidence rate for high-risk MSM in the absence of PrEP. In Region II, a proportion of the population decides to use PrEP (i.e., $0 < \hat{p}(\varepsilon, r) < 100\%$) at the given cost, but the PrEP coverage is not enough for epidemic elimination. Hence, the epidemic is controlled and there is a reduction in the endemic incidence. Region I, the striped area, corresponds to the case where $R(\hat{p}(\varepsilon, r), \varepsilon) \leq 1$. In Region I, the relative cost is low (i.e., $0 \leq r \leq r_E(\varepsilon)$), so high levels of PrEP coverage — and thus, high levels of effective PrEP coverage (i.e., $\hat{p}(\varepsilon, r) \varphi(\varepsilon) \geq K$) — are reached, and the epidemic may be averted; i.e., the endemic force of infection can be 0. In particular, for a PrEP effectiveness of $\varepsilon = 86\%$, the minimum PrEP coverage $\hat{p}(\varepsilon, r)$ to reach Region I is $K/\varphi(\varepsilon) = 56\%$.

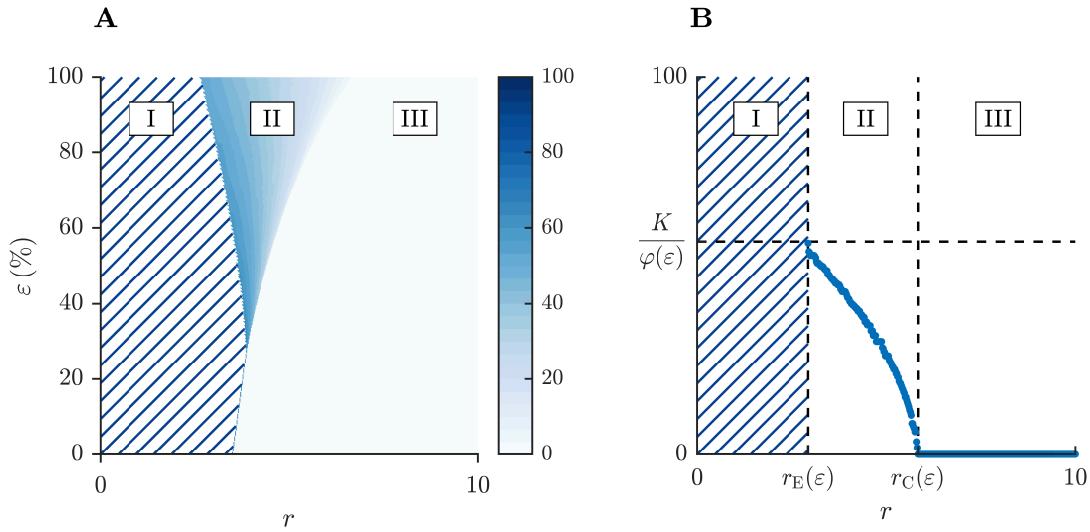


Figure S5: Impact of risk compensation on the voluntary PrEP coverage

The voluntary PrEP coverage obtained for a typical parameter set calibrating our model, (A) assuming a complete drop in condom use among PrEP users and (B) under the baseline scenario, where condom use drops from 30% to 20% among PrEP users.

S6 References

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3.3 Additional material

Section 3.3.1 presents the computations and proofs of the results shown in section 3.2.3. Namely, the explicit computations of some epidemiological indicators, using the ODE system (see sections a) to c)), the thresholds for the PrEP effectiveness and the perceived relative cost yielding epidemic control and elimination (see sections d), e) and h), and a description of the numerical approximation of the voluntary PrEP coverage (see g)).

Section 3.3.2 contains some additional figures that were not included in the paper submission, but may help visualizing the system behavior from other perspectives. For instance, we present the values of the reproduction number before PrEP introduction for the calibrated model and the number of HIV infections among on-PrEP MSM —despite PrEP adoption— for the baseline scenario (that is, assuming that individuals have a fair perception of HIV risk, a PrEP-induced condom drop from 30% to 20% and a 3-monthly HIV testing rate among on-PrEP MSM; see fig. 3.10). Additional results for the scenario where on-PrEP MSM do not follow the recommendations on frequently testing for HIV are presented as well.

3.3.1 Computations and proofs of our analytical results

a) The effectiveness of PrEP

PrEP effectiveness has been estimated at 86% (95% CI: 40%–98%) in two clinical trials conducted among MSM (Molina and Earn, 2015; McCormack et al., 2016) and at 85%–96% in simulation studies (Dimitrov et al., 2019), using the PrEP-induced relative reduction of the HIV incidence,

$$1 - \frac{\text{HIV incidence with PrEP}}{\text{HIV incidence without PrEP}}.$$

Here, we analyze a reduced version of our HIV transmission model (cf. eq.(S6) of section 3.2.3) adapted to describe the IPERGAY trial (Molina et al., 2018), in order to estimate the parameter representing the effectiveness of PrEP, ε .

We consider the population at high risk of infection, exclusively. We use Q to denote the individuals in the control group and P to denote the individuals using PrEP. We suppose the

control group and the study group are matched and use Λ to denote the force of infection. Then, the following ODE system models the HIV infections dynamics that occur during the study:

$$\frac{dQ}{dt} = -\Lambda Q, \quad (3.1)$$

$$\frac{dP}{dt} = -(1 - \varepsilon)\Lambda P. \quad (3.2)$$

We use τ to denote the duration of the study follow-up. Dividing eq. (3.1) by eq. (3.2), and integrating on the interval $[0, \tau]$, we obtain

$$\int_0^\tau \frac{dQ}{Q} = \int_0^\tau \frac{dP}{(1 - \varepsilon)P}. \quad (3.3)$$

We solve eq. (3.3) for the PrEP effectiveness, ε :

$$\varepsilon = 1 - \frac{\ln P(\tau) - \ln P(0)}{\ln Q(\tau) - \ln Q(0)}. \quad (3.4)$$

Using the number of participants and the number of seroconversions that took place during the ANRS IPERGAY study ([Molina and Earn, 2015](#)),

$$\begin{aligned} P(0) &= 199, & Q(0) &= 201, \\ P(\tau) &= 197, & Q(\tau) &= 187, \end{aligned} \quad (3.5)$$

we obtain $\varepsilon = 0.86$. Hence, we found the same value as the efficacy estimated in from the ANRS IPERGAY trial, thus corroborating our modeling choices in [section 3.2.3](#).

b) The disease-free equilibrium

The equations for the disease-free state (DFS) of the ODE system (S6) are given by

$$P^{\text{DFS}} = \frac{\pi_h p}{\mu}, \quad S_h^{\text{DFS}} = \frac{\pi_h(1 - p)}{\mu}, \quad S_\ell^{\text{DFS}} = \frac{\pi_\ell}{\mu}, \quad (3.6)$$

and

$$I_i^{k, \text{DFS}} = T_i^{\text{DFS}} = 0, \quad \text{for all } i \in \{h, \ell\}, k \in \{a, c\}. \quad (3.7)$$

The total population at i risk of infection at the DFS is thus given by $N_i^{\text{DFS}} = \pi_i/\mu$, for

$i \in \{h, \ell\}$. Then, the total population at the DFS is given by

$$N^{\text{DFS}} = N_h^{\text{DFS}} + N_\ell^{\text{DFS}} = \frac{\pi_h + \pi_\ell}{\mu}. \quad (3.8)$$

Equations [eq. \(3.6\)](#)–[eq. \(3.8\)](#) are used to compute the effective reproduction number, below.

c) Computing the effective reproduction number

To compute the effective reproduction number for the ODE system [\(S6\)](#), we follow the methods and notation developed by [van den Driessche and Watmough \(2002\)](#), where $R(p, \varepsilon)$ is defined as the largest eigenvalue of the *next generation matrix* ([van den Driessche and Watmough, 2008](#); [Diekmann et al., 1990](#)).

We start with the state vector of our ODE system,

$$X = \begin{pmatrix} I_P^a \\ I_h^a \\ I_\ell^a \\ I_P^c \\ I_h^c \\ I_\ell^c \\ T_h \\ T_\ell \\ P \\ S_h \\ S_\ell \end{pmatrix}, \quad (3.9)$$

where the first eight compartments correspond to infected individuals. Then, we identify the vectors \mathcal{F} and \mathcal{V} , which represent the new infections and the transfers in and out of the compartments, respectively. They satisfy $dX/dt = \mathcal{F} - \mathcal{V}$:

$$\mathcal{F} = \begin{pmatrix} (1 - \varepsilon)\Lambda_P P \\ \Lambda_h S_h \\ \Lambda_\ell S_\ell \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}, \quad \mathcal{V} = \begin{pmatrix} (\sigma_P + \theta_P + \mu) I_P^a \\ (\sigma + \theta + \mu) I_h^a \\ (\sigma + \theta + \mu) I_\ell^a \\ -\sigma_P I_P^a + (\theta_P + \mu) I_P^c \\ -\sigma I_h^a + (\theta + \mu) I_h^c \\ -\sigma I_\ell^a + (\theta + \mu) I_\ell^c \\ -\theta_P (I_P^a + I_P^c) - \theta (I_h^a + I_h^c) + \mu_T T_h \\ -\theta (I_\ell^a + I_\ell^c) + \mu_T T_\ell \\ -p\pi_h + [(1 - \varepsilon)\Lambda_P + \mu] P \\ -(1 - p)\pi_h + (\Lambda_h + \mu) S_h \\ -\pi_\ell + (\Lambda_\ell + \mu) S_\ell \end{pmatrix}. \quad (3.10)$$

We use the subscript n to denote the n -th entry of a vector and the subscript nm to denote the (n, m) entry of a matrix. The matrix V , with elements $V_{mn} = \partial \mathcal{V}_m / \partial X_n \Big|_{\text{DFS}}$, where $n, m = 1, \dots, 8$, is given by

$$V = \begin{pmatrix} \sigma + \theta_P + \mu & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \sigma + \theta + \mu & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \sigma + \theta + \mu & 0 & 0 & 0 & 0 & 0 \\ -\sigma & 0 & 0 & \theta_P + \mu & 0 & 0 & 0 & 0 \\ 0 & -\sigma & 0 & 0 & \theta + \mu & 0 & 0 & 0 \\ 0 & 0 & -\sigma & 0 & 0 & \theta + \mu & 0 & 0 \\ -\theta_P & -\theta & 0 & -\theta_P & -\theta & 0 & \mu_T & 0 \\ 0 & 0 & -\theta & 0 & 0 & -\theta & 0 & \mu_T \end{pmatrix}, \quad (3.11)$$

Similarly, the elements of the matrix F are defined as $F_{mn} = \partial \mathcal{F}_m / \partial X_n \Big|_{\text{DFS}}$. Therefore,

we calculate the values for $\partial\Lambda_i/\partial I_j^k$. Recalling the definition (S5), we have

$$\Lambda_h = \frac{\lambda_{hh}^a (I_P^a + I_h^a) + \lambda_{hh}^c (I_P^c + I_h^c)}{N_h} + \frac{\lambda_{\ell h}^a I_\ell^a + \lambda_{\ell h}^c I_\ell^c}{N_\ell}, \quad (3.12)$$

and

$$\Lambda_\ell = \frac{\lambda_{h\ell}^a (I_P^a + I_h^a) + \lambda_{h\ell}^c (I_P^c + I_h^c)}{N_h} + \frac{\lambda_{\ell\ell}^a I_\ell^a + \lambda_{\ell\ell}^c I_\ell^c}{N_\ell}, \quad (3.13)$$

where

$$\lambda_{ji}^k = c_i \rho_{ij} \beta_j^k,$$

for $i, j \in \{h, \ell\}$ and $k \in \{a, c\}$. Then,

$$\frac{\partial \Lambda_i}{\partial I_j^k} = \frac{\lambda_{ji}^k}{N_j} - \sum_m \left(\frac{\lambda_{hi}^m I_P^m + \lambda_{hi}^m I_h^m}{N_h^2} + \frac{\lambda_{\ell i}^m I_\ell^m}{N_\ell^2} \right), \quad (3.14)$$

where the sum is considered for all the values of $m \in \{a, c\}$. Evaluating eq. (3.14) at the DFS defined in eqs. eq. (3.7) and eq. (3.8), we get $\partial\Lambda_i/\partial I_j^k|_{\text{DFS}} = \lambda_{ji}^k \mu/\pi_j$. Therefore,

$$\frac{\partial}{\partial I_j^k} \left(\Lambda_h S_h + (1 - \varepsilon) \Lambda_P P \right) \Bigg|_{\text{DFS}} = (1 - \varphi(\varepsilon) p) \left(\frac{\lambda_{jh}^k \pi_h}{\pi_j} \right), \quad (3.15)$$

and

$$\frac{\partial}{\partial I_j^k} \Lambda_\ell S_\ell \Bigg|_{\text{DFS}} = \frac{\lambda_{j\ell}^k \pi_\ell}{\pi_j}. \quad (3.16)$$

The matrix F is thus given by

$$F = \begin{pmatrix} p(1 - \varepsilon)\phi\lambda_{hh}^a & p(1 - \varepsilon)\phi\lambda_{hh}^a & p(1 - \varepsilon)\phi\lambda_{\ell h}^a \pi_h/\pi_l & p(1 - \varepsilon)\phi\lambda_{hh}^c & p(1 - \varepsilon)\phi\lambda_{\ell h}^c & p(1 - \varepsilon)\phi\lambda_{\ell h}^c \pi_h/\pi_l & 0 & 0 \\ (1 - p)\lambda_{hh}^a & (1 - p)\lambda_{hh}^a & (1 - p)\lambda_{\ell h}^a \pi_h/\pi_l & (1 - p)\lambda_{hh}^c & (1 - p)\lambda_{\ell h}^c & (1 - p)\lambda_{\ell h}^c \pi_h/\pi_l & 0 & 0 \\ \lambda_{h\ell}^a \pi_l/\pi_h & \lambda_{h\ell}^a \pi_l/\pi_h & \lambda_{\ell\ell}^a & \lambda_{h\ell}^c \pi_l/\pi_h & \lambda_{h\ell}^c \pi_l/\pi_h & \lambda_{\ell\ell}^c & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \quad (3.17)$$

where

$$\phi \equiv \left(\frac{1 - \xi \eta_P}{1 - \xi \eta_h} \right).$$

d) The PrEP effectiveness threshold for epidemic control

Epidemic control induced by PrEP uptake is defined as a reduction of the effective reproduction number due to PrEP adoption, i.e., $R(p, \varepsilon) < R(0, \varepsilon)$; see section 3.2.3. Here, we study the monotony of the reproduction number $R(p, \varepsilon)$ with respect to the PrEP parameters, PrEP effectiveness, ε , and PrEP coverage, p , in order to find the conditions necessary and sufficient to have $R(p, \varepsilon) < R(0, \varepsilon)$.

Monotony with respect to PrEP effectiveness

Recall the definition of $R(\varepsilon, p)$; see section 3.2.3, eqs. (S14)–(S20). Since $A > 0$, the function $R(p, \varepsilon)$ verifies $\partial R(p, \varepsilon)/\partial \varepsilon \leq 0$ if and only if

$$\left(\frac{\partial}{\partial \varepsilon} H(p, \varepsilon) \right) \left(1 + \frac{(H(p, \varepsilon) - M) + 2BM}{\sqrt{(H(p, \varepsilon) - M)^2 + 4BH(p, \varepsilon)M}} \right) \leq 0. \quad (3.18)$$

Indeed, we have $\partial H(p, \varepsilon)/\partial \varepsilon \leq 0$; and, on the other hand, $A > 0$, $M > 0$ and $B \geq 1$, so

$$H(p, \varepsilon) + M(2B - 1) + \sqrt{(H(p, \varepsilon) - M)^2 + 4BH(p, \varepsilon)M} \geq 0. \quad (3.19)$$

Therefore, $\partial R(p, \varepsilon)/\partial \varepsilon \leq 0$. That is, the higher the level of PrEP effectiveness, the bigger the reduction of the effective reproduction number.

Monotony with respect to PrEP coverage

Similarly, $\partial R(p, \varepsilon)/\partial p \leq 0$ if and only if

$$\left(\frac{\partial}{\partial p} H(p, \varepsilon) \right) \left(1 + \frac{(H(p, \varepsilon) - M) + 2BM}{\sqrt{(H(p, \varepsilon) - M)^2 + 4BH(p, \varepsilon)M}} \right) \leq 0. \quad (3.20)$$

From eq. (3.19), we have $\partial R(p, \varepsilon) / \partial p \leq 0$ if and only if

$$\frac{\partial}{\partial p} H(p, \varepsilon) = -H_h + (1 - \varepsilon) \left(\frac{1 - \xi \eta_P}{1 - \xi \eta_h} \right) H_P \leq 0; \quad (3.21)$$

Hence, $\partial R(p, \varepsilon) / \partial p \leq 0$ if and only if $\varepsilon \geq \varepsilon_C$, where

$$\varepsilon_C \equiv 1 - \left(\frac{1 - \xi \eta_h}{1 - \xi \eta_P} \right) \left(\frac{H_h}{H_P} \right). \quad (3.22)$$

e) The PrEP effectiveness threshold for epidemic elimination

Epidemic elimination is defined by $R(p, \varepsilon) \leq 1$; see section S1.2.3. That is,

$$A \left[H(p, \varepsilon) + M + \sqrt{(H(p, \varepsilon) - M)^2 + 4BH(p, \varepsilon)M} \right] \leq 1. \quad (3.23)$$

Therefore, $R(p, \varepsilon) \leq 1$ can be rewritten as $p \varphi(\varepsilon) \leq K$, where

$$\varphi(\varepsilon) \equiv H_h - (1 - \varepsilon) \left(\frac{1 - \xi \eta_h}{1 - \xi \eta_P} \right) H_P, \quad (3.24)$$

is a function of PrEP and condom effectiveness, and

$$K \equiv H_h - \left(L - \frac{1}{2A} \right) \left(\frac{1}{1 - 2AL(B - 1)} \right) \quad (3.25)$$

is independent of the PrEP parameters.

In addition, assuming $p = 1$, $R(1, \varepsilon) \leq 1$ can be rewritten as $\varphi(\varepsilon) \leq K$, which is equivalent to $\varepsilon > \varepsilon_E$, where

$$\varepsilon_E \equiv 1 - \left(1 - \frac{K}{H_h} \right) (1 - \varepsilon_C). \quad (3.26)$$

In other words, ε_E is the minimum value of PrEP effectiveness for which epidemic elimination is possible, provided that PrEP coverage verifies $p \varphi(\varepsilon) \leq K$. We say that ε_E is the threshold for the PrEP effectiveness above which epidemic elimination is possible.

Note that eq. (3.22) can also be obtained from looking to conditions on ε for which $\varphi(\varepsilon) \geq 0$. Therefore, $\varphi(\varepsilon)$ can be interpreted as the combined effectiveness of PrEP and condoms; which can be straightforwardly identified in the scenario where individuals do not change testing behavior, i.e., where $\theta = \theta_P$; see fig. 3.11 below.

f) The rescaled perceived costs for the PrEP-adoption strategies

We expanded analytically the costs defined by integrals in [eqs. \(S26\)–\(S27\)](#) of [section 3.2.3](#)

$$C_{\text{No-PrEP}}(p; \varepsilon) = \begin{cases} L e^{-\Lambda_h^{\text{ES}}(p; \varepsilon)L} + L_T \left(1 - e^{-\Lambda_h^{\text{ES}}(p; \varepsilon)L} \right) - \frac{1 - e^{-\Lambda_h^{\text{ES}}(p; \varepsilon)L}}{\Lambda_h^{\text{ES}}(p; \varepsilon)}, & \text{if } R > 1 \\ 0, & \text{if } R \leq 1, \end{cases} \quad (3.27)$$

and

$$C_{\text{PrEP}}(p; \varepsilon, r) = \begin{cases} r \left(\frac{1 - e^{-(1-\varepsilon)\Lambda_P^{\text{ES}}(p; \varepsilon)L}}{(1-\varepsilon)\Lambda_P^{\text{ES}}(p; \varepsilon)} \right) + L e^{-((1-\varepsilon)\Lambda_P^{\text{ES}}(p; \varepsilon)+\theta)L} \\ \quad + L_T \left(1 - e^{-(1-\varepsilon)\Lambda_P^{\text{ES}}(p; \varepsilon)L} \right) - \frac{1 - e^{-(1-\varepsilon)\Lambda_P^{\text{ES}}(p; \varepsilon)L}}{(1-\varepsilon)\Lambda_P^{\text{ES}}(p; \varepsilon)}, & \text{if } R > 1 \\ rL, & \text{if } R \leq 1. \end{cases} \quad (3.28)$$

These equations were used to compute the expected utility directly and efficiently, rather than their integral form; cf. [algorithm 3.1](#).

g) Numerical approximation of the voluntary PrEP coverage

The voluntary PrEP coverage was obtained numerically, as detailed in [algorithm 3.1](#) below.

Algorithm 3.1 Numerical approximation of the voluntary PrEP coverage

Require: Set of parameters for HIV transmission, small $\delta < 0$.

Ensure: The voluntary PrEP coverage, $\hat{p}(\varepsilon, r)$

```

1: procedure ENDEMIC FORCE OF INFECTION,  $\Lambda_i^{\text{ES}}(p, \varepsilon)$  for  $i \in \{h, P\}$      $\triangleright$  We used parallel
   computation.

2:   for  $0 \leq p \leq 1$  do
3:     for  $0 \leq \varepsilon \leq 1$  do
4:       Compute  $R(p, \varepsilon)$ ; cf. eqs. (S14)–(S20)
5:       if  $R(p, \varepsilon) > 1$  then
6:         Set  $T$ 
7:         while  $\log(|(N(t) - N(t-1)) / N(t-1)|) > \delta$  do
8:           Increase  $T$ 
9:           Solve ODE system (S6) until  $t = T$ 
10:          end while
11:          Endemic state (ES)  $\leftarrow$  ODE system at  $t = T$ 
12:          Compute  $\Lambda_h^{\text{ES}}(p, \varepsilon)$ ; see eq. (S9)
13:        else
14:           $\Lambda_h^{\text{ES}}(p, \varepsilon) = 0$ 
15:        end if
16:      end for
17:    end for
18:    Compute  $\Lambda_P^{\text{ES}}(p, \varepsilon)$ ; see eq. (S13)
19: end procedure

20: procedure UTILITY MAXIMIZATION,  $\max_p U(p; \varepsilon, r)$ 
21:   Compute  $U(p; \varepsilon, r)$ ; cf. eq. (S25) and eqs. (3.27)–(3.28)
22:   for  $0 \leq r \leq 1$  do
23:     for  $0 \leq \varepsilon \leq 1$  do
24:        $\hat{p} \leftarrow$  The value of  $p$  for which  $U(p, \varepsilon, r)$  attains its maximum
25:     end for
26:   end for
27: end procedure
28: Return  $\hat{p}(\varepsilon, r)$ 

```

h) Identifying the thresholds in relative cost for epidemic control and elimination

The relative cost thresholds for epidemic control and elimination, $r_C(\varepsilon)$ and $r_E(\varepsilon)$ (cf. section 3.2.3), were numerically extracted from $\hat{p}(\varepsilon, r)$, by identifying the boundaries between the regions I, II and III; see fig. 3.9. On one hand, $r_C(\varepsilon)$ is the boundary between region III and region II: we defined $r_C(\varepsilon)$ as the lowest value of r for which $\hat{p}(\varepsilon, r) = 0$, for any given PrEP effectiveness level ε . On the other hand, $r_E(\varepsilon)$ is the boundary between region II and region I. Therefore, we identified $r_E(\varepsilon)$ as the highest value of r for which the difference between $\hat{p}(\varepsilon, r)$ and the theoretical threshold for PrEP coverage to yield epidemic elimination, $K/\varphi(\varepsilon)$, was lower than the tolerance set in our algorithm. See algorithm 3.2 below for the numerical implementation and fig. 3.9 for an illustration of $r_C(\varepsilon)$ and $r_E(\varepsilon)$ for the baseline scenario.

Algorithm 3.2 Identifying the relative cost thresholds for epidemic control and epidemic elimination

Require: $\hat{p}(\varepsilon, r)$ and Δp , the discretization step of the interval $[0, 1]$ of p .

Ensure: r_C and r_E

```

1: for  $0 \leq \varepsilon \leq 1$  do
2:    $r_C(\varepsilon) \leftarrow$  The lowest value of  $r$  for which  $\hat{p}(\varepsilon, r) = 0$ 
3:   if  $\varepsilon < \varepsilon_E$  then
4:      $r_E(\varepsilon) \leftarrow$  The highest value of  $r$  for which  $\hat{p}(\varepsilon, r) = 1$ 
5:   else
6:      $r_E(\varepsilon) \leftarrow$  The highest value of  $r$  for which  $|\hat{p}(\varepsilon, r) - K/\varphi(\varepsilon)| \leq \Delta p$ 
7:   end if
8: end for

9: Return  $r_C(\varepsilon)$  and  $r_E(\varepsilon)$ 

```

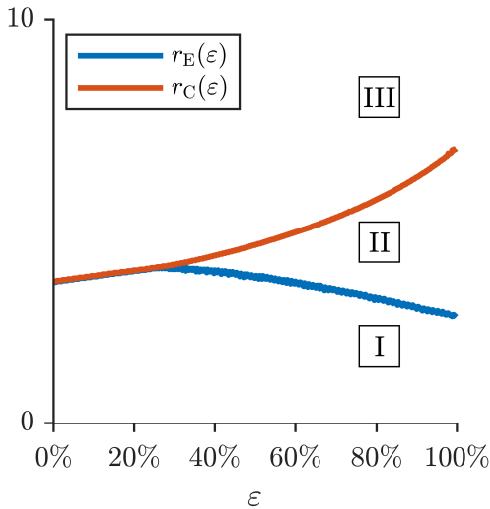


Figure 3.9 – The relative cost thresholds for epidemic control and elimination

The thresholds in relative cost for epidemic control and elimination as functions of PrEP effectiveness ($r_C(\varepsilon)$ and $r_E(\varepsilon)$, respectively) assuming fair perception of the risk of HIV infection, for a typical parameter set calibrating our model; see table S4 of [section 3.2.3](#). $r_C(\varepsilon)$ is the boundary between region III and region II, while $r_E(\varepsilon)$ is the boundary between region II and region I.

3.3.2 Additional results

The effective reproduction number in the absence of PrEP

We computed the effective reproduction number in the absence of PrEP, i.e., $R(0,0)$, for the ~ 500 simulations calibrating our model. A mean value of 2.2 (95% CI: 1.7–2.6) resulted from our model calibration, which is broadly in agreement with the traditionally used results of [Anderson and May \(1991\)](#), where R_0 has been estimated at 2–5 among MSM.

The number of new HIV infections despite PrEP uptake

In the baseline scenario, we assumed that on-PrEP MSM incur in risk compensation, decreasing their condom use from 30% to 20%. The impact of risk compensation can be clearly seen in [fig. 3.10](#), which shows the number of new infections among on-PrEP MSM at the endemic

state (ES), given by $(1 - \varepsilon)\Lambda_P^{\text{ES}} P^{\text{ES}} = (1 - \varepsilon)(1 - \xi\eta_P)\Lambda_h^{\text{ES}} P^{\text{ES}} / (1 - \xi\eta_h)$, where Λ_P^{ES} and P^{ES} are functions of p and ε ; cf. eq. (S13).

Given a fixed value for the PrEP effectiveness, the number of new infections among on-PrEP MSM behaves as follows. For low levels of PrEP coverage, the increase in the risk of infection induced by risk-compensation outweighs the protection offered by PrEP adoption and thus, the number of infections increases with the number of MSM using PrEP. Then, the trend reverses, and PrEP offers protection despite risk compensation. The number of new infections reduces with PrEP coverage, reaching zero when herd immunity threshold is reached.

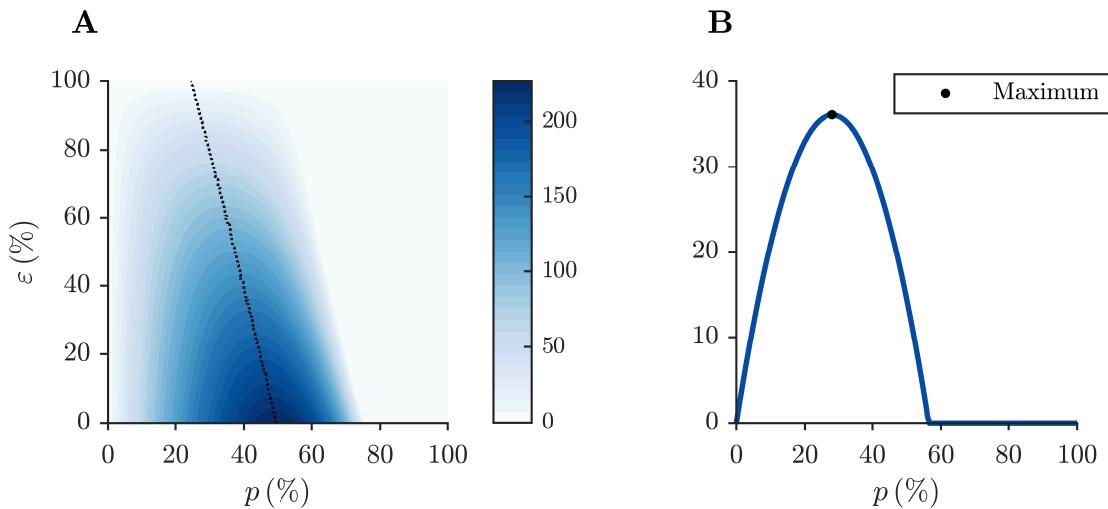


Figure 3.10 – Number of new HIV infections despite PrEP uptake

The number of new infections among on-PrEP MSM for the baseline scenario, at the endemic state, (A) as a function of PrEP coverage (p) and PrEP effectiveness (ε), and (B) for $\varepsilon = 86\%$. For low levels of PrEP coverage, the PrEP-induced risk compensation (i.e., drop on condom use from 30% to 20% among PrEP users) outweighs the protection offered by PrEP, and the number of new HIV infections among on-PrEP MSM increases with PrEP coverage. The critical values are depicted by black bullets.

The scenario where on-PrEP MSM do not change their HIV testing behavior

Current guidelines for PrEP prescription require testing for HIV every 3 months (Molina et al., 2018). However, frequent HIV screening may be perceived as a barrier for some individuals (Calabrese et al., 2016) and thus, frequent HIV testing may not be guaranteed in the long run.

We ran our algorithm considering a scenario where MSM do not follow these recommendations, and keep testing for HIV at the same rate than before adopting PrEP (i.e., every $\theta_P = \theta = 3.1$ years). The resulting voluntary coverage for PrEP is shown in [section 3.2.3](#). Here, we show additional figures, similar to those included in [section 3.2.3](#), such as the function $\varphi(\varepsilon)$, the number of infections among on-PrEP MSM ([fig. 3.12](#)), the PrEP-induced reduction in HIV incidence (depicted in [fig. 3.13A](#)), the relative costs thresholds (computed using [algorithm 3.2](#); see [fig. 3.13B](#)) and the voluntary PrEP coverage resulting from misperception of HIV risk ([fig. 3.15](#)), for the scenario where individuals do not change their HIV testing behavior.

We also used ~ 500 sets of parameters calibrating our model, in order to compute the probability of epidemic elimination (see [fig. 3.14A](#)) and to obtain confidence intervals for the PrEP effectiveness thresholds for epidemic control, ε_C , and elimination, ε_E (see [fig. 3.14B](#)). [fig. 3.14C](#) depicts the relative cost thresholds for epidemic control and elimination, computed numerically for the ~ 500 parameters sets. Similarly to [section 3.3.1](#), $r_E(\varepsilon)$ is the boundary between region II and regions I–IV together. Therefore, for $\varepsilon < \varepsilon_E$, we identified $r_E(\varepsilon)$ as the highest value of r for which $\hat{p}(\varepsilon, r) = 1$; cf. [fig. 3.13](#) and [fig. 3.14C](#).

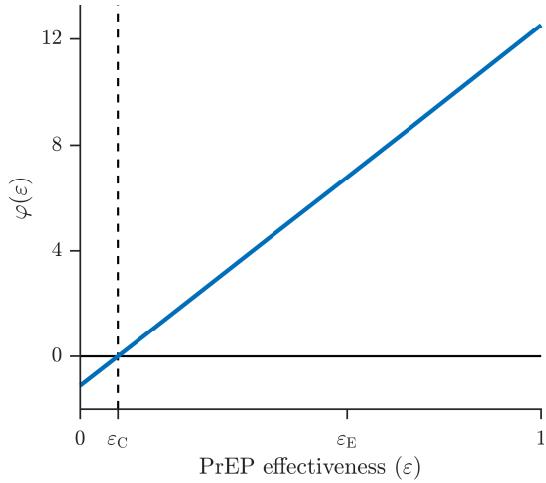


Figure 3.11 – The combined effectiveness of PrEP and condom use

The combined effectiveness of PrEP and condom use among on-PrEP high-risk MSM, relative to the effectiveness of condom use alone among off-PrEP high-risk MSM, $\varphi(\varepsilon)$, when MSM do not change their testing behavior (i.e., $\theta_P = \theta = 3.1$ years), for a condom effectiveness of 70% and a PrEP-induced drop in condom use from 30% to 20%; see [section 3.2.3](#), eq. (S4). As stated in [section 3.3.1](#), epidemic control induced by PrEP and condom use is possible if and only if $\varphi(\varepsilon) > 0$; that is, if $\varepsilon \geq \varepsilon_C$.

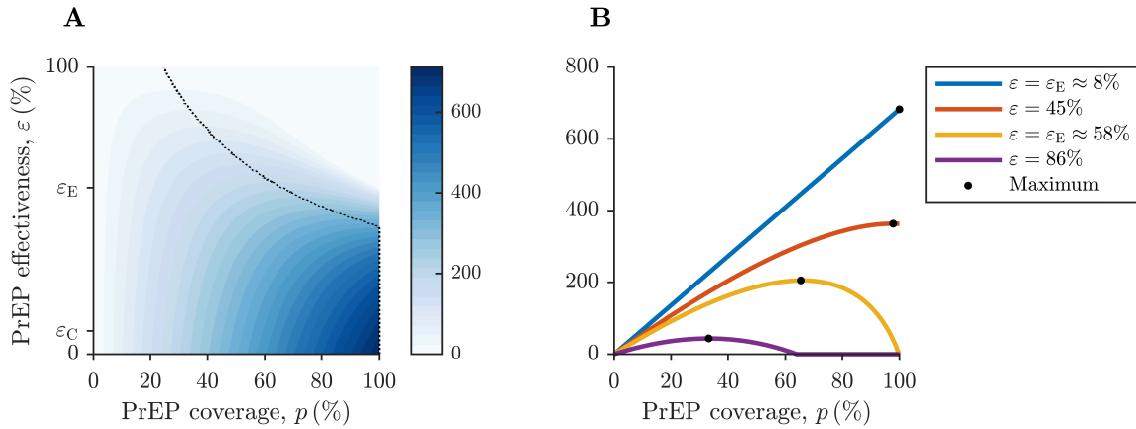


Figure 3.12 – HIV infections despite PrEP uptake

Number of infections among on-PrEP MSM (A) as a function of PrEP coverage (p) and PrEP effectiveness, and (B) for several fixed values of ε . For a given value of ε , the maximum is depicted by a black circle. For low values of PrEP effectiveness, the number of infections among on-PrEP MSM is strictly increasing with PrEP coverage. For high levels of PrEP effectiveness, the behavior of the infections among on-PrEP MSM is similar to that in fig. 3.10: a threshold for PrEP coverage may be identified, from which the number of new infections among on-PrEP MSM decreases with PrEP coverage.

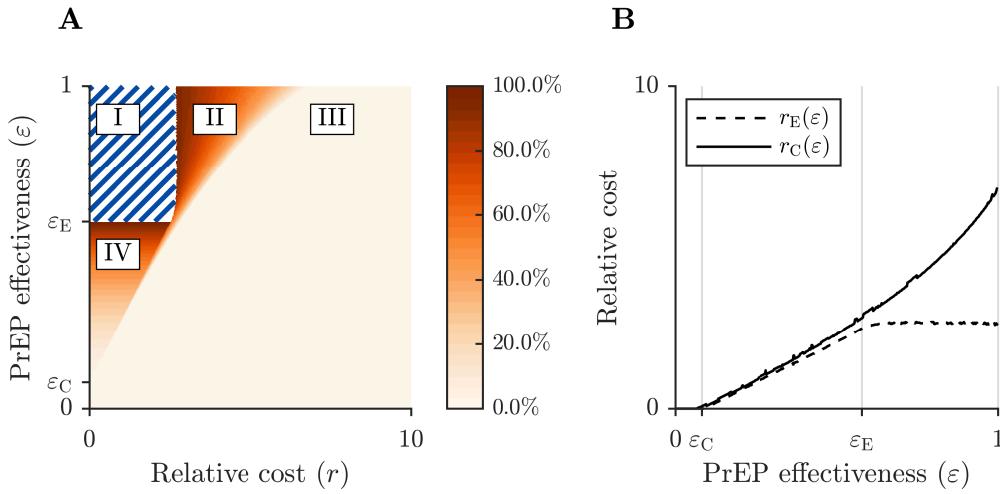


Figure 3.13 – The PrEP-induced relative reduction in HIV incidence and the relative cost thresholds for epidemic control and elimination

(A) Color map of the PrEP-induced reduction in the overall endemic HIV incidence rate, as a function of ε and r . PrEP effectiveness thresholds required to reach epidemic control and epidemic elimination are given by $\varepsilon_C = 8\%$ and $\varepsilon_E = 58\%$, respectively. Four regions can be identified: region IV, where all individuals adopt PrEP ($\hat{p} = 100\%$; cf. fig. 3 of [section 3.2.3](#)) and $\varepsilon_C \leq \varepsilon < \varepsilon_E$, so the epidemic is controlled; region III, where no MSM uses PrEP ($\hat{p} = 0\%$) and thus, there is no reduction in HIV incidence; region II, where some, but not enough MSM use PrEP ($0\% < \hat{p} < 100\%$) because r remains high and thus the epidemic is controlled; and region I (marked by blue stripes), where epidemic elimination is possible. **(B)** The relative costs thresholds for epidemic control and elimination as functions of PrEP effectiveness (denoted $r_C(\varepsilon)$ and $r_E(\varepsilon)$, respectively); cf. fig. 3 in [section 3.2.3](#). $r_C(\varepsilon)$ is the boundary between regions II and region III, while $r_E(\varepsilon)$ is the boundary between region II and regions I–IV together. We identified these thresholds numerically, from the voluntary PrEP coverage, using [algorithm 3.2](#). Both figures were obtained for a typical parameter set calibrating our model (cf. table S4 of [section 3.2.3](#)), assuming that individuals have a fair perception of HIV risk and do not change their testing behaviors once adopting PrEP (i.e., $\theta_P = \theta = 3.1$ years).

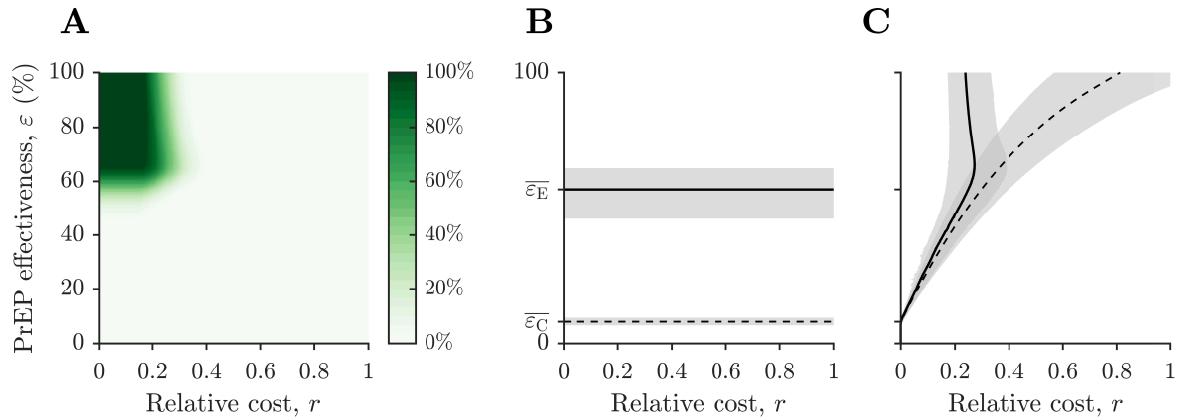


Figure 3.14 – The probability of HIV elimination and boundary uncertainty for the four-regions structure

(A) The probability of HIV epidemic elimination due to voluntary PrEP coverage, obtained from the ~ 500 calibrated parameter sets. (B) The mean values for the epidemic control and epidemic elimination thresholds are given by $\varepsilon_C = 8\%$ (95% CI: 7%–9%) and $\varepsilon_E = 57\%$ (95% CI: 46%–65%), respectively. (C) The boundaries (mean and 95% CI) between region II and regions I and IV (continuous line) and between region II and region III (dashed line).

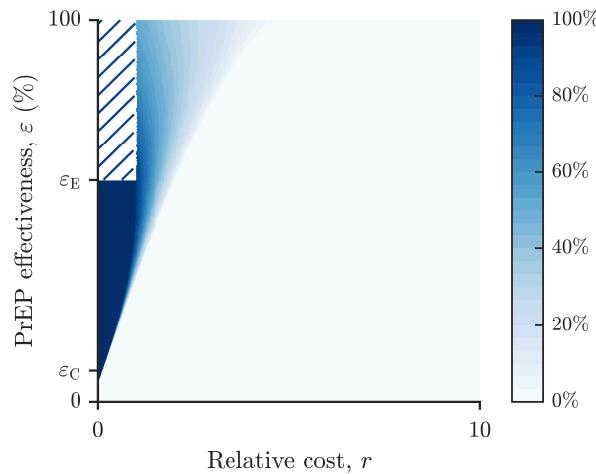


Figure 3.15 – The voluntary PrEP coverage assuming misperception of the HIV infection risk

Decision-making based on a misperceived risk of acquiring HIV significantly reduces the size of region I, where epidemic elimination is possible (blue stripes). The figure was obtained using the same calibrated parameter set as in fig. 3.13. The PrEP effectiveness thresholds for epidemic control and epidemic elimination are, respectively, $\varepsilon_C = 8\%$ and $\varepsilon_E = 58\%$.

3.4 Further discussion

3.4.1 Implementing HIV prevention programs aiming at epidemic elimination

Targeted versus universal PrEP

Our approach considers the current recommendations, where PrEP is targeted to populations most at risk of HIV infection ([WHO, 2016b](#)). Therefore, in our model, only individuals at high risk of infection may make a decision about PrEP adoption. However, it has been recently discussed that including PrEP into routine prevention healthcare and thus, allowing all sexually active adults to decide whether or not adopt PrEP, may improve PrEP adoption by reducing PrEP-related stigma and access inequalities ([Calabrese et al., 2017](#)).

From the modeling perspective, we found that targeting high-risk MSM allowed to control and eventually eliminate the epidemic at the population level. However, comparing the results between targeted and universal PrEP interventions remains to be studied. In our model, the HIV epidemic is driven by high risk MSM (we hypothesized that there is no epidemic at the population level if HIV transmission is interrupted among high-risk MSM) and thus, PrEP-induced epidemic elimination relies heavily on the MSM population at high risk of infection. It might be interesting to study universal PrEP access to evaluate the contribution of low-risk MSM to epidemic elimination.

Decreasing the perceived cost of PrEP in the French context

Under our modeling assumptions, high-risk MSM adopting PrEP would be required to maintain high adherence to PrEP for 30 years in average; cf. [Table S2](#). According to our results, increasing PrEP coverage among high-risk MSM in France is essential to eliminate HIV transmission among MSM. Even though PrEP is fully reimbursed by the social security system, not enough MSM have adopted PrEP, which reflects that French MSM value non-monetary aspects when deciding about HIV prevention.

Some difficulties regarding PrEP adoption still need to be addressed. For instance, med-

ical visits are covered only ~70% by the social security system. In addition, the first PrEP prescription and the yearly renewal must still be done by HIV-specialized doctors working in hospitals or HIV-specialized health centers ([Haute Autorité de Santé; EPI-PHARE, 2020](#)). This may perpetuate social stigma and discourage some individuals. Training general practitioners and allowing them to prescribe PrEP may facilitate and, thus, broaden PrEP access.

In addition, the healthcare providers' attitudes towards PrEP should be considered. PrEP is currently a medication requiring medical prescription. Hence, an increase in PrEP adoption requires an increase in PrEP prescription. Unfortunately, some healthcare providers may be reluctant to agree with PrEP use, due to concerns about risk compensation and potential increase in STI transmission ([Caumes, 2018](#)). As of the end of 2017, STI diagnoses among MSM have significantly increased at the national level ([Santé Publique France, 2018](#)), which could be due to low condom use among the MSM population (and not only among PrEP users). Promoting condom use among MSM may help not only preventing STIs, but also increasing PrEP acceptability.

3.4.2 Modeling limitations and perspectives

Assuming perfect PrEP adherence

We assume that, in the long term, high-risk MSM on PrEP practice high-quality adherence. That is, we assume that PrEP users, take PrEP pills correctly, continuously and for life. This assumption may not represent current reality in the Paris region, where only about 85% of PrEP users got a prescription renewal the following year, since PrEP rollout ([EPI-PHARE, 2019, 2020](#)). Modeling recurrent decision-making or the drop of PrEP while being sexually active may thus be interesting to study.

Still, our results may be useful for future presentations of prevention against HIV, which may perceived as less costly by individuals, such as long-lasting injectable PrEP ([Marshall et al., 2018](#)) and vaccination against HIV ([Burton, 2019](#)).

Obtaining data on sexual behavior

Including heterogeneity in sexual behavior in modeling studies allows to account for essential behavioral data (for instance, the number of sexual contacts and the proportion of condomless interactions), to which the epidemiology might be very sensitive. However, data on sexual behavior may depend heavily on self-reporting⁷, resulting in high variation of results among some papers (Hess et al., 2017). For instance, there may be some difficulties in obtaining data about the size of the MSM population and the individuals' sexual practices (which gives the population stratification by risk of infection) (Marcus et al., 2013; Baral et al., 2018). Also, data on the number of sexual partners (Hess et al., 2017) and most risky contacts might be hard to trace (van Aar et al., 2015).

Data about stable and occasional relationships (Velter et al., 2015) could also be included in the model in order to account for different probabilities of transmission, as well as different probabilities of condom use during the corresponding sexual encounters. This would allow to define the high-risk group not only in terms of the number of sexual contacts but also in terms of the nature of the sexual encounters.

These difficulties point to the importance of better data collection, but also to the importance of fighting stigma around sexual behaviors and preventive methods, so self-declaration becomes more common and reliable. Online tools may help obtaining more and accurate data on sexual behavior (Velter et al., 2015; Baral et al., 2018), but population samples may be more biased than those of traditional surveys.

Targeting other subpopulations

Considering risk compensation among non-PrEP users (Phanuphak and Phanuphak, 2018) and explicitly modeling condom use among individuals at low risk of infection might strengthen HIV and other sexually transmitted diseases prevention programs. In addition, considering an age-structured model might help better targeting of high-risk subpopulations, such as young MSM (Siguier and Molina, 2018; WHO, 2016b).

⁷It was indeed the case of the data on sexual behavior that we used in our study, collected through the Presse Gays et Lesbiennes survey (Velter et al., 2015)

Considering heterogeneity in the risk and cost perception

In our model, we assumed a homogeneous perception of both the risk of infection and the relative cost of PrEP versus ART, among high-risk MSM. However, in reality, individuals who are eligible for PrEP may perceive their risk of infection and/or the cost of PrEP very differently ([Blumenthal et al., 2019](#)). It would be useful to study how the results of our current project change considering heterogeneity in the decision-making and the implications for PrEP rollouts.

Chapter 4

General discussion

4.1 Summary

4.1.1 Reaching epidemic elimination through the voluntary adoption of prevention

We modeled the individual response to an epidemic threat through the resolution of a prevention-versus-treatment dilemma, and studied its impact on epidemic spreading. The individual willingness (respectively, refusal) to adopt preventive methods relies on the perception that the strategy of preventing the infection is more (respectively, less) beneficial than facing the risk of being infected, which could lead to acquiring the disease, and consequently being treated. To model the individual-level risk assessment, we assumed that individuals acknowledge, directly or indirectly, some epidemiological data (e.g., the disease prevalence ([Jijón et al., 2017](#)) and the incidence rate ([Jijón et al., 2021](#))) provided by, for instance, public health authorities, through communication campaigns.

We used our approach to address two public health issues. First, we studied voluntary vaccination against treatable childhood infectious diseases in a context where efficient, yet imperfect vaccines are available (cf. [chapter 2](#) and ([Jijón et al., 2017](#))). The results of the vaccination model were obtained analytically, and provided important insights into the system properties, thus constituting a theoretical guide for the programming choices and the interpretation of the

results of the second project that involved numerical implementation. Second, we studied the voluntary use of PrEP to avoid HIV infection, among the population of MSM (cf. [chapter 3](#) and ([Jijón et al., 2021](#))). We accounted for population heterogeneity regarding the risk of infection (namely, due to heterogeneity in sexual behaviors). We considered that the high-risk population drives the epidemic, and thus becomes the target population of PrEP implementation policies (unlike childhood vaccination, which is recommended for the vast majority of newborns and young children).

Our model's main outcome is the prevention coverage reached voluntarily by individuals, expressed as a function of the dynamical system's parameters. In particular, we obtained the voluntary prevention coverage as a function of prevention effectiveness and the relative cost of prevention versus treatment perceived by individuals. From a general point of view, our results suggest that epidemic elimination through the voluntary adoption of prevention is possible, even for imperfect preventive methods, provided that they are highly effective and that individuals perceive the cost of prevention relative to that of treatment being low.

However, epidemic elimination may be only temporary. We found that the game-theoretic assumption of an equilibrium resolution of the prevention versus treatment dilemma is not ensured. In other words, there is no long-term individual motivation to adopt prevention once the epidemic is eliminated. Indeed, an important decrease in the number of infections may induce individuals to witness less disease burden (such as disease morbidity, difficulties regarding treatment adoption, disease mortality, etc.) and thus, to perceive less benefits from prevention. Therefore, epidemic elimination may induce a higher cost of prevention perceived by individuals, provoking the system dynamics to return to its endemic status.

Another key outcome of our model is the effective reproduction number, which we obtained analytically (and not only numerically). This allowed us to study it as a function of the system parameters and thus find the conditions to be met in order to ensure epidemic control (i.e., a decrease in the reproduction number) and/or elimination (i.e., reproduction number below 1).

In the case of vaccination against childhood infectious diseases, we found that epidemic elimination required the vaccine-induced immunity to be long-lasting, in addition to high vaccine effectiveness. In the case of PrEP uptake against HIV infection, we found that the HIV epidemic may be eliminated by targeting the prevention interventions to those who identify themselves most at risk of infection. We study epidemic elimination as a function of the level

of risk compensation incurred by on-PrEP high-risk MSM. In addition, we considered an alternative scenario where individuals misperceive their risk of infection, by acknowledging only the proportion of diagnosed individuals among their peers as being infected with HIV.

In both projects, we found that risk perception plays a major role in achieving epidemic elimination: the higher the risk perceived, the wider the area in the parameters space where epidemic elimination can be reached. That is, if the perceived risk decreases, the cost that individuals are willing to pay to adopt prevention decreases as well, regardless of the level of prevention effectiveness. In other words, if individuals do not perceive themselves as being at high enough risk of infection, they are less willing to adopt preventive methods.

4.1.2 Establishing public health policies aiming at the end of communicable diseases

Our results give insights into the issue of voluntary prevention and epidemic behavior in the long run. This allows to place our research within the discussion about sustainability of health behaviors and may thus be helpful for public health policies aiming at epidemic elimination ([WHO, 2020](#)).

Reaching and maintaining epidemic elimination in the long run requires active efforts to keep the cost of prevention perceived as low, as well as ensuring that individuals have access to accurate, updated epidemiological data allowing them to evaluate their risk of infection. Indeed, global immunization programs aiming to end vaccine-preventable infectious diseases have already pointed to the need of sustaining “trust in vaccines and immunization services in communities, to increase health literacy with a focus on vaccination at all levels, and to build resilience against misinformation” ([WHO, 2019](#)); while PrEP programs have identified the need to fight uptake-related difficulties perceived by individuals ([Desai et al., 2018; Sidebottom et al., 2018](#)), misinformation regarding PrEP effectiveness ([Young et al., 2014; Underhill et al., 2016](#)) and social stigma and discrimination ([Young et al., 2014; Pérez-Figueroa et al., 2015; Arnold and Steward, 2016](#)), to increase PrEP adoption and adherence.

Roughly speaking, our results suggest that two main strategies could be established by public health policies aiming at disease elimination. During an ongoing epidemic, increasing prevention coverage by decreasing the barriers regarding acceptability and accessibility, as well

as offering information about the risk of infection and the disease and treatment burden; In the case of epidemic elimination, maintaining high levels of prevention coverage by ensuring accessibility, but also by sharing information about the achievements of preventive programs and the epidemic severity previous to their implementation.

In addition, our results may add new perspectives in the discussion about voluntary versus mandatory prevention, by supporting individual informed decision-making, which may actually accompany public efforts towards epidemic elimination, under the proper circumstances.

4.2 Limitations and perspectives

4.2.1 The complexity of modeling human behavior

Simple models are useful to understand epidemic dynamics by interpreting their results, while keeping some flexibility for application to other contexts. However, they may leave aside essential factors reflecting the complexity of human behavior. Notably, we use a system of ordinary differential equations to model disease transmission, which fails to take into account individual heterogeneity. We try to overcome this limitation in the application concerning PrEP and HIV by accounting for two subpopulations, represented by additional compartments. However, we assign fixed parameters for each subpopulation to transit from one compartment to another; that is, all individual behaviors are summarized into an average behavior that is assumed to be the same for all individuals within a given compartment. In addition, we model decision-making as a maximization of utility, which was mainly based in individuals' perception of the relative cost and the risk of infection. However, individuals may perceive these factors differently and the utility function may also thus be defined to explicitly account for heterogeneity in risk and cost perception.

In that regard, network-based epidemic models may offer the possibility of modeling population heterogeneity, by defining individuals' profile (demographics, health status, prevention adoption, adherence, etc.) in detail. Network models are also useful to further couple the epidemic spreading and the individual-level decision-making, with information spreading ([Chang et al., 2020](#)), which may be interesting to evaluate in a perception-based decision-making framework.

4.2.2 Determining and interpreting the relative cost of prevention versus treatment

Since the decision-making relies not only on monetary, quantitative factors, but also on subjective factors like prevention acceptability and accessibility, as well as self-awareness regarding risk of infection, the resulting values for the total expected utility and the relative cost were read from a qualitative point of view. Therefore, it is not possible to place a specific situation in a specific point of the *cost-axis*: in our framework, one cannot read that a real-life strategy is “perceived as being x times more beneficial” than another strategy.

Nevertheless, the qualitative interpretation of our results might still offer insight about the dynamical system’s behavior: from an intuitive point of view, a very low cost perceived by individuals and/or cost reduction may be easier to interpret and to aim to. In addition, our interpretation of the (in)stability of the disease-free equilibria may offer insight on how the dynamical system may respond to interventions.

4.2.3 Considering other behavioral models

In our model, we considered a single-player game, where individuals act in their own interest. This can be interpreted as a game between individuals and public health authorities aiming at epidemic elimination. Considering multi-player games would take into account the interactions between individuals. For instance, accounting for individuals’ acknowledgment of herd immunity and other players’ decisions would allow to model explicitly *free riders*, individuals who decide to delay or not to adopt prevention, hoping to benefit from others’ preventive behaviors. In the case of vaccination, previous studies have found that high vaccination rate decreased the individual’s acceptance of vaccination ([Ibuka et al., 2014](#)). In the case of the use of PrEP, the free-rider phenomenon could be studied by considering, for instance, the probability of undergoing condomless sex with on-PrEP individuals.

Another modeling choice we made was that every individual makes a decision based in an individual utility, equal for everybody. Including the heterogeneity in the perception of infection risk and cost among individuals may help better understanding dynamics in terms of population heterogeneity and developing targeted implementations of prevention programs. On the other

hand, considering altruism into the model by including a component for the collective utility may allow to study if voluntary prevention coverage may reach levels that optimize the payoff at the collective level ([Shim et al., 2012](#)).

4.2.4 Studying epidemics in other socio-economical settings

Our results point to cost reduction being a key public health's objective to yield epidemic elimination. Our work focuses in fighting epidemic spread within high-income settings, where the notion of cost denotes mostly non-monetary aspects, specially involving the individuals' acceptability of the preventive methods. However, in low-income settings, the consequences of infections may be far more severe, and cost-reducing policies may require to target prevention accessibility rather than prevention acceptability.

For instance, in the case of the measles epidemiology, the mortality rates can be as high as 2% to 15% among children in low-income settings, and mild symptoms like diarrhea and rash can become serious complications, due to malnutrition and hemorrhages ([Sever et al., 2011](#)). Hence, the MMR vaccine is often well accepted in low-income countries ([Larson et al., 2016](#)) but availability issues persist: as of August 2019, 23 countries had yet to introduce the second dose of MMR vaccine in the national vaccination schedules ([WHO, August 2019](#)).

Similarly, in the case of the HIV epidemiology, accessing HIV care in low- and middle-income settings and, in particular, the availability of PrEP might still be challenging ([UNAIDS, 2019a](#)). Hence, context-specific strategies to facilitate access to PrEP should be implemented ([Rebe et al., 2019](#)).

4.2.5 Game-theoretic models of the COVID-19 pandemic

From early January 2020 to mid-February 2021, around 109 million cases of SARS-CoV-2¹ infections resulting in ~ 2.4 million deaths were reported to the WHO, worldwide ([WHO, 2021a](#)). Public health authorities have established a variety of mandatory non-pharmaceutical interventions (NPI) aiming to control de epidemic, which have successfully reduced the number of new

¹Severe acute respiratory syndrome coronavirus 2, the causative agent of COVID-19, the severe coronavirus disease. See the review by [Salzberger et al. \(2020\)](#) for more details on the epidemiology of SARS-CoV-2.

infections (Bo et al., 2021). However, heavy interventions such as national-level lockdowns and closing schools and stores are not tenable in the long run, so the development of immunization tools was of great interest. Since mid-December 2020, several vaccines were placed on the market (WHO, 2021b), and vaccination campaigns started around the world. As of mid-February 2021, ~ 180 million vaccination doses² were administered worldwide (Our World in Data, 2021).

Mathematical models have been used to estimate epidemiological parameters (such as the effective reproduction number and time intervals of disease progression (Xiang et al., 2021)), as well as to predict the impact of intervention measures (Xiang et al., 2021) on the still ongoing COVID-19 pandemic. In particular, behavioral epidemiology has been used to study the impact of epidemic control interventions demanding the voluntary participation of individuals, such as social distancing (Gupta et al., 2020), stay-at-home (SAH) interventions (Kabir and Tanimoto, 2020) and vaccination (Choi and Shim, 2020; Jentsch et al., 2020). All four studies used SEIR-type compartmental model for disease transmission, including symptomatic and asymptomatic individuals. Gupta et al. (2020) published a working paper where compliance to social distancing interventions was studied via mobility data and in terms of the production and consumption of commodities. They defined the utility function explicitly over regular commodities, occupation and health status. The authors found that information-based interventions had a large impact on mobility during the early stages of the epidemic, and that late adoption of state closure may induce lesser compliance of social-distance adoption and mobility reduction. Kabir and Tanimoto (2020) studied the compliance of SAH interventions by including quarantine after exposure to the virus into the transmission model, as well as hospitalizations and immunity after recovery. The payoff depended on the relative costs perceived by individuals and the number of infected individuals. The authors found that individuals' compliance for SAH interventions wanes with time. In addition, they studied the final size of the epidemic and the fraction of hospitalized population in terms of the perceived cost and the transmission rate, concluding that SAH and natural immunity complement each other in controlling the epidemic and thus, hospital occupation, as long as cost is perceived low. Choi and Shim (2020) accounted for imperfect vaccination and social distancing (reduction of the number of contacts, by a constant factor) in their transmission model. They analyzed the individuals' expected payoffs (which depended on the strategies' adoption rates and relative perceived costs) when individuals may adopt the strategies of social distancing, vaccination, or both, to avoid infection, finding the

²These data do not allow to infer the number of vaccinated people, since it is unknown how many of these shots are second doses.

threshold relative costs (of vaccination and social distancing) that determined the selection over one strategy over the other. [Jentsch et al. \(2020\)](#) studied vaccination prioritizing, considering three strategies: i) targeting older first, ii) targeting younger first, iii) vaccinating the whole population uniformly, and iv) a contact-based strategy. The authors used an age-structured compartmental model accounting for imperfect vaccination and contacts by age and location. The decision model concerned the individual adherence to NPI. They calibrated their model using and using mobility data. Their main result in the best strategy (determined by the reduction in the number of deaths), depending on the reported cases and the proportion of vaccinated individuals.

The subject of ending the COVID-19 epidemic at the regional level has been recently discussed. A petition to end SARS-CoV-2 infections at the European level started in Germany in January 2021 ([ZeroCovid, 2021](#)), suscitating a debate in other European countries, such as France ([Tribune, 2021](#)) and UK ([Nuki, 2021](#)). Our approach may give insights into the subject of vaccination against COVID-19 and health programs aiming at epidemic elimination, by highlighting how essential an accurate perception of the infection risk and a reduction of the perceived cost of preventing SARS-Cov-2 infection are.

Individuals' perception of the risk of SARS-CoV-2 infection may be strongly related to the direct experience with the virus and the local epidemic situation ([Domínguez et al., 2020](#); [Elharake et al., 2021](#)). In addition, a recent study found that the individuals' knowledge and beliefs about the pandemic were associated with individuals' information sources, which were strongly determined by sociodemographic characteristics ([Ali et al., 2020](#)). Therefore, availability and broad access to accurate information need to be ensured. Official, governmental sources may help ensuring individuals' trust in the information, which may translate in the successful adoption of preventive behaviors ([Lim et al., 2021](#)).

Reducing the perceived cost of prevention in the early stages of an epidemic, specially in a context where therapeutic and immunization tools are not yet available, may be strongly related to disease morbidity and infection scares. However, as times goes by and control measures show their efficacy, individuals' attitudes towards preventive methods may vary more and more. Indeed, vaccine attitudes towards vaccination vary widely between countries. A survey about the acceptability of the COVID-19 vaccine by [Wouters et al. \(2021\)](#) found that only 44% of the French respondents where potentially getting vaccinated, versus a 81% of the UK responders.

Vaccine hesitancy may be addressed, for instance, by increasing communication about vaccines, as well as ensuring broad availability and accessibility (Wouters et al., 2021). In addition, facilitating vaccine adoption may be reached by facilitating the vaccination process itself, for instance, through single-dose vaccines (Sanchez-Felipe et al., 2020).

4.2.6 The impact of the COVID-19 pandemic on prevention interventions against measles and HIV

The COVID-19 epidemic provoked a sanitary crisis worldwide, also impacting public health programs aiming for disease elimination. For instance, the COVID-19 epidemic impacted childhood immunization, with 37 countries delaying immunization activities during the first wave of the epidemic (WHO, 14 April 2020). Hence, to maintain measles on the path of epidemic elimination, public health authorities around the world will need to address the decrease in prevention coverage that the COVID-19 epidemic provoked during the year 2020.

The COVID-19 epidemic also impacted PrEP uptake in France. The so far increase in PrEP use in France was slower during the first semester of 2020 (cf. fig. 3.3). A survey made to $\sim 8\,350$ French MSM regarding their sexual behaviors during the period June-July 2020 found that 60% of respondents had declared a complete drop in casual sexual encounters, and that 59% of PrEP users had stopped using PrEP due to a decrease in sexual activity (Velter et al., 2020).

The completion of our research project took place before the emergence of the COVID-19 pandemic. However, our results may still be relevant, since we analyze the system at the equilibrium, which is not impacted by perturbations (i.e., short-term changes in epidemic dynamics).

4.3 Conclusion

The methods developed in this doctoral research program allowed us to study infectious disease epidemics in terms of individual's attitudes towards the available preventive methods against infection, as well as their perception of the risk of infection. In particular, we focused on studying the conditions under which epidemic elimination could be reached through the voluntary participation of the target population.

We found that public health programs may yield epidemic elimination, provided that i) highly-effective preventive methods are available and perceived as being at low cost; and ii) that so individuals have a fair perception of their risk of infection. However, once the epidemic is eliminated, active efforts from public health authorities are needed to maintain the individual perception of the prevention cost low, so the willingness to keep using prevention maintains voluntary-prevention coverage at sufficiently high levels.

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Open-source acknowledgements

LaTeX packages

- `algorithmx` (available at: <https://ctan.org/pkg/algorithmicx>)
- `fancyhdr` (available at: <https://www.ctan.org/pkg/fancyhdr>)
- `pseudocode` (available at: <https://ctan.org/pkg/pseudocode>)
- `pdfpages` (available at: <https://ctan.org/pkg/pdfpages>)

Matlab packages

- `ColorBrewer` (available at: <https://www.mathworks.com/matlabcentral/fileexchange/45208-colorbrewer-attractive-and-distinctive-colormaps>)
- `hatchfill2` (available at: <https://www.mathworks.com/matlabcentral/fileexchange/53593-hatchfill2>)

Appendices

A Interdisciplinary note

During my PhD, I was registered to the RDSP³ (Public health doctoral network), which is organized by the EHESP⁴ (School of high studies in public health). As a part of the RDSP program, I wrote an interdisciplinary note that places my doctoral research within a broader, interdisciplinary context. The corresponding document, titled « *Prevention of infectious diseases: from a game-theoretic approach to a multi-level, interdisciplinary perspective* », is included in the following pages.

Interdisciplinary note

³Réseau doctoral en santé publique.

⁴École des hautes études en santé publique.

INTERDISCIPLINARY NOTE

B Résumé détaillé

« La prévention des maladies infectieuses dans le contexte de traitements efficaces : une approche par la théorie des jeux »

B1. Introduction

Malgré l'existence de méthodes efficaces, la prévention des maladies infectieuses continue de poser des défis aux autorités de santé publique. Face au risque d'infection, les individus décident d'utiliser une méthode de prévention ou bien d'être traités en cas d'acquisition de la maladie ; ceci est appelé *le dilemme de la prévention versus le traitement*. Alors que le traitement est généralement bien accepté par les individus infectés, l'acceptabilité de la prévention peut varier entre individus. La perception individuelle du risque d'infection et l'évaluation des avantages et les inconvénients de la prévention versus le traitement peuvent conduire les individus à adopter des comportements de prévention qui diffèrent des recommandations des autorités de santé publique.

La prise de décision individuelle peut être biaisée et pourtant, étroitement liée au cours de l'épidémie. En effet, le risque d'infection dépend de la prévalence de la maladie, qui elle-même dépend notamment de l'efficacité et de la couverture tant des outils préventifs que des traitements disponibles. En conséquence, la décision de chaque individu est indirectement influencée par les décisions des autres, puisque la somme des décisions détermine la *couverture volontaire* de la méthode préventive, qui à la fois a un impact sur la progression de l'épidémie.

Ainsi, pour étudier l'impact de la prévention sur une épidémie, il est essentiel de prendre en compte le comportement des individus. Afin d'étudier l'impact de la prévention volontaire, des modèles mathématiques combinant des modèles de transmission de la maladie au niveau populationnel avec des modèles concernant le comportement individuel ont été utilisés ([Verelst et al., 2016](#); [Wang et al., 2016](#)).

L'objectif principal de ma thèse a été de développer un modèle mathématique permettant de déterminer quel peut être l'impact de la prévention adoptée volontairement par les individus sur une épidémie, dans le contexte où il existe des traitements efficaces.

B2. Description générale des méthodes utilisées

Dans cette thèse, nous avons proposé un modèle à deux composants, combinant un modèle pour la transmission d'une maladie infectieuse, avec un modèle pour la prise de décision individuelle d'adopter ou pas une méthode préventive afin de diminuer le risque d'infection. Ce modèle a pour but d'évaluer les conditions pour lesquelles la couverture volontaire de la prévention peut contrôler et, éventuellement, éliminer une épidémie.

B2.1. La modélisation de la transmission d'une maladie infectieuse au niveau populationnel

Nous avons utilisé un modèle compartimental déterministe, décrivant la transition des individus d'un état à l'autre au cours du temps, défini par un système d'équations différentielles ordinaires (EDO). Un modèle classique de transmission de la maladie de ce genre a deux états d'équilibre possibles : un état où l'épidémie reste endémique et un autre où il n'y a plus d'épidémie (ici notés ES et DFS, respectivement, par ses acronymes en anglais) ([Hethcote, 2000](#)).

Le système d'EDO permet de calculer les indicateurs épidémiologiques reflétant la progression de l'épidémie. Nous calculons notamment le *taux de reproduction effectif*, R , défini comme le nombre moyen d'individus infectés par une personne pendant la période où elle est infectieuse. Le taux de reproduction effectif permet de déterminer l'impact de la prévention sur l'épidémie à long terme : si $R > 1$, l'état ES est atteint et l'épidémie persiste ; si $R \leq 1$, l'état DFS est atteint, et on dit que l'épidémie est *éliminée*.

Nous étudions le taux de reproduction effectif en fonction des paramètres concernant la méthode preventive (notamment, la couverture et l'efficacité). En particulier, en fixant la couverture de la prévention à 0, nous obtenons le *taux de reproduction de base*, R_0 : le nombre moyen d'individus infectés par une personne pendant la période où elle est infectieuse, en absence d'interventions de prévention. Autrement dit, le taux de reproduction de base reflète le comportement de l'épidémie à long terme, dans le cas où aucune méthode préventive n'est disponible. Si le taux de reproduction effectif est inférieur au taux de reproduction de base (c'est à dire, $R < R_0$), l'épidémie atteint un nouvel état endémique, moins sévère, et on dit que l'épidémie est *contrôlée* par la méthode préventive. En effet, une réduction du taux de reproduction se traduit par une

réduction du nombre de nouvelles infections.

Nous couplons ce modèle de transmission à un modèle au niveau individuel qui permet de déterminer si une couverture de la prévention permettant d'obtenir $R < 1$ peut être atteints volontairement.

B2.2. La modélisation de la prise de décision concernant l'adoption de la prévention au niveau individuel

Afin de modéliser la résolution du dilemme de la prévention versus le traitement au niveau individuel, nous avons utilisé un jeu individuel non-coopératif (modèle issu de la théorie des jeux). Nous avons supposé que les individus décident d'adopter ou pas une méthode de prévention en évaluant leur probabilité de devenir infectés, la couverture et efficacité de la méthode préventive et le *coût relatif* de la prévention versus le traitement. Ce coût représente les inconvénients associés et à la prévention et au traitement, et concerne des aspects monétaires et/ou non monétaires comme le prix, les effets indésirables, les difficultés d'accès, la morbidité de la maladie, etc.

Une *fonction d'utilité* a été définie en termes de ces éléments. La théorie des jeux postule que la prise de décision des individus maximise l'utilité (ou, de manière équivalente, minimise le coût total affronté par l'individu). La couverture de la méthode préventive qui maximise l'utilité individuelle donne la probabilité d'adopter la prévention pour un individu typique et ainsi, détermine à la fois la *couverture volontaire de la prévention* au niveau populationnel.

Nous avons étudié la couverture volontaire en fonction notamment de l'efficacité de la prévention et du coût relatif de la prévention versus le traitement. En particulier, nous avons étudié les conditions nécessaires et suffisantes pour obtenir l'élimination de l'épidémie (c'est à dire, un taux de reproduction effectif issu de la couverture volontaire de la prévention inférieur à 1).

B3. Travaux de recherche

Nous avons construit des modèles couplés afin d'explorer deux problèmes de santé publique. La première partie de ma thèse concerne un modèle pour la vaccination dans le contexte de maladies

infectieuses infantiles évitables par vaccination, dans un contexte où les traitements permettent la guérison (Jijón et al., 2017). La seconde partie de ma thèse concerne la modélisation de la prise volontaire de la prophylaxie pré-exposition (PrEP) comme méthode de prévention contre l'infection à VIH, au sein de la population des hommes qui ont des rapports sexuels avec les hommes (HSH) en Île-de-France (IdF), et son application numérique (Jijón et al., 2021).

B3.1. La vaccination volontaire dans le cadre des maladies infectieuses infantiles

L'état de confiance vis-à-vis les vaccins est globalement élevé (Larson et al., 2016). Cependant, il existe des régions où l'hésitation face à la vaccination demeure un problème de santé publique. Sept des dix pays qui ont le moins confiance dans la vaccination ont été identifiés dans la région européenne en 2016 (Larson et al., 2016). En 2017, douze pays de l'Union Européenne avaient signalé une diminution de la couverture du vaccin infantile contre la rougeole, les oreillons et la rubéole (ROR) (Larson et al., 2018). Les sentiments des parents vis-à-vis de la vaccination de leur enfants varient considérablement d'un individu à l'autre, les causes sous-jacentes allant de la désinformation sur les effets indésirables, la méfiance à l'égard du système de santé, la pression sociale, les convictions religieuses, entre autres (Brown et al., 2010; Dubé et al., 2013; Larson et al., 2014; Dubé et al., 2018; Quinn et al., 2019).

Des études de modélisation ont conclu que l'élimination d'une épidémie ne serait pas possible via la vaccination volontaire (Bauch and Earn, 2004). Néanmoins, on a témoigné l'éradication globale de la variole (CDC, 2001), et de la déclaration d'élimination de maladies infectieuses dans certaines régions (a.e., la rougeole en Amérique (Sever et al., 2011)), grâce à des programmes de vaccination. Ainsi, l'objectif principal de la première partie de ma thèse était de développer un modèle mathématique permettant de réétudier la vaccination volontaire comme prévention contre une maladie infectieuse de type infantile, afin de déterminer si elle peut contrôler et/ou éliminer une épidémie, et sous quelles conditions.

Modèle

Le modèle de transmission au niveau populationnel a été défini par un modèle compartimental : les individus pouvant rester susceptibles ou être vaccinés (et puis redevenir susceptibles, à cause de la perte de l'immunité induite par la vaccination), les individus récemment infectés passant par une période de latence de l'infection et puis devenant infectieux, enfin guérissant soit naturellement, soit grâce à une thérapie. Ainsi, deux facteurs rendant le vaccin imparfait ont été considérés : i) l'efficacité du vaccin n'est pas totale (une proportion de la population n'est pas protégée contre la maladie après vaccination) ; et ii) l'immunité induite par le vaccin a une durée limitée.

En ce qui concerne le modèle de décision, nous avons défini la fonction d'utilité en termes de l'efficacité et la couverture du vaccin, le coût relatif du vaccin versus le la guérison, et le risque d'infection perçu par les individus. Le coût, dans le contexte de la vaccination, comprend des aspects comme le prix, les effets secondaires de la vaccination, l'accessibilité à la vaccination, la morbidité de la maladie, les effets secondaires du traitement, etc. Le risque d'infection a été défini par la prévalence endémique : la proportion d'individus infectés dans la population quand le système dynamique atteint son état d'équilibre.

Résultats

En maximisant la fonction d'utilité, nous avons obtenu une expression pour la probabilité d'être effectivement vacciné en fonction notamment du coût relatif. Contrairement aux études précédents ([Bauch and Earn, 2004](#)), nous avons montré que la vaccination volontaire peut éliminer une épidémie, même si le vaccin est imparfait, pourvu que le coût relatif soit suffisamment bas.

Toutefois, cette élimination ne peut être que temporaire et requiert de maintenir un coût relatif de la vaccination versus le traitement suffisamment bas. En effet, il n'y a pas un équilibre stable pour la stratégie individuelle quand il n'y a pas d'épidémie. Lorsque la couverture vaccinale est élevée, le nombre de cas de la maladie est faible. Ainsi, les individus ne perçoivent plus la morbidité et la mortalité liées à la maladie et des controverses concernant l'innocuité du vaccin peuvent apparaître. Cela peut changer la perception du coût de la prévention versus le traitement et entraîner une diminution de la couverture vaccinale, qui a son tour provoque un retour vers la situation $R = 1$.

Les conditions nécessaires et suffisantes pour éliminer l'épidémie ont donné lieu à une discussion sur les paramètres concernant le vaccin. Nous avons trouvé que deux conditions sont nécessaires pour atteindre et maintenir l'élimination de l'épidémie : i) Développer des vaccins qui fournissent une immunité de longue durée (nous avons trouvé une borne inférieure pour la durée de l'immunité induite par le vaccin) ; et ii) Maintenir le coût relatif de la vaccination versus du traitement suffisamment bas (nous avons trouvé un intervalle pour le coût relatif).

Il est important de noter que, une fois le stade d'élimination est atteint, la transition vers $R = 1$ peut être ralentie considérablement grâce aux efforts des autorités de santé pour maintenir le coût de la vaccination faible. Des interventions peuvent être mises en place pour maintenir une perception du coût bas et donc une motivation pour se faire vacciner. Par exemple, des incentives (monétaires et non monétaires) ont été utilisés. Nous proposons trois possibles interventions additionnelles : a) l'incentive via la diminution des mensualités de l'assurance de santé au fur et à mesure que le calendrier vaccinal est complété ; b) informer sur le succès des programmes de prévention dans les médias ; et c) La promotion d'une perception juste via le rappel en continu des conséquences des maladies évitables par prévention et ses données épidémiologiques, en parallèle d'une information claire sur les effets indésirables du vaccin et du traitement.

Les résultats de ce premier travail de recherche ont été obtenus de façon entièrement analytique et ont fourni des informations importantes sur les propriétés du système, constituant ainsi un guide théorique pour les choix des algorithmes et l'interprétation des résultats la seconde partie de la thèse, qui impliquait une implémentation numérique

Application à la rougeole. Nous avons appliqué nos méthodes à l'épidémiologie de la rougeole, qui a été notamment déclaré éliminée dans la région panaméricaine dans les années 90 ([Sever et al., 2011](#); [De Quadros, 2004](#)), et a subi une réemergence récemment ([CDC, August 2019](#)), suite à une baisse de la couverture vaccinale ([WHO, 2018b](#)).

Nos résultats suggèrent que l'élimination de la rougeole pourrait s'expliquer par la longue durée de l'immunité induite par le vaccin ROR, ainsi que du coût relatif de la vaccination par rapport au traitement qui était certainement perçu comme faible pendant les programmes de vaccination de masse des années 90. Nous concluons que la diminution de la couverture vaccinale observée dans plusieurs pays à revenu élevé peut être due à une augmentation du coût de la vaccination perçue par les individus dans le contexte actuel, où les individus ne témoignent que

rarement des cas de rougeole et ses séquelles.

Afin d'atteindre l'élimination de l'épidémie par l'adoption volontaire de la vaccination, et de maintenir le statut d'élimination à long terme, le coût perçu par les individus doit être bas, notamment, en tenant la population informée sur l'épidémiologie de la rougeole à l'ère de la pré-vaccination, des séquelles possibles de la maladie et de l'innocuité et la haute performance actuelles du vaccin contre la rougeole.

B3.2. L'utilisation volontaire de la prophylaxie pré-exposition comme méthode de prévention contre l'infection par le VIH

Malgré les efforts réalisés pour prévenir et traiter l'infection à VIH, l'épidémie continue de progresser ([UNAIDS, 2018](#)). Dans la plupart des pays à revenu élevé, c'est parmi la population des HSH que le taux d'incidence est le plus élevé ([UNAIDS, 2018; WHO, 2016b; Beyer et al., 2012](#)). La PrEP est une méthode de prévention hautement efficace qui a été récemment développée et qui est recommandée pour les populations à haut risque d'infection par le VIH ([Siguier and Molina, 2018](#)).

Des études de modélisation ont estimé que la PrEP pourrait conduire à une réduction considérable du nombre de nouvelles infections ([Punyacharoen et al., 2016; Kim et al., 2014; Robineau et al., 2017; Gomez et al., 2012](#)) et même l'élimination de l'épidémie ([Palk et al., 2018; Rozhnova et al., 2018](#)) chez les HSH. Dans ces études, les auteurs font l'hypothèse, et donc imposent, qu'une certaine fraction de la population utiliseront la PrEP. Or la fraction de la population qui acceptera d'utiliser la PrEP reste incertaine. Le succès d'un programme de prévention basé sur la PrEP dépendra de la participation active et continue de la population cible.

Les individus feront face au dilemme d'adopter ou pas la PrEP, dans le contexte actuel de l'épidémie du VIH, où des traitement par antirétroviraux (TARV) efficaces existent. Les individus prendront leur décision en évaluant leur risque d'infection au VIH, ses conséquences, ainsi que les bénéfices et contraintes associés à la PrEP et aux TARV (par exemple, les effets secondaires, le prix, les politiques de remboursement, l'accessibilité, la stigmatisation sociale, la morbidité de la maladie, la peur de contracter d'autres infections sexuellement transmissibles en raison de la baisse de l'utilisation du préservatif, etc. ([Young et al., 2014; Taylor et al., 2014; Pérez-Figueroa](#)

et al., 2015; Holt et al., 2018; Desai et al., 2018)).

À notre connaissance, aucune étude de modélisation sur l'impact de la PrEP n'a pris en compte et analysé la prise de décision individuelle provoquant la participation volontaire de la population cible. L'objectif principal de ce travail de recherche a été de modéliser la transmission du VIH en prenant en compte le dilemme de la prévention versus le traitement, dans le contexte actuel. Ainsi, nous avons pris en compte l'utilisation du préservatif comme méthode préventive supplémentaire, une haute efficacité des TARV et un choix d'adopter ou pas la PrEP parmi les individus qui sont à haut risque d'infection.

Nous cherchions à déterminer si l'utilisation volontaire de la PrEP par la sous-population la plus à risque d'infection pourrait contrôler et éventuellement éliminer l'épidémie du VIH au niveau de la population globale, et sous quelles conditions. En particulier, notre but a été d'étudier cette problématique dans le contexte d'une des communautés les plus touchées par le VIH en France métropolitaine : les HSH en IdF.

Modèle

Le modèle compartimental a été défini par un système d'EDO décrivant la transmission du VIH au niveau populationnel, en prenant en compte la progression de l'infection et son TARV. L'hétérogénéité en termes du risque d'infection (à savoir, en raison de l'hétérogénéité des comportements sexuels) auquel les individus sont exposés a été prise en compte en stratifiant la population en deux groupes, selon leurs comportements sexuels (Velter et al., 2015) : le groupe des individus à haut risque d'infection et transmission, et le groupe à risque faible. Nous avons considéré des contacts non-aléatoires entre les individus (Jacquez et al., 1988). De plus, nous avons considéré que la population à haut risque est le moteur de l'épidémie, et devient ainsi la population cible des politiques de mise en œuvre de la PrEP (contrairement à la vaccination des enfants, qui est recommandée pour la grande majorité des nouveau-nés et des jeunes enfants).

La PrEP a été introduite dans le modèle compartimental en supposant que uniquement les individus à haut risque d'infection peuvent adopter la PrEP comme prévention contre l'infection à VIH. Nous avons considéré que les MSM sous PrEP peuvent utiliser moins le préservatif (diminution de la couverture du préservatif du 30% au 20%) et que la prescription de la PrEP peut être renouvelée tous les 3 mois sous condition de rester séronégatif (Molina and Earn, 2015).

En ce qui concerne le modèle de décision, la fonction d'utilité a été définie en termes de la perception individuelle du risque d'infection au VIH (donné par le taux d'incidence) chez les HSH en ÎdF, de la couverture et l'efficacité de la PrEP, du coût associé à la PrEP et du coût associé aux TARV.

Analyses de sensibilité

Nous avons réalisé des analyses de sensibilité du modèle en ce qui concerne :

- i) **La perception du risque d'infection.** Nous avons considéré un scénario où les individus à haut risque d'infection perçoivent leur risque en évaluant la proportion de leur pairs qui sont infectés par le VIH (au lieu de considérer le taux d'incidence).
- ii) **L'utilisation du préservatif par les HSH sous PrEP.** Nous avons considéré que les HSH sous PrEP arrêtent complètement d'utiliser le préservatif lors des rapports sexuels (au lieu de seulement diminuer leur utilisation).
- iii) **La fréquence à laquelle les HSH à haut risque d'infection se font tester.** Nous avons considéré que les individus sous PrEP ne suivent pas les recommandations des autorités de santé publique en ce qui concerne la fréquence de dépistage du VIH, et maintiennent leur comportement d'avant d'adopter la PrEP, en se faisant tester tous les ~ 3 ans ([Marty et al., 2018](#)), au lieu de tous les 3 mois ([Molina et al., 2018](#)).

Résultats

Nous avons étudié le rôle de la prise de décision au niveau individuel pour évaluer l'impact de la PrEP sur l'épidémie de VIH, et déterminé comment un certain niveau de couverture PrEP peut être atteint volontairement.

Les résultats de ce travail de recherche ont été obtenus de façon numérique. Le modèle compartimental a été calibré afin de reproduire la situation épidémiologique actuelle chez les HSH en ÎdF ([Marty et al., 2018](#)). Nous avons trouvé la couverture volontaire de la PrEP parmi les HSH à haut risque d'infection par le VIH, en fonction de l'efficacité de la PrEP et le coût relatif de la PrEP versus le TARV. Nous avons ensuite identifié les conditions pour lesquelles le contrôle et/ou l'élimination de l'épidémie au niveau de la population globale sont possibles.

Nous avons obtenu quatre résultats principaux pour les déploiements de la PrEP : i) Les épidémies de VIH peuvent être éliminées par l'utilisation volontaire de la PrEP à condition que le coût relatif de l'utilisation de la PrEP versus le TARV soit perçu suffisamment bas ; ii) Des tests de dépistage du VIH fréquents pendant la prise de PrEP peuvent compenser une mauvaise adhésion à la PrEP et agir comme une intervention ‘test and treat’, où l'on dépiste et soigne tout de suite ; iii) La perception du risque de VIH peut jouer un rôle majeur pour l'élimination, tandis que la baisse de l'utilisation du préservatif chez les MSM sous PrEP non ; et iv) L'élimination de l'épidémie peut n'être que temporaire.

En particulier, en supposant une efficacité de 86% de la PrEP, comme on l'a observé lors de deux essais cliniques ([Siguier and Molina, 2018](#)), et une perception juste du risque d'infection, l'élimination de l'épidémie serait possible si la couverture de la PrEP serait au minimum de 55% parmi les HSH à haut risque. Une chute totale de l'utilisation du préservatif parmi les utilisateurs de la PrEP augmente légèrement ce taux à 57%. Cependant, si les individus sous-estiment leur risque d'infection, il serait nécessaire de réduire le coût de la PrEP d'un facteur de ~ 2, pour que le programme PrEP permette l'élimination de l'épidémie.

Ainsi, nous avons trouvé que les conditions d'élimination ne sont pas encore réunies en région parisienne, où au plus 47% des HSH à haut risque d'infection utilisaient la PrEP mi-2019. Il est nécessaire de réduire davantage le coût perçu de la PrEP et de promouvoir une perception juste du risque de VIH pour parvenir à l'élimination. Ces conditions doivent être maintenues à long terme pour maintenir le statut d'élimination.

B4. Conclusions

Le résultat principal de notre modèle est la couverture de la prévention atteinte volontairement par les individus. En particulier, nous avons étudié la couverture de cette prévention volontaire en fonction de l'efficacité de la prévention et du coût relatif de la prévention par rapport au traitement perçu par les individus. D'un point de vue général, nos résultats suggèrent que l'élimination des épidémies par l'adoption volontaire de la prévention est possible, même en utilisant les méthodes imparfaites et des perceptions des risques individuelles biaisées, à condition que l'efficacité de la prévention soit élevée et que le coût de la prévention perçu par les individus soit faible.

Nous avons constaté que la perception du risque joue un rôle majeur dans la réussite de l'élimination de l'épidémie. Si le risque perçu diminue, le coût auquel les individus sont prêts à faire face pour adopter la prévention diminue également, quel que soit le niveau d'efficacité de la prévention. En d'autres termes, si les individus ne se perçoivent pas comme étant à un risque d'infection suffisamment élevé, ils sont moins disposés à adopter des méthodes préventives.

Nos résultats peuvent être utiles pour les politiques de santé publique visant à éliminer les épidémies, et en particulier dans le cadre des objectifs pour le développement durable de l'Organisation Mondiale de la Santé ([WHO, 2020](#)). Deux phases peuvent être établies afin d'atteindre et maintenir l'élimination des maladies infectieuses à long terme. Pendant une épidémie en cours, la couverture de la prévention peut augmenter grâce à la diminution des barrières perçues par les individus, ainsi qu'en offrant des informations sur le risque d'infection et la maladie et la charge de traitement. Puis, en cas d'élimination d'une épidémie, les niveaux élevés de couverture de prévention peuvent être maintenus grâce à l'accessibilité à la prévention, mais aussi grâce à l'accès aux informations sur le succès des programmes de prévention passés, ainsi que sur la gravité de l'épidémie avant leur mise en place.

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