Infectious Disease Modelling 9 (2024) 805–815

Contents lists available at ScienceDirect

Infectious Disease Modelling

journal homepage: www.keaipublishing.com/idm

# An effectiveness study of vaccination and quarantine combination strategies for containing mpox transmission on simulated college campuses

Qiangru Huang [a, 1], Yanxia Sun [a, 1], Mengmeng Jia [b], Mingyue Jiang [a], Yunshao Xu [a], Luzhao Feng [a, **], Weizhong Yang [a, *]

[a] School of Population Medicine and Public Health, Chinese Academy of Medical Sciences & Peking Union Medical College, Beijing, 100730, China
[b] National Institute of Pathogen Biology, Chinese Academy of Medical Sciences & Peking Union Medical College, Beijing, 100730, China

ARTICLE INFO

*Article history:*
Received 14 September 2023
Received in revised form 4 April 2024
Accepted 10 April 2024
Handling Editor: Dr Yiming Shao

*Keywords:*
Infectious diseases
Mpox
Vaccination
Quarantine

ABSTRACT

The ongoing transmission of mpox in specific countries and regions necessitates urgent action. It is essential to implement targeted containment strategies that concentrate on high-risk populations and critical locations, such as college campuses, to effectively curb the spread of mpox. This study is dedicated to evaluating the performance of various vaccination and quarantine strategies in curbing the spread of mpox and estimating the outbreak risk. To accomplish this, we constructed a stochastic, agent-based, discrete-time susceptible-latent-infectious-recovered (SLIR) model, to examine mpox transmission on a simulated college campus. Our findings reveal that relying solely on PEP is insufficient in containing mpox effectively. To bolster the population immunity and protect the vulnerable, pre-exposure vaccination among high-risk populations prior to an outbreak is imperative. Our study demonstrates that a pre-exposure vaccination rate of 50% in high-risk populations can led to a remarkable 74.2% reduction of infections. This translated to a mere 1.0% cumulative infection incidence in the overall population. In cases where the desired vaccination coverage is not attainable, enhancing case detection and isolation measures can serve as an effective emergency response to contain mpox outbreaks. For pre-exposure vaccination coverage of 20% or lower, a 40% isolation ratio is necessary to keep the cumulative number of infections in check. However, when the coverage exceeds 30%, a reduced isolation ratio of 20% becomes sufficient to manage the outbreak effectively. These insights underscore the importance of strategic pre-exposure vaccination in conjunction with robust surveillance and isolation protocols to safeguard public health and prevent the escalation of mpox outbreaks.



* Corresponding author.
** Corresponding author.
*E-mail addresses:* fengluzhao@cams.cn (L. Feng), yangweizhong@cams.cn (W. Yang).
Peer review under responsibility of KeAi Communications Co., Ltd.
[1] These authors contributed equally to this work.

https://doi.org/10.1016/j.idm.2024.04.004

## 1. Introduction

A multi-country outbreak of mpox (monkeypox) has been ongoing since May 2022 (Wenham & Eccleston-Turner 2022). The global peak in weekly cases reported occurred in August 2022, and followed by a steady decline (WHO, 2022). As of February 2024, the WHO has reported 94,707 laboratory-confirmed mpox cases and 181 deaths across 117 countries, casting a profound effect on human health and the security of public health (WHO, 2024). The potential for mpox transmission persists in select countries and regions. A cumulative total of 890 confirmed cases has been reported in China. Since June 2023, there has been a discernible uptick in the prevalence of widespread confirmed or suspected cases, capturing the interest of medical professionals and policymakers alike (PREVENTION CCFDCA, 2023a)(WHO, 2023).

Significant challenges remain in the containment of multi-country mpox outbreak. Many cases in newly-affected areas do not present with classically described clinical signs for mpox (fever, swollen lymph nodes, followed by a centrifugal rash). Atypical features described include: presentation of only a few or even just a single lesion, absence of skin lesions in some cases with anal pain and bleeding, and lesions in the genital or perineal/perianal area that do not spread further (WHO, 2022a). These symptoms can complicate the clinical picture, making it difficult for healthcare providers to suspect and confirm mpox, especially in regions where mpox is not commonly encountered. In addition, the lack of readily available screening and detecting tools for the mpox virus (MPXV) exacerbates this issue, as current strategies largely depend on self-reporting and contact tracing to establish transmission chains (Sabeena).

University and college leaders have crafted plans to address potential mpox outbreaks within campuses (Prevention CfDCa, 2022d) (A, 2022; Taylor 2022), which reflects their concern that MPVX could spread rapidly beyond the dense networks originally confined to men who have sex with men (MSM) and into other gathering places and populations with high levels of physical contact. Despite efforts to control the outbreak, the situation is still not fully contained at national and global levels, and college students remain a vulnerable population. In the United States, approximately half of all sexually transmitted infections (STIs) occur among college-age individuals. Direct medical costs associated with chlamydia, gonorrhea, and syphilis alone account to $1.1 billion, with 60% of expenditures targeting individuals the 15–24 age group (Prevention CfDCa, 2022a). As a result, the sporadic emergence of mpox among young MSM and other sexually active individuals, including those on college campuses, poses ongoing public health and economic impacts.

Critical actions to address the mpox outbreak include providing pre- and post-exposure prophylaxis to at-risk populations, instituting isolation procedures or reducing close contact (e.g., sexual contact) to hinder further transmission, and furnishing at-risk populations potentially susceptible to MPXV with accurate information (Gupta et al). Current available data indicates that vaccination against smallpox may provide 85% cross-protection against MPXV (Prevention CfDCa, 2022c). Two smallpox vaccines, ACAM2000 and JYNNEOS, are recommended for pre-exposure prophylaxis. JYNNEOS, which has been granted approval for use and exhibits a lower incidence of adverse effects compared to ACAM 2000, is also suitable for post-exposure prophylaxis, preferably administered within 4 days of exposure (Wolff Sagy et al.,). In addition, early detection, diagnosis, isolation, and reduction of close contacts are recommended for individuals in close contact with infected cases (Guarner et al).

The Predicting the dissemination of emerging infectious diseases such as mpox in a variety of settings, especially in unique environments like college campuses, is a challenging endeavor that necessitates effective means to evaluate the effectiveness of integrated control interventions. In this study, we utilize an agent-based modeling approach to simulate the spread of mpox on a residential college campus. We aimed to estimate the likelihood of an outbreak and to evaluate the potential effectiveness of interventions, including post- and pre-exposure vaccinations for high-risk populations, as well as the transfer and isolation of cases. To implement targeted and scientifically precise containment initiatives, this study assessed the effectiveness of individual interventions and their combinations within the collegiate context. A set of measures was proposed to curtail the spread of MPXV on campus, and offering a framework to inform decision-making for the containment of mpox.

## 2. Methods

### 2.1. Model structure

This decision-support analytical modeling study utilized simulated data and parameters of mpox transmission, thereby obviating the need for Ethics Committee approval. We developed a stochastic, agent-based, discrete-time Susceptible-Latent-Infectious(protected/symptomatic)-Recovered(SLIR) model to investigate the transmission of MPXV on a simulated college campus. The entire population within the simulated campus setting was divided into high- and low-risk groups, comprising of 500 and 5000 individuals, respectively, at a ratio of 1:10 (JM 2022; Yale 2022). Daily time steps over 180 days were modeled, starting with a fully susceptible population. The initial infection seed consisted of six cases: five from the high-risk group and one from the low-risk group.

WHO identifies the high-risk populations as being at higher risk of MPXV infection, which include: 1) Individuals living with or having close contact (including sexual contact) with mpox patients, including MSM population, 2) Individuals in contact with mpox patients, including healthcare workers dealing with MPXV; 3) Individuals with compromised immunity, such as children and pregnant women (WHO, 2024a). MPXV can be transmitted through the following ways: 1) Direct skin-to-skin, skin-to-mucosal or mouth-to-mucosal physical contact; 2) Contact with contaminated materials such as clothing or

bedding; 3) Prolonged face-to-face respiratory exposure in close proximity (inhalation of respiratory droplets and possibly short-range aerosols); 4) Respiratory or mucosal exposure to lesion material (e.g., scabs/crusts) from a person with mpox (WHO, 2024a).

Considering the characteristics of the aforementioned high-risk populations of mpox and the transmission pathways of MPXV, in the context of college campuses, the high-risk group is defined as MSM community and individuals in close contact with infected cases, such as frequently interacting friends and teachers, dormitory roommates, or classmates. The remaining individuals in university campus are categorized as the low-risk group, such as regular classmates, faculty, and staff who do not have close contact with infected cases.

Susceptible individuals are at risk of infection when exposed to unisolated symptomatic MPXV cases. The risk of infection is posed by both the high-risk and low-risk groups. Infected individuals develop symptoms after the latent period. Timely administration of post-exposure vaccination (i.e., post-exposure prophylaxis, PEP) during the latent period can provide immunoprotection, i.e., some individuals do not develop symptoms after receiving post-exposure vaccine. Currently, there is no evidence that asymptomatic individuals are infectious. The aforementioned asymptomatic and non-infectious individuals are denoted as “P”, with the corresponding state transition process illustrated by the green line in Fig. 1. Those in the latent period but not protected by PEP will furth progress to symptomatic infection, denoted as “I”. The model assumes that only symptomatic infections contribute to mpox transmission, as depicted by the gray dotted line in Fig. 1, where susceptible individuals in both risk groups face the risk of transmission from infectors in both the high- and low-risk groups. As depicted by the red line in Fig. 1, symptomatic infectors, once identified, are transferred with a certain probability to a separate quarantine cohort, such as self-isolation or transfer to designated hospitals, where they have no contact with the remaining susceptible individuals. All Infected individuals in the quarantine cohort are transferred back to the non-quarantine cohort upon recovery. Detailed state transitions of the SLIR process are provided in Table S1 and S2.

### 2.2. Setting of disease transmission

Four types of daily contact are explicitly modeled within and between the high- and low-risk populations. An individual's daily risk of infection primarily derived from three sources: contacts within their own risk group, contacts between different risk groups, and social interactions. The daily infection probability for each individual follows a binomial distribution, which is determined by the combined product of the infectivity of the three distinct sources they contacted and the corresponding contacts.

Considering the characteristics of the high-risk population, it is posited that their internal contact frequency is three times that of their contact frequency with low-risk population. Additionally, due to the minority nature of the high-risk population, the frequency of low-risk individuals in contact with high-risk individuals was significantly lower than the frequency from the high-risk to the low-risk individuals.

Each of the four types of contact (i.e., high-risk to high-risk, high-risk to low-risk, low-risk to high-risk, and low-risk to low-risk) is assigned a weight to represent different levels of contact intensity. We aimed to capture the heterogeneity in transmission risk, thus contact proximity and duration are not explicitly incorporate. Excluding internal transmission among high-risk individuals, the.

The basic reproductive number ($R_0$) of mpox for the high-risk and low-risk populations differs, being 2.4 and 0.8, respectively (Savinkina et al., 2023)(DHS SCIENCE AND TECHNOLOGY, 2022)(Branda et al., 2023). The high-risk population poses the highest transmission risk due to intimate contact, whereas the transmission risk among low-risk individuals,

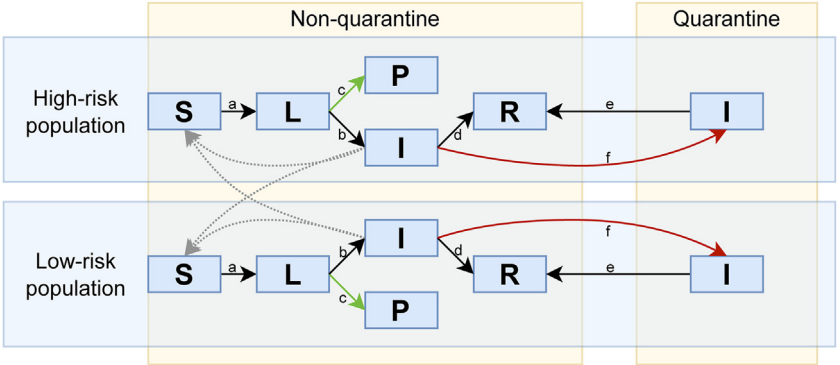


**Fig. 1.** Flowchart of Movement Through Susceptible–Latent–Infectious–Recovered Model
The gray dotted line represents the pathway by which symptomatic infected individuals (I) infect susceptible individuals (S). The green line indicates that some of the latent individuals (L) were transformed into protected individuals (P) by post-exposure vaccination. The red line indicates that some symptomatic infected individuals (I) were detected and transferred to the quarantine cohort. S: susceptible individuals; L: latent individuals; I: infected symptomatically; P: individuals protected by post-exposure vaccination; R: individuals who have recovered from mpox.

excluding internal transmission among high-risk individuals, is set at the baseline level. The transmission probability is calculated by dividing the $R_0$ of mpox by the average number of daily contacts, with the baseline transmission probability established at 0.004 (Mossong et al). Detailed parameters for the four types of contact modalities are presented in the supplementary materials (Table S2).

### 2.3. Simulated interventions

Three types of interventions were evaluated to contain the transmission: the post- and pre-exposure vaccination targeted at high-risk groups, and the transfer and isolation for infected individuals.

Given that China discontinued mass vaccination against smallpox after 1980, and the majority of university students were born were born post-vaccination cessation, the preliminary post- and pre-exposure vaccination coverage for the simulated population was established at zero. For susceptible individuals who received the vaccine, the vaccine efficacy (VE) was presumed to be 80% for pre-exposure vaccination (i.e., pre-exposure prophylaxis, PrEP), designed to prevent MPXV infection (Reynolds et al., 2003; Fine et al; Prevention CfDCa, 2022b; Rimoin et al). For pre-symptomatic infected individuals who received PEP, the VE was downgraded to 40% to account for those not vaccinated early enough during the latent period (vaccination is considered most effective within 4 days of exposure) (Prevention CfDCa, 2022b). Consequently, vaccination as a post-exposure prophylaxis was modeled to prevent symptom onset in 40% of the vaccinated exposed individuals.

We first explored the effectiveness of various PEP coverages in high-risk populations as a strategy to contain mpox transmission. In instances where PEP proved to be inadequate, we further examined the effectiveness of varying PrEP coverages on curtailing transmission. Specifically, we assessed scenarios spanned from 0% to 100% PEP coverage among the exposed high-risk population during the latent period. Furthermore, we investigated the efficacy of PrEP by considering scenarios where 0%–100% of the high-risk population received vaccination before the commencement of the simulation.

To explore the necessary percentage of detection and isolation to effectively control the transmission of MPXV at various vaccination rate, we examined five transfer and isolation ratios: 0%, 20%, 40%, 60%, 80%, and 100%. Confirmed cases that were diverted, either transferred to a designated hospital or self-isolation, were assumed to remain in quarantine until recovery, without causing further transmission during the isolated period. Conversely, undetected and unquarantined infected symptomatic cases remained contagious until they recovered within the simulated campus environment, known as the non-quarantine cohort.

### 2.4. Effectiveness assessments

The effectiveness of vaccination and quarantine strategies was assessed by analyzing the cumulative number of infections (mean ± standard deviation) in both high- and low-risk populations. Trends in the daily infected case counts over a 180-day period were calculated to evaluate the effectiveness of different intervention strategies on the propagation and severity of outbreaks. We further explored the scale and probability of campus outbreaks under different movement and quarantine rates. Within this simulated college campus setting, an outbreak was characterized as the occurrence of one or more cases beyond the initial infections. For each analysis, the model was executed 200 times to calculate the likelihood of an outbreak. All analyses were conducted using R statistical software version 3.6.3 (R Project for Statistical Computing). The source codes for the study are available online (Huang 2023).

## 3. Results

### 3.1. Efficiency of PEP in high-risk population

In the outbreak scenario without PEP and PrEP (baseline), the estimated mean cumulative number of symptomatic infections in the total population after 180 days was 530 (9.6%): 465 (93.0%) in the high-risk group and 65 (1.3%) in the low-risk group. As PEP coverage increased among the high-risk population, the proportion of protected individuals also increased, which rises from 0% to 39.5%, resulting in a gradual decrease in the cumulative infection number (Fig. 2 and Table S3). When the PEP coverage reached 50%, the estimated mean cumulative symptomatic infection number in the total population was reduced to 382 (6.9%): 337 (67.4%) in the high-risk group and 45 (0.9%) in the low-risk group. With 100% coverage, the estimated mean cumulative symptomatic infection number in the total population reduced further to 159 (2.9%): 141 (28.2%) in the high-risk group and 18 (0.4%) in the low-risk group. These results suggest that PEP coverage can effectively increase the proportion of protected individuals, and it also can partially reduce the number of infections, it is not sufficient to effectively contain the outbreak. It indicates that PrEP and other quarantine strategies remain critical for the containment of mpox.

### 3.2. Efficiency of PrEP in high-risk population

Based on PEP in all exposed high-risk populations, we investigated different coverages of PrEP in high-risk populations to evaluate its efficiency.

As the PrEP coverage increased, the number of infections sharply decreased (Fig. 3 and Table S4). Compared to PEP alone, when PrEP covered 20% of the high-risk population, the number of symptomatic infections reduced by 31.4%, and the

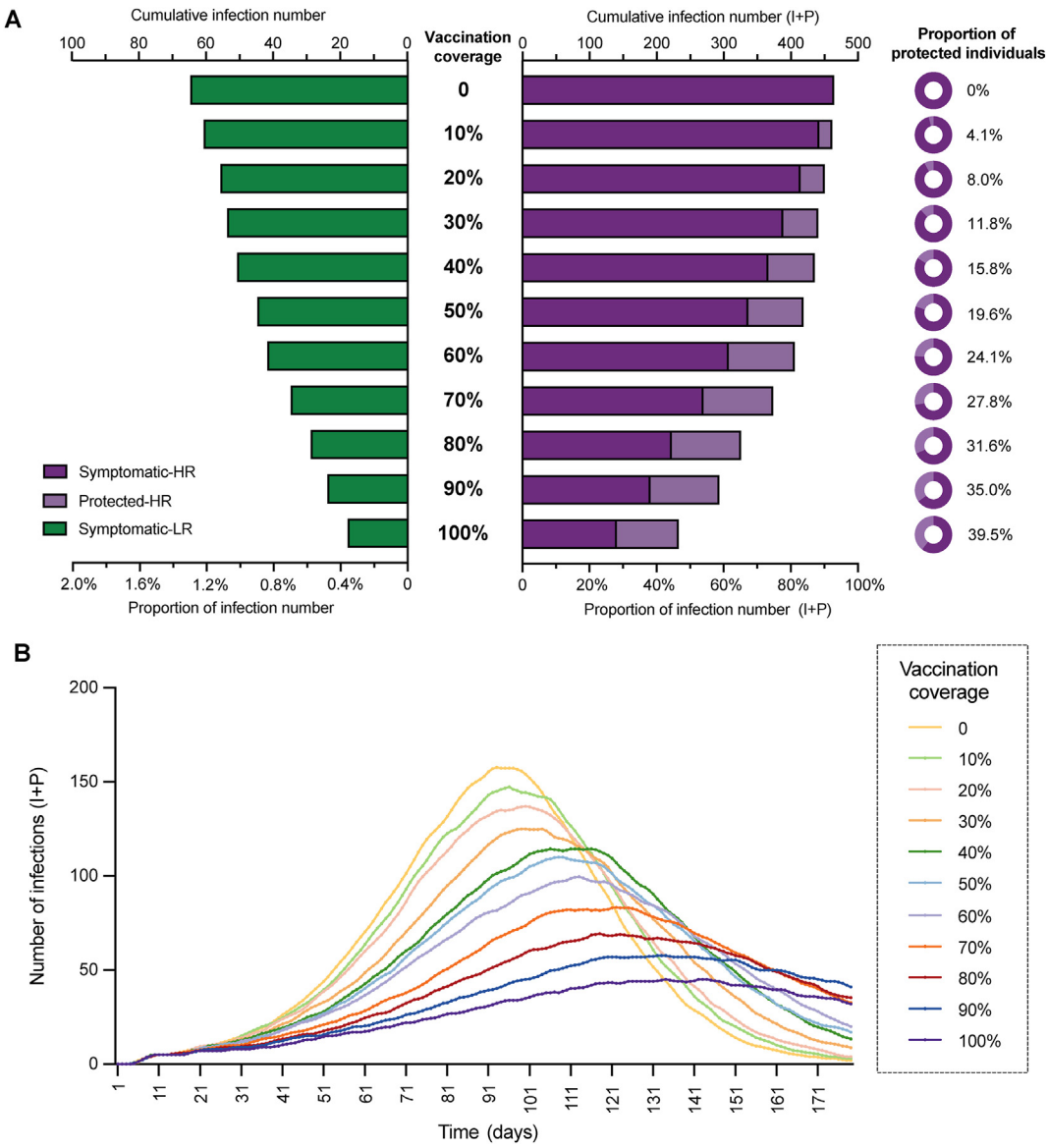


**Fig. 2.** Comparison of Intervention Effectiveness Under Different Post-Exposure Vaccination Coverage Levels in the High-Risk Population
(A) The bars represent the cumulative infection number in high- and low-risk populations at different post-exposure vaccine coverage levels. Dark purple represents symptomatically infected individuals in the high-risk population, light purple represents asymptomatically infected individuals in the high-risk population, and green represents symptomatically infected individuals in the low-risk population. (B) Line chart showing trends in the number of daily infections over time at different rates of post-exposure vaccination coverage. Cumulative number of infections (I + P) refers to the number of symptomatically infected individuals (I) and the latent individuals shielded by post-exposure vaccination (P). HR: high-risk; LR: low-risk.

estimated mean symptomatic infection in the total population reduced to 109 (2.0%). With a coverage of 50% in the high-risk population, the number of symptomatic infections decreased by 74.2%, with the estimated mean symptomatic infection number in the total population of 41 (0.7%) and 35 (7.0%) in the high-risk population. At 80% coverage, the number of symptomatic infections dropped by 87.4%, and the estimated mean symptomatic infection number in the total population reduced to 20 (0.4%).

In addition, as PrEP coverage increased among the high-risk population, the proportion of protected individuals slowly decreased, which rises from 39.5% to 11.1%. It indicates that the effect of PrEP is considerable. In scenarios where the PrEP rate is high, the protective effect of vaccinating all high-risk individuals who have already been exposed is lower.

When the coverage reached 50%, the daily number of infections remained consistently below 10, with no significant increase in new infections (Fig. 3). As the coverage increased to 60% or higher, the daily number of infections gradually

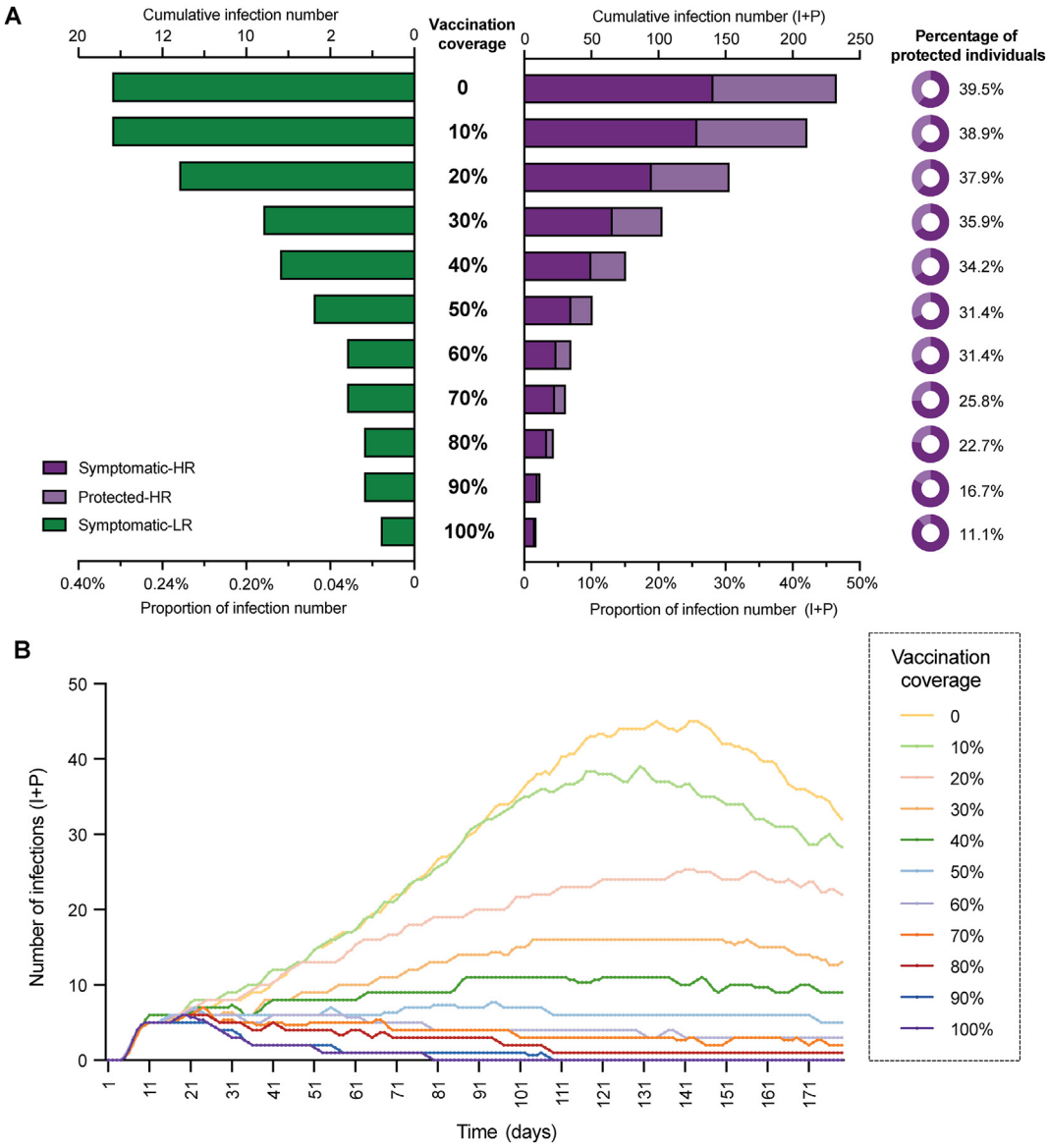


**Fig. 3.** Comparison of Intervention Effectiveness Under Different Pre-Exposure Vaccination Coverage levels in the High-Risk Population
(A) The bars represent the cumulative infection number in high- and low-risk populations at different post-exposure vaccine coverage levels. Dark purple represents symptomatically infected individuals in the high-risk population, light purple represents asymptomatically infected individuals in the high-risk population, and green represents symptomatically infected individuals in the low-risk population. (B) Line chart showing trends in the number of daily infections over time at different rates of pre-exposure vaccination coverage. Cumulative number of infections (I + P) refers to the number of symptomatically infected individuals (I) and the latent individuals shielded by post-exposure vaccination (P). HR: high-risk; LR: low-risk.

declined. These findings suggest that achieving a PrEP coverage of ≥50% in the high-risk population can provide promising efficiency in containing an mpox outbreak.

### 3.3. *Efficiency of isolation in symptomatic infected individuals*

The 50% PrEP rate in high-risk populations was relatively high. We further explored the size and likelihood of campus outbreaks with varying isolation rates at the vaccination coverage rates of <50%.

At ≤20% coverage, a 40% isolation ratio was required to keep the cumulative number of infections in the high-risk population below 50 and limit the number of infections in the low-risk population to around three or four (Fig. 4 and Table 1). With PrEP coverage of 0%, 10%, and 20%, the predicted likelihood of outbreaks in low-risk population was 35%, 35%, and 24%, respectively, all below 50%. Although the predicted likelihood of outbreaks in the high-risk population was still high, the size

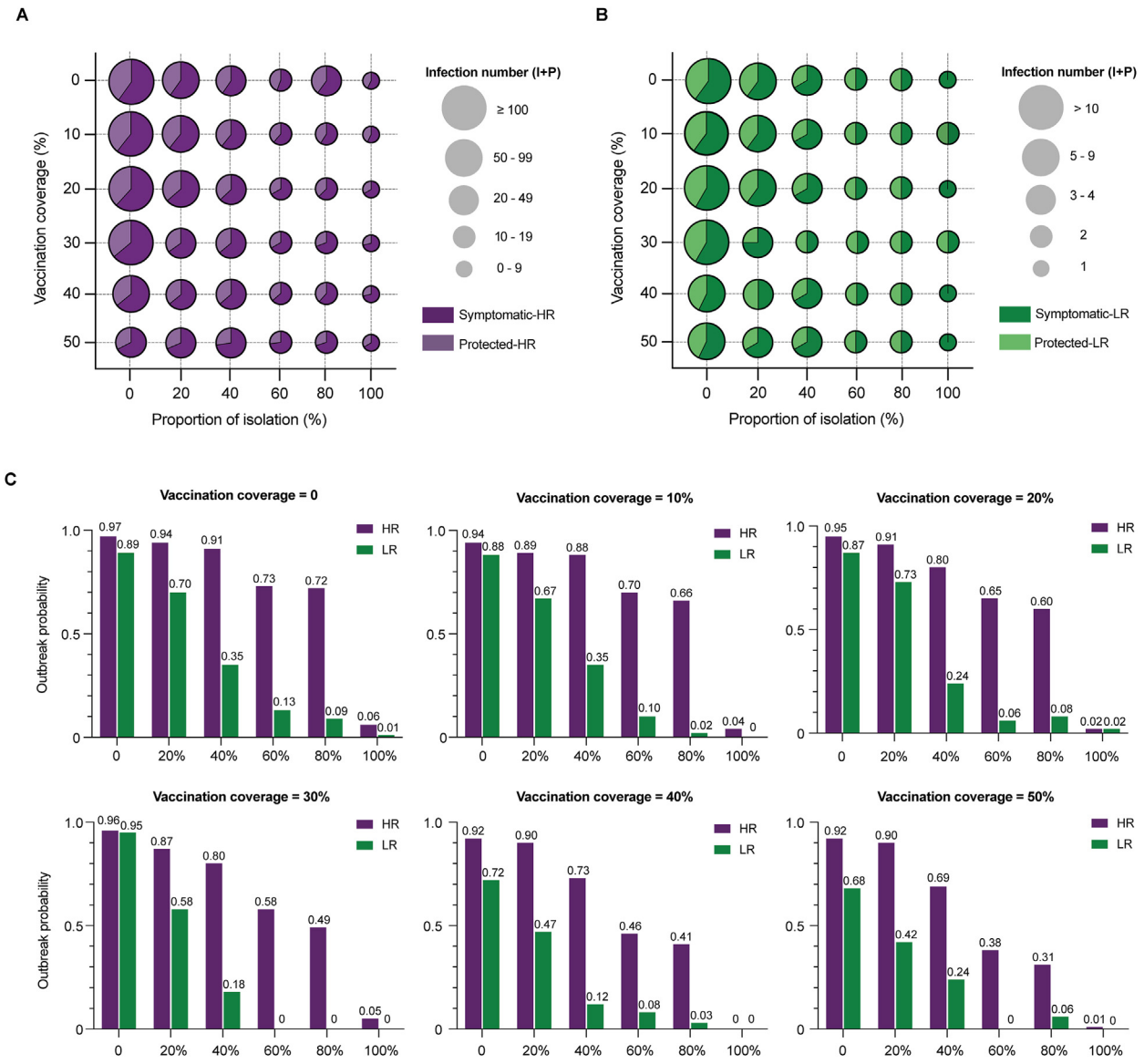


**Fig. 4.** Effectiveness of Isolation of Infected Cases as Emergency Measure for Inadequate Vaccination Coverage
(A) Cumulative number of infections in high-risk populations under interventions with different pre-exposure vaccination coverages in high-risk populations combined with different rates of isolation in infected cases. The size of the pie chart represents the cumulative number of infections. (B) Cumulative number of infections in low-risk populations under interventions with different pre-exposure vaccination coverages in high-risk populations combined with different rates of isolation in infected cases. The size of the pie chart represents the cumulative number of infections. (C) Likelihood of outbreaks with varying pre-exposure vaccination coverages and isolation rates. The horizontal bar graph coordinates represent the proportion of isolation. An outbreak was defined if > 1 additional cases occurred in addition to the initial number of infections. For each analysis, the model was run 200 times and the likelihood of an outbreak was calculated. Infection number (I + P) refers to the number of symptomatically infected individuals (I) and the latent individuals shielded by post-exposure vaccination (P). HR: high-risk; LR: low-risk.

of the outbreak was significantly reduced and could be effectively contained. The results demonstrate that even with a relatively low vaccination coverage rate, the outbreaks risk can be significantly reduced through the implementation of appropriate isolation measures.

When the PrEP coverage reached ≥30%, a 20% isolation ratio was required to effectively contain the cumulative number of infections. With PrEP coverage of 30%, 40%, and 50%, along with an isolation ratio of 20%, the predicted likelihood of outbreaks in the low-risk population was 58%, 47%, and 42%, respectively. When the vaccination coverage reached 40% or 50%, along with an isolation ratio of ≥60%, the predicted likelihood of outbreaks in the high-risk population dropped <50%. As the vaccination coverage rate increases, the required proportion of isolation can be reduced, which indicates that vaccination

**Table 1**
Effectiveness of isolation of infected symptomatic cases as emergency measure for inadequate vaccination coverage.

| Interventions | | Total Population | | High-Risk Group | | | | | | Low-Risk Group | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Cumulative infection number | | Cumulative infection number | | Symptomatic infection | | Protected individuals | | Cumulative infection number | | Symptomatic infection | | Protected individuals | |
| | | Mean Cases (IQR) | % | Mean Cases (IQR) | % | Mean Cases (IQR) | % | Mean Cases (IQR) | % | Mean Cases (IQR) | % | Mean Cases (IQR) | % | Mean Cases (IQR) | % |
| PrEV = 0% | Isolation = 0% | 289(272–365) | 5.25 | 269(255–337) | 53.80 | 165(143–199) | 33.00 | 104(93–129) | 20.80 | 20(17–28) | 0.40 | 12(8–15) | 0.24 | 8(4–10) | 0.16 |
| | Isolation = 20% | 90(78–112) | 1.64 | 85(75–104) | 17.00 | 49(40–63) | 9.80 | 33(27–38) | 6.60 | 5(3–8) | 0.10 | 3(2–4) | 0.06 | 2(1–3) | 0.04 |
| | Isolation = 40% | 46(32–66) | 0.84 | 43(30–62) | 8.60 | 25(16–35) | 5.00 | 17(12–21) | 3.40 | 3(2–4) | 0.06 | 2(1–2) | 0.04 | 1(1–2) | 0.02 |
| | Isolation = 60% | 20(11–27) | 0.36 | 18(10–25) | 3.60 | 10(6–13) | 2.00 | 8(4–10) | 1.60 | 2(1–2) | 0.04 | 1(1–2) | 0.02 | 1(0–1) | 0.02 |
| | Isolation = 80% | 22(11–30) | 0.40 | 20(10–28) | 4.00 | 12(6–15) | 2.40 | 8(5–12) | 1.60 | 2(1–2) | 0.04 | 1(1–2) | 0.02 | 1(0–1) | 0.02 |
| | Isolation = 100% | 8(6–9) | 0.15 | 7(5–8) | 1.40 | 4(2–6) | 0.80 | 3(2–4) | 0.60 | 1(1–1) | 0.02 | 1(0–1) | 0.02 | 0(0–1) | 0.00 |
| PrEV = 10% | Isolation = 0% | 233(187–317) | 4.24 | 216(175–294) | 43.20 | 126(101–169) | 25.20 | 82(68–107) | 16.40 | 17(12–23) | 0.34 | 10(5–14) | 0.20 | 7(5–9) | 0.14 |
| | Isolation = 20% | 79(66–100) | 1.44 | 74(63–94) | 14.80 | 43(34–55) | 8.60 | 28(25–34) | 5.60 | 5(3–6) | 0.10 | 3(1–3) | 0.06 | 2(1–3) | 0.04 |
| | Isolation = 40% | 37(23–52) | 0.67 | 34(21–48) | 6.80 | 20(12–28) | 4.00 | 13(8–18) | 2.60 | 3(2–4) | 0.06 | 2(1–3) | 0.04 | 1(1–2) | 0.02 |
| | Isolation = 60% | 20(11–27) | 0.36 | 18(10–25) | 3.60 | 11(6–15) | 2.20 | 7(4–9) | 1.40 | 2(1–2) | 0.04 | 1(0–1) | 0.02 | 1(0–1) | 0.02 |
| | Isolation = 80% | 19(12–24) | 0.35 | 17(11–22) | 3.40 | 10(6–11) | 2.00 | 7(4–9) | 1.40 | 2(1–2) | 0.04 | 1(0–1) | 0.02 | 1(0–1) | 0.02 |
| | Isolation = 100% | 9(7–10) | 0.16 | 7(6–8) | 1.40 | 4(3–5) | 0.80 | 3(2–3) | 0.60 | 2(1–2) | 0.04 | 1(0–1) | 0.02 | 1(0–1) | 0.02 |
| PrEV = 20% | Isolation = 0% | 168(96–240) | 3.05 | 156(90–222) | 31.20 | 92(49–132) | 18.40 | 57(31–76) | 11.40 | 12(6–18) | 0.24 | 7(3–11) | 0.14 | 5(3–7) | 0.10 |
| | Isolation = 20% | 73(59–86) | 1.33 | 68(56–80) | 13.60 | 42(33–49) | 8.40 | 24(20–29) | 4.80 | 5(3–6) | 0.10 | 3(2–3) | 0.06 | 2(1–2) | 0.04 |
| | Isolation = 40% | 30(15–39) | 0.55 | 27(14–36) | 5.40 | 17(8–25) | 3.40 | 10(6–13) | 2.00 | 3(1–3) | 0.06 | 2(1–2) | 0.04 | 1(0–1) | 0.02 |
| | Isolation = 60% | 17(10–22) | 0.31 | 15(9–20) | 3.00 | 10(5–13) | 2.00 | 5(3–7) | 1.00 | 2(1–2) | 0.04 | 1(1–1) | 0.02 | 1(0–1) | 0.02 |
| | Isolation = 80% | 18(9–25) | 0.33 | 16(8–22) | 3.20 | 10(5–14) | 2.00 | 6(3–8) | 1.20 | 2(1–3) | 0.04 | 1(0–2) | 0.02 | 1(0–1) | 0.02 |
| | Isolation = 100% | 7(6–8) | 0.13 | 6(5–7) | 1.20 | 4(3–5) | 0.80 | 2(1–3) | 0.40 | 1(1–1) | 0.02 | 1(0–1) | 0.02 | 0(0–1) | 0.00 |
| PrEV = 30% | Isolation = 0% | 154(120–191) | 2.80 | 142(113–177) | 28.40 | 87(62–110) | 17.40 | 49(37–59) | 9.80 | 12(7–14) | 0.24 | 7(4–8) | 0.14 | 5(2–6) | 0.10 |
| | Isolation = 20% | 52(31–71) | 0.95 | 48(29–66) | 9.60 | 30(18–43) | 6.00 | 16(11–22) | 3.20 | 4(2–5) | 0.08 | 3(1–3) | 0.06 | 1(1–2) | 0.02 |
| | Isolation = 40% | 27(12–40) | 0.49 | 25(11–37) | 5.00 | 16(6–22) | 3.20 | 9(5–13) | 1.80 | 2(1–3) | 0.04 | 1(0–2) | 0.02 | 1(0–1) | 0.02 |
| | Isolation = 60% | 17(10–22) | 0.31 | 15(9–20) | 3.00 | 10(5–14) | 2.00 | 5(3–6) | 1.00 | 2(1–2) | 0.04 | 1(1–1) | 0.02 | 1(0–1) | 0.02 |
| | Isolation = 80% | 15(9–17) | 0.27 | 13(8–15) | 2.60 | 9(5–10) | 1.80 | 4(3–6) | 0.80 | 2(1–2) | 0.04 | 1(0–1) | 0.02 | 1(0–1) | 0.02 |
| | Isolation = 100% | 9(6–9) | 0.16 | 7(5–7) | 1.40 | 5(3–5) | 1.00 | 2(1–3) | 0.40 | 2(1–2) | 0.04 | 1(0–1) | 0.02 | 1(0–1) | 0.02 |
| PrEV = 40% | Isolation = 0% | 89(53–124) | 1.62 | 82(50–114) | 16.40 | 50(28–72) | 10.00 | 28(18–39) | 5.60 | 7(3–10) | 0.14 | 4(1–6) | 0.08 | 3(1–4) | 0.06 |
| | Isolation = 20% | 43(26–61) | 0.78 | 39(24–56) | 7.80 | 25(13–37) | 5.00 | 14(9–18) | 2.80 | 4(2–5) | 0.08 | 2(1–3) | 0.04 | 2(1–2) | 0.04 |
| | Isolation = 40% | 25(11–34) | 0.45 | 22(10–31) | 4.40 | 14(5–20) | 2.80 | 8(5–10) | 1.60 | 3(1–3) | 0.06 | 2(1–2) | 0.04 | 1(0–1) | 0.02 |
| | Isolation = 60% | 13(8–14) | 0.24 | 11(7–12) | 2.20 | 7(4–9) | 1.40 | 4(2–5) | 0.80 | 2(1–2) | 0.04 | 1(0–1) | 0.02 | 1(0–1) | 0.02 |
| | Isolation = 80% | 14(8–17) | 0.25 | 12(7–15) | 2.40 | 8(5–9) | 1.60 | 5(3–6) | 1.00 | 2(1–2) | 0.04 | 1(0–2) | 0.02 | 1(0–1) | 0.02 |
| | Isolation = 100% | 7(6–8) | 0.13 | 6(5–7) | 1.20 | 5(4–6) | 1.00 | 2(1–3) | 0.40 | 1(1–1) | 0.02 | 1(0–1) | 0.02 | 0(0–1) | 0.00 |
| PrEV = 50% | Isolation = 0% | 73(39–106) | 1.33 | 66(36–98) | 13.20 | 43(23–64) | 8.60 | 21(11–30) | 4.20 | 7(3–8) | 0.14 | 4(1–5) | 0.08 | 3(1–4) | 0.06 |
| | Isolation = 20% | 39(23–54) | 0.71 | 36(21–49) | 7.20 | 24(15–33) | 4.80 | 11(7–15) | 2.20 | 3(2–5) | 0.06 | 2(1–3) | 0.04 | 1(1–2) | 0.02 |
| | Isolation = 40% | 26(15–34) | 0.47 | 23(13–31) | 4.60 | 16(10–21) | 3.20 | 6(4–8) | 1.20 | 3(2–3) | 0.06 | 2(1–2) | 0.04 | 1(1–2) | 0.02 |
| | Isolation = 60% | 13(8–15) | 0.24 | 11(7–13) | 2.20 | 8(5–10) | 1.60 | 3(2–4) | 0.60 | 2(1–2) | 0.04 | 1(1–2) | 0.02 | 1(0–1) | 0.02 |
| | Isolation = 80% | 12(7–13) | 0.22 | 10(6–11) | 2.00 | 7(4–8) | 1.40 | 3(2–4) | 0.60 | 2(1–2) | 0.04 | 1(0–1) | 0.02 | 1(0–1) | 0.02 |
| | Isolation = 100% | 7(6–7) | 0.13 | 6(5–6) | 1.20 | 4(3–5) | 0.80 | 2(1–2) | 0.40 | 1(1–1) | 0.02 | 1(0–1) | 0.02 | 0(0–1) | 0.00 |

PrEV = pre-exposure Vaccination coverage; Isolation refers to the proportion of isolation in symptomatic infected individuals (%).

plays a significant role in controlling the epidemic. Moreover, the results also emphasize the effectiveness of combining vaccination and isolation measures in epidemic management.

As shown in Table 1, we listed the number of symptomatic infections and the number of protected individuals for comprehensive strategies combining different PrEP rates with various isolation rates, to evaluate the effectiveness of different strategies against mpox outbreaks. The results highlight the importance of PrEP and isolating infected individuals, and the combination of measures listed in the table can provide decision support for healthcare professionals in mpox containment. Policymakers can assess and choose appropriate combination strategies based on actual medical resource capabilities.

## 4. Discussion

The 2022 global mpox outbreak has been recognized as the most regionally widespread and contagious mpox outbreak on record. Although there has been a steady decline in global case numbers, small clusters of cases continue to appear in certain countries and regions, which raises concerns among public health officials (Huang 2022). Specifically in China, the gradual resumption of cross-border population exchanges following the lifting of the strict international travel ban associated with COVID-19 has increased the risk of cross-border transmission of MPXV. Since May 2023, there has been a gradual increase in reported mpox cases in China, with 106 new cases reported in June and 491 in July (PREVENTION CCFDCA, 2023a; PREVENTION CCFDCA, 2023b). The case numbers have yet to show a downward trend, highlighting the need for vigilance and close monitoring of the situation. Furthermore, it is worth noting that while the mpox outbreak has not significantly affected college campuses thus far, occasional outbreaks of STIs and HIV have occurred among university students, particularly among MSM (Di Giulio & Eckburg 2004; Maria et al., 2023). Therefore, unless the disease is eradicated within China and imported cases are effectively eliminated, there remains a potential for mpox outbreaks on college campuses.

Our decision-support model can serve as a basis for contingency planning to assist college administrators in addressing potential mpox outbreaks within residential college campuses. Our study demonstrates that without intervention, an outbreak is highly probable, and it is therefore prudent to prepare for such an eventuality. Our findings suggest that, in the absence of PrEP, PEP of high-risk individuals during latent periods can partially reduce the number of infections. However, relying solely on PEP is not a sufficient strategy for preventing mpox outbreaks; PrEP is indispensable for certain high-risk groups. As the coverage of PrEP increases, there is a significant decrease in the number of infections. Achieving a PrEP coverage of $\geq$50% in the high-risk population holds promising potential for containing mpox. In situations where the coverage is <50%, isolating a certain percentage of infected individuals can be highly effective in minimizing the likelihood and severity of potential outbreaks. This study provides various options for implementing containment measures based on different levels of immunization and isolation conditions. Furthermore, the objective of this study is to provide university and college administrators with a framework for making informed decisions regarding interventions to contain future potential nascent outbreaks.

Mpox containment strategies should involve comprehensive interventions at various levels. It is crucial to prioritize early vaccination of high-risk populations and individuals who have been exposed to the virus. Guidelines were issued recommending PEP for all individuals who had direct or indirect contact with skin lesions or biological fluid of a confirmed infected patient. Additionally, those who were exposed to droplet risk, defined as spending more than 3 h within a 2-m proximity of an mpox-positive patient, were also encouraged to receive PEP (PRESSE 2022). These guidelines were later expanded to incorporate PrEP for specific at-risk populations, including MSM, transgender individuals with multiple sexual partners, people describing themselves as sex workers, and people working in sex service locations (HAS AEDDL, 2022). PEP has limited efficacy and must be administered within 4 days of exposure to achieve promising protective effectiveness (Thy et al). In contrast, PrEP demonstrates greater effectiveness in containing mpox outbreaks and rapidly reducing infection numbers. Therefore, increasing the immunization levels of high-risk groups through PrEP remains a vital intervention for mpox containment.

Increasing PrEP coverage in high-risk populations within a short timeframe poses a significant challenge. In situations where optimal vaccine coverage cannot be achieved, it becomes crucial to implement enhanced management measures (e.g., testing and isolation) for infected individuals. Our study suggests specific thresholds for PrEP coverage and isolation ratios to effectively contain outbreaks. According to our findings, when PrEP coverage is $\leq$ 20%, an Isolation ratio of 40% is necessary to effectively contain the outbreak. On the other hand, when PrEP rates reach $\geq$30%, combined with an isolation rate of 20%, the risk of an outbreak becomes significantly lower. To minimize further transmission, it is recommended that individuals diagnosed with mpox should practice self-isolation and avoid intimate close contact. However, case detection, early treatment and isolation are challenging due to the lack of convenient screening tools for MPXV and the reliance on self-reporting and contact tracing for chain-of-transmission (Sabeena). Therefore, it is essential to raise disease awareness and promote prompt medical consultation (Huang et al., 2022), ultimately improving the efficiency of case detection and isolation for mpox.

This study has several limitations. We made certain conservative simplified assumptions to facilitate model building and analysis. Firstly, we did not explicitly incorporate different agent roles and their varying levels of risk in the transmission. This simplification was made to enhances the generalizability of the results. Secondly, due to limited sources of real data on this multi-country mpox outbreak, it is difficult to obtain sufficient from a single source, and combining parameter values from different sources may result in discrepancies with the actual situation. More original studies of systematic assessment are needed in the future with a view to providing a reliable basis for modeling studies. In addition, it is challenging to

comprehensively consider all the influencing factors, evolutionary mechanisms, or simulate a real-world outbreak. Importation of cases, sex structures, and exposure patterns were not taken into account in this study, which should be included in future research.

## 5. Conclusion

In conclusion, the containment of mpox outbreaks should primarily focus on managing high-risk populations and infected individuals. Relying solely on PEP has shown limited efficacy in containing mpox, underscoring the necessity of PrEP among high-risk populations before an outbreak occurs. Such proactive measures are crucial for increasing population immunity levels and safeguarding susceptible populations. Moreover, in situations where the desired vaccination coverage is not achieved, enhanced case detection and isolation strategies can serve as effective emergency responses to contain mpox outbreaks. There is currently limited modeling available for mpox outbreaks outside endemic regions. This analysis presents a valuable framework for quantitative targets toward mpox containment. Consequently, our study carries significant implications for preventing future mpox outbreaks.

## Conflict of interest Disclosures

Qiangru Huang, Yanxia Sun, Mengmeng Jia, Mingyue Jiang, Yunshao Xu, Luzhao Feng, and Weizhong Yang declare that they have no conflict of interest or financial conflicts to disclose.

## Funding/support

This study was supported by grants from the Chinese Academy of Medical Sciences (CAMS) Innovation Fund for Medical Sciences (2021-I2M-1–044).

## Role of the funder/sponsor

The funders had no role in the design and conduct of the study; collection, management, analysis, and interpretation of the data; preparation, review, or approval of the manuscript; and decision to submit the manuscript for publication.

## Data sharing statement

The study's source codes are available online (https://github.com/hqraiwxy/Containment_Strategy_Mpox).

## CRediT authorship contribution statement

**Qiangru Huang:** Formal analysis, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing, Conceptualization. **Yanxia Sun:** Formal analysis, Methodology, Software, Writing – original draft, Writing – review & editing, Conceptualization. **Mengmeng Jia:** Data curation, Methodology, Writing – original draft, Writing – review & editing. **Mingyue Jiang:** Methodology, Software, Writing – original draft. **Yunshao Xu:** Data curation, Writing – original draft, Writing – review & editing. **Luzhao Feng:** Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Weizhong Yang:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Supervision, Writing – original draft, Writing – review & editing.

## Acknowledgments

The co-authors would extend their heartfelt thanks to all the individuals who generously shared their time and materials for this study.

## Appendix ASupplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.idm.2024.04.004.

## References

A, D. (2022). Concern about monkeypox spread shifts to college campuses. Available at: www.axios.com/2022/09/15/monkeypox-spread-college-campuses. (Accessed 15 September 2022).

Branda, F., Pierini, M., & Mazzoli, S. (2023). *Monkeypox: Early estimation of basic reproduction number R0 in Europe*.

DHS SCIENCE AND TECHNOLOGY. (2022). Master Question list for monkeypox virus. www.dhs.gov/science-and-technology/publication/st-master-question-list-monkeypox. (Accessed 29 July 2022). Published 2022.

Di Giulio, D. B., & Eckburg, P. B. (2004). Human monkeypox: An emerging zoonosis. *The Lancet Infectious Diseases, 4*, 15–25. https://doi.org/10.1016/s1473-3099(03)00856-9

Fine PE, Jezek Z Fau - Grab B, Grab B Fau - Dixon H, and Dixon H. The transmission potential of monkeypox virus in human populations.
Guarner J, Del Rio C, and Malani PN. Monkeypox in 2022-What Clinicians need to Know.
Gupta AA-O, Talukder M, Rosen T, and Piguet V. Differential diagnosis, prevention, and treatment of mpox (monkeypox): A review for Dermatologists.
HAS AEDDL. (2022). Avis n°2022.0039/AC/SESPEV du 7 juillet 2022 du collège de la Haute Autorité de santé relatif à la vaccination contre le virus Monkeypox en préexposition des personnes à haut risque d'exposition. Available at: https://www.has-sante.fr/jcms/p_3351308/fr/avis-n2022-0039/ac/sespev-du-7-juillet-2022-du-college-de-la-haute-autorite-de-sante-relatif-a-la-vaccination-contre-le-virus-monkeypox-en-preexposition-des-personnes-a-haut-risque-d-exposition2022.
Huang, Q. (2022). Risk assessment of cross-border transmission of Monkeypox in 2022. Available at: https://github.com/hqraiwxy/MPX.
Huang, Q. (2023). Containment strategy mpox. Available at: https://github.com/hqraiwxy/Containment_Strategy_Mpox2023.
Huang, Q., Jia, M., Feng, L., & Yang, W. (2022). Recent situation of monkeypox outbreaks abroad and suggestions for epidemic containment in China. *Chinese Journal of Viral Diseases, 12*, 241–244. https://doi.org/10.16505/j.2095-0136.2022.0027
Jm, J. (2022). LGBT identification in U.S. ticks up to 7.1%. Gallup. Available at: https://news.gallup.com/poll/389792/lgbt-identification-ticks-up.aspx2022.
Maria, X., Fuminari, M., Philippe, A., Eline, O.de C., John, de W., & Jacco, W. (2023). The fading of the mpox outbreak among men who have sex with men: A mathematical modelling study. *medRxiv.* , Article 23285294. https://doi.org/10.1101/2023.01.31.23285294, 2023.2001.2031.
Mossong J, Hens N Fau - Jit M, Jit M Fau - Beutels P, et al. Social contacts and mixing patterns relevant to the spread of infectious diseases.
Presse, C. D. (2022). Monkeypox : vacciner les adultes et professionnels de santé après une exposition à la maladie. Available at: https://www.has-sante.fr/jcms/p_3340419/fr/monkeypox-vacciner-les-adultes-et-professionnels-de-sante-apres-une-exposition-a-la-maladie.
PREVENTION CCFDCA. (2023a). Monkeypox outbreak surveillance for June 2023. Available at: https://www.chinacdc.cn/jkzt/crb/qt/szkb_13037/gwjszl_13092/202307/t20230714_267790.html. (Accessed 14 July 2023).
PREVENTION CCFDCA. (2023b). Mpox outbreak surveillance for july 2023. Available at: https://www.chinacdc.cn/jkzt/crb/qt/szkb_13037/gwjszl_13092/202308/t20230809_268502.html. (Accessed 9 August 2023).
Prevention CfDCa. (2022a). Incidence, prevalence, and cost of sexually transmitted infections in the United States. Available at: www.cdc.gov/nchhstp/newsroom/fact-sheets/std/STI-Incidence-Prevalence-Cost-Factsheet.html. (Accessed 19 November 2022).
Prevention CfDCa. (2022b). Interim clinical Considerations for Use of JYNNEOS and ACAM2000 vaccines during the 2022 U.S. Mpox outbreak. Available at: www.cdc.gov/poxvirus/monkeypox/clinicians/smallpox-vaccine.html#anchor_1545415186164. (Accessed 19 October 2022).
Prevention CfDCa. (2022c). *Mpox (monkeypox) and smallpox vaccine guidance.2022*.
Prevention CfDCa. (2022d). Mpox Toolkit for Institutions of higher education. Available at: www.cdc.gov/poxvirus/monkeypox/community/higher-education.html. (Accessed 18 October 2022).
Reynolds, M. G., Davidson Wb Fau - Curns, A. T., Curns At Fau - Conover, C. S., Conover Cs Fau - Huhn, G., Huhn, G., Fau - Davis, J. P., Davis Jp Fau - Wegner, M., Wegner, M., Fau - Croft, D. R., Croft, D. F.-N. A., Newman, A., Fau - Obiesie, N. N., Obiesie Nn Fau - Hansen, G. R., Hansen, G., Fau - Hays, P. L., Hays Pl Fau - Pontones, P., Pontones, P., Fau - Beard, B., Beard, B., … Damon, I. K. (2003). *Spectrum of infection and risk factors for human monkeypox*. United States.
Rimoin AW, Mulembakani Pm Fau - Johnston SC, Johnston S. Fau - Lloyd S.JO, Lloyd Smith Jo Fau - Kisalu NK, Kisalu N.F.-K.TL, Kinkela T.F.-B.S, Blumberg S Fau - Thomassen HA, Thomassen Ha Fau - Pike BL, Pike Bl Fau - Fair JN, Fair J. Fau - Wolfe ND, Wolfe N. Fau - Shongo RL, Shongo Rl Fau - Graham BS, Graham Bs Fau - Formenty P, Formenty P Fau - Okitolonda E, Okitolonda E Fau - Hensley LE, Hensley Le Fau - Meyer H, Meyer H Fau - Wright LL, Wright Ll Fau - Muyembe J-J, and Muyembe JJ. Major increase in human monkeypox incidence 30 years after smallpox vaccination campaigns cease in the Democratic Republic of Congo.
Sabeena SA-O. The changing epidemiology of monkeypox and preventive measures: An update.
Savinkina, A., Chitwood, M., & Kwon, J. (2023). *Planning for mpox on a college campus: A model-based decision-support tool*.
Taylor, S. (2022). Monkeypox infections reported by colleges raise concerns of campus spread. https://www.yorkdispatch.com/story/news/2022/09/12/monkeypox-infections-reported-colleges-raise-concerns-campus-spread/50729173/2022.
Thy MA-OX, Peiffer-Smadja N, Mailhe M, Kramer L, Ferré VM, Houhou N, Tarhini H, Bertin C, Beaumont AL, Garé M, Le Pluart D, Perrineau S, Rahi M, Deconinck L, Phung B, Mollo B, Cortier M, Cresta M, De La Porte Des Vaux C, Joly V, Lariven S, Rioux C, Somarriba C, Lescure FX, Charpentier C, Yazdanpanah Y, and Ghosn J. Breakthrough infections after Postexposure vaccination against mpox.
Wenham, C., & Eccleston-Turner, M. (2022). Monkeypox as a PHEIC: Implications for global health governance. *The Lancet*. https://doi.org/10.1016/S0140-6736(22)01437-4
(WHO) WHO. (2022). 2022 mpox (monkeypox) outbreak: Global trends. Available at: https://worldhealthorg.shinyapps.io/mpx_global/. (Accessed 20 July 2023).
(WHO) WHO. (2022a). Multi-country monkeypox outbreak: Situation update. Available at: https://www.who.int/emergencies/disease-outbreak-news/item/2022-DON396. (Accessed 27 June 2022).
(WHO) WHO. (2023). 2022-23 mpox (monkeypox) outbreak: Global trends. Available at: https://worldhealthorg.shinyapps.io/mpx_global/. (Accessed 14 August 2023).
(WHO) WHO. (2024). 2022-23 mpox (monkeypox) outbreak: Global trends. Available at: https://worldhealthorg.shinyapps.io/mpx_global/#1_Overview. (Accessed 14 February 2024).
(WHO) WHO. (2024a). *Surveillance, case investigation and contact tracing for mpox (monkeypox)*. Available at: https://iris.who.int/bitstream/handle/10665/376306/WHO-MPX-Surveillance-2024.1-eng.pdf?sequence=1. (Accessed 14 February 2024).
Wolff Sagy Y, Zucker R, Hammerman AA-O, Markovits H, Arieh NG, Abu Ahmad W, Battat E, Ramot N, Carmeli G, Mark-Amir A, Wagner-Kolasko G, Duskin-Bitan H, Yaron S, Peretz A, Arbel RA-O, Lavie G, and Netzer D. Real-world effectiveness of a single dose of mpox vaccine in males.
Yale. (2022). By the numbers. www.yale.edu/about-yale/yale-facts. (Accessed 20 July 2023).