BMJ Public Health

Modelling the potential spread of Clade Ib MPXV in Asian cities

Shihui Jin ,[1] Gregory Gan,[1] Akira Endo,[1,2,3] Kiesha Prem,[1,2] Rayner Kay Jin Tan,[1] Jue Tao Lim,[4] Keisuke Ejima,[4] Borame L Dickens[1]

To cite: Jin S, Gan G, Endo A, *et al*. Modelling the potential spread of Clade Ib MPXV in Asian cities. *BMJ Public Health* 2025;**3**:e002285. doi:10.1136/bmjph-2024-002285

► Additional supplemental material is published online only. To view, please visit the journal online (https://doi.org/10.1136/bmjph-2024-002285).

Received 5 November 2024
Accepted 31 March 2025

[1]Saw Swee Hock School of Public Health, National University of Singapore, Singapore
[2]Department of Infectious Disease Epidemiology, London School of Hygiene & Tropical Medicine, London, UK
[3]Nagasaki University, Nagasaki, Nagasaki, Japan
[4]Lee Kong Chian School of Medicine, Nanyang Technological University, Singapore

Correspondence to
Dr Borame L Dickens;
ephdbsl@nus.edu.sg

ABSTRACT

Background The ongoing 2023–2024 mpox outbreak in several African countries, driven by the novel Clade Ib strain, has resulted in imported cases being reported in Sweden, Thailand and India. The potential high transmissibility of this new strain and shifts in transmission modes may make territories in Asia, which were minimally affected by previous mpox waves, susceptible to community-wide transmission following importation. While this highlights the importance of early preparedness, current knowledge of the virus's transmission dynamics remains too limited to effectively inform policymaking and resource planning.

Methods A compartmental model was constructed to characterise potential mpox transmission dynamics. Importation-triggered outbreaks were simulated in 37 Asian cities under scenarios with one, three and five initial local infections. The impacts of various non-pharmaceutical interventions (NPIs), including isolation and quarantine, were projected and compared.

Findings Our simulations revealed substantial disparities in outbreak sizes among the 37 Asian cities with large-scale outbreaks expected in territories with a high proportion of sexually active individuals at risk or low immunity from smallpox vaccination. Total case counts in 1 year following initial local infections would increase linearly with initial infection size. In the scenario with three initial local infections, up to 340 cases per million residents were expected without interventions. Isolation for diagnosed cases was projected to lower the outbreak size by 43.8% (IQR: 42.7–44.5%), 67.8% (IQR: 66.5–68.9%), 80.8% (IQR: 79.5–82.0%) and 88.0% (IQR: 86.8–89.1%) when it reduced interpersonal contacts by 25%, 50%, 75% and 100%, respectively. Quarantining close contacts would contribute to a further decrease in cases of up to 22 percentage points over 1 year.

Interpretation A potential mpox outbreak in an Asian setting could be alleviated through strong surveillance and a timely response from stakeholders. NPIs are recommended for outbreak management due to their demonstrated effectiveness and practicability.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Clade Ib monkeypox virus is circulating in the Democratic Republic of the Congo and its neighbouring countries, with imported cases being identified globally. Meanwhile, evidence indicates that the virus can be transmitted through both sexual and non-sexual routes, raising concerns about its potential spread in the general population. To prevent a global outbreak, WHO suggested countries around the globe to prepare in advance.

WHAT THIS STUDY ADDS

⇒ Our simulations quantified the potential disease burden of an mpox outbreak triggered by a once-time importation event in 37 major Asian cities with varying pre-existing immunity levels and populations at higher risk due to frequent sexual activities. The compartmental modelling framework developed in this study also projected the effectiveness of diverse non-pharmaceutical intervention (NPI) strategies in outbreak control, providing policymakers with guidance for effective public health crisis management.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ An importation-triggered mpox outbreak can be substantially mitigated with powerful disease surveillance and a prompt response of the stakeholders, but may also lead to severe consequences with high morbidity and mortality if not addressed in time in cities with a large highly sexually active population. Various NPIs, particularly isolating infected cases, are recommended for curbing the disease outbreak due to their feasibility and effectiveness in the Asian setting.

INTRODUCTION

An outbreak caused by Clade I monkeypox virus (MPXV) was estimated to have emerged in September 2023 in South Kivu province,[1] Democratic Republic of the Congo (DRC), with transmission likely driven primarily by sexual contact. The novel strain of the outbreak, later designated as Clade Ib, resulted in surging cases reported in the DRC, alongside the endemic Clade Ia already circulating in other provinces, and quickly spread to neighbouring African countries, including Burundi, Rwanda, Uganda and Kenya. As of September 2024, importation has also been detected outside the African continent, in Sweden, Thailand and India.[2 3] In response to the rapid spread of Clade Ib in Africa, WHO

re-declared mpox as a public health emergency of international concern, aiming to raise the global awareness and prevent a repeat of the 2022 mpox outbreak, whose global circulation could potentially be attributed to initial negligence in surveillance and prevention.[4]

During the 2022 wave caused by Clade IIb MPXV, over 90% of the cases reported were from Europe and the Americas. In contrast, the Western Pacific, Southeast Asia and Eastern Mediterranean regions—encompassing most Asian countries—collectively accounted for fewer than 5% of all Clade IIb cases.[5] While the possibility of high under-ascertainment exists due to the limited surveillance efforts and reluctance in seeking medical help due to stigmas associated with the infection,[6] the proportion of the population in Asia with active infection-induced immunity against the virus is still likely to be much lower compared with other regions of the world with higher cumulative prevalence.

While Clade IIb MPXV was predominantly spread through sexual transmission within the gay, bisexual and other men-who-have-sex-with-men (GBMSM) community,[7] heterosexual contact appears to play a more critical role in the ongoing 2023–2024 mpox outbreak driven by Clade Ib in the DRC and neighbouring countries as female cases, especially sexual workers, comprised approximately half of all the confirmed infections.[1 8] Apart from the well-documented sexual mode of transmission, evidence from the ongoing outbreak, including the non-trivial contribution of children to reported case counts, has suggested potential higher prevalence of non-sexual transmission routes compared with the previous 2022 outbreak.[8–10] These two possible changes in transmission modes, together with the high global connectivity and international travel, raise the risk of an importation-triggered mpox outbreak affecting the general population, particularly in an Asian setting with minimal prior exposure to the virus.

Throughout the COVID-19 pandemic, territories in Asia gained valuable experience in implementing non-pharmaceutical interventions (NPIs).[11 12] Social distancing measures like quarantine and isolation, which reduced interpersonal contact, effectively contained the disease transmission.[13] These successful stories offer hope for the authorities in this area to leverage NPIs to curb a potential mpox outbreak, should it become widespread in the general community. Furthermore, the absence of definitive evidence for respiratory transmission[14] for MPXV implies that effective outbreak management might be achieved through less stringent NPIs, such as isolating infected individuals, compared with those implemented during the COVID-19 pandemic.

Nevertheless, few NPIs were applied to manage the 2022 mpox outbreak, which affected only a limited subpopulation. This creates great uncertainty about their true effectiveness and sufficiency in averting a more widespread mpox outbreak once it establishes itself in the general population. In addition, the distinct transmission patterns of Clade Ib MPXV, especially regarding the prolonged infectious duration and the combination of sustained transmission through sexual and non-sexual routes,[10 15] make it challenging to directly extrapolate the impacts of these containment measures from COVID-19 surveillance data.

To address these gaps, we performed this study to model potential mpox outbreaks in 37 Asian cities, covering all key territories in this region. We collected territory-specific data on the immunity levels from smallpox vaccination, age structure and sexually active populations which were assumed to be of higher transmission risk. These statistics enabled us to simulate importation-triggered outbreaks using a modified deterministic susceptible-exposed-infectious-recovered (SEIR) model and the transmissibility parameters estimated from the surveillance data in the DRC. We further projected the impacts of NPIs on curbing outbreaks and reducing disease burden. These results collectively provide insights into factors shaping the outbreak dynamics, informing policymakers of strategies to pre-empt or mitigate mpox transmission across the continent.

METHODS

SEIR-style transmission model

We adapted a deterministic SEIR compartmental model to characterise potential disease transmission patterns, as shown in figure 1. Additional compartments, including quarantined (Q), diagnosed (C) and dying (D), were incorporated into the model to facilitate a more accurate reflection of a real-world outbreak, with disease surveillance, variations in disease burden among individuals and the probable presence of intervention measures. Nevertheless, the number of individuals transitioning to compartment Q from the other compartments was calculated separately at each time step, rather than being solved simultaneously with the differential equation system.

To account for the possible disparity in transmission potential of mpox via community and additional sexual contacts and heterogeneity in contact patterns within the population, we segregated the affected population into two groups: high-risk (H) and low-risk (L) individuals. Compared with low-risk individuals (the general population), high-risk people were assumed to have an increased infection risk due to higher contact rates within this subpopulation, primarily driven by more frequent sexual contacts. Diagnostic rate and disease severity were not distinguished between these two groups.

Infections who underwent clinical testing would be diagnosed and reported, while those untested were assumed to have mild symptoms and would recover without medical assistance. Both groups were assumed to have the same infectious period, which was later varied in a sensitivity analysis (online supplemental figure S1–S2). We further stratified the diagnosed cases by severity. The majority (97%) were expected to have mild symptoms and be able to recover, while the remaining 3% were at

high risk of death,[2] with their survival status depending on the accessibility of medical resources.

Intervention measures built into the model include isolating diagnosed cases and quarantining the close contacts of confirmed cases. Both groups were presumed to have limited daily interactions with others. Please refer the section 'Intervention effect projection' and online supplemental file 1 for more details.

Outbreak simulations for Asian cities

Using the established compartmental model, we simulated potential mpox outbreaks in 37 major municipals across Asia, each being either the capital or with the largest population size in its respective territory. We set the average number of secondary infections generated by an infector through community and additional sexual contacts in a fully susceptible population to be 1.02 (R_c) and 1.62 (R_s), respectively, implicitly presuming uniform baseline disease transmissibility across different territories. These values were derived from the estimated overall effective reproduction number and contributions of the two transmission routes during the 2024 mpox outbreak in South Kivu.[16] This extrapolation assumed that Clade Ib MPXV transmission in the local community in Asian cities would mirror the patterns observed in South Kivu except for the population-level immunity from smallpox vaccination or composition of high-risk and low-risk individuals. Using this combination of R_s and R_c and other predetermined parameter values (online supplemental table S1–S2), we simulated the number of deaths and compared the model predictions with the confirmed death counts in South Kivu, the DRC,[17] to validate this model at least within its original context (online supplemental figures S3–S4, tables S3–S4). Our simulated trajectory traced the index animal-to-human transmission event back to September 2023, which is consistent with the findings in literature,[1] substantiating the plausibility of the model and the corresponding parameter values used in projection.

Given the uncertainties surrounding travel volumes and interactions between travellers and local residents, we initiated the importation-triggered outbreaks by modelling the outcome of a one-time importation event, in which one or more susceptible individuals in the city were converted to exposed status. These individuals are henceforth referred to as *initial local infections*. We assumed no pre-existing exposed or active infections in the population prior to the importation. Neither did we account for cross-protection from previous mpox outbreaks due to the limited exposure to previous waves among individuals outside the GBMSM community and the few documented mpox cases in the region.[5] However, protection from smallpox vaccines was considered given their high efficacy and proven ability to prevent mpox infections, particularly among individuals aged over 45 years.[18 19] In our model, smallpox vaccines were treated as a leaky vaccine, where a reduced risk of infection was assumed among vaccinated individuals,[20] while the alternative assumption of an all-or-nothing vaccine was evaluated in a sensitivity analysis (online supplemental figure S5–S6). We obtained the territory-specific and age-specific vaccination rates in 2024 using the model developed by Taube *et al*[21] and aggregated the overall population immunity level using the United Nations age distribution data[22] and a geospatial-invariant 80.7% vaccine effectiveness,[21] based on which we scaled R_s and R_c to obtain city-specific risks of infection.

Following the approach of Murayama *et al*,[16] we approximated the size of the high-risk subpopulation by considering the number of sex workers and their male clients as they were more likely to engage in higher frequencies of sexual activity compared with the general population, thus more likely to contract the disease or infect others. Territory-specific sex worker statistics were collected from the Joint United Nations Programme on HIV/AIDS (UNAIDS) and the International Union of Sex Workers,[23 24] while the estimated proportions of clients among males aged 15–49 years were obtained from Carael *et al*.[25] We further assumed that males comprised half of the population in each city and that all high-risk individuals fell in the age group of 15–49 years. Based on these assumptions, we calculated the proportions of sexually active individuals at high risk in each territory

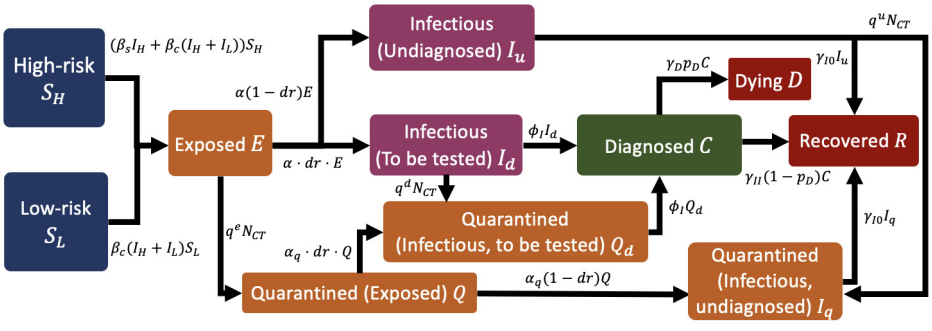

Figure 1 Model schematic. $I_H = I_{uH} + I_{dH} + (1 - c_{iso})(C_H + Q_{dH} + I_{qH})$ and $I_L = I_{uL} + I_{dL} + (1 - c_{iso})(C_L + Q_{dL} + I_{qL})$ refer to the effective infectious high-risk active and low-risk subpopulations, respectively, where c_{iso} is the reduction in the capacity of disease spreading due to quarantine or isolation and equals 0 in the absence of them. N_{CT} is the number of traced close contacts, whose value depends on contact tracing capacity, number of newly diagnosed cases and existing infected population. See online supplemental table S1–S2 for more details for these parameters.

and their corresponding immunity level. To account for the potential bias in the territory-specific estimates due to limited data and potential temporal changes in the statistics,[25] we additionally conducted a sensitivity analysis to explore how variations in the high-risk population could shape the outbreak dynamics in each city (online supplemental figures S7–S10).

We first simulated the outbreaks initiated by a single local infection resulting from a one-time importation event, modelling the scenarios in which the index infection occurred in either the low-risk or high-risk subpopulation. To assess the impact of importation size on disease transmission, we generated epidemic curves for the initial local infection sizes of one, three and five. We set the probability of each initial local infection belonging to the high-risk group to be equal to the proportion of high-risk individuals within the overall population, assuming that initial local infections were all acquired through community contact. Nevertheless, we performed a sensitivity analysis to test this assumption, in which varying numbers of initial infections belonged to the high-risk group (online supplemental figures S11–S13). We did not assume any subsequent importation events or the implementation of NPIs (eg, isolation or quarantine) in these scenarios.

Intervention effect projection

We evaluated two community-level NPIs: mandatory stay-at-home requirement for diagnosed cases (henceforth referred to as 'isolation') and quarantine of their close contacts captured by contact tracing (henceforth referred to as 'quarantine'). These measures aimed at segregating the susceptible population from the detected infections and individuals exposed but not yet infectious, thereby reducing the risk of secondary infection.

Two intervention strategies, including

1. Isolation alone and
2. Isolation combined with quarantine

were proposed and assessed under the scenario of three initial local infections due to a one-time importation event. For each strategy, four levels of quarantine or isolation effectiveness were assessed, in which the segregation was expected to reduce contacts between the susceptible and quarantined or isolated individuals by 25%, 50%, 75% or 100%. The varying isolation effectiveness levels would allow for potential secondary infection of close contacts due to incomplete adherence, particularly in the case when community transmission is an established pathway of transmission.[10] Further details regarding these NPIs are elaborated in online supplemental file 1.

We simulated epidemic trajectories over a 5-year (ie, 60-month) period for all the aforementioned scenarios, from which we derived statistics to reflect epidemic growth and outbreak size, including cumulative infections, cases or potential deaths within 1 or 5 years following the initial local infection(s). Region-level trends were summarised as medians and IQRs of the 37 city-specific projections. All the analyses and visualisation were performed using the R software.[26] Data and analytical scripts are available at https://github.com/ShihuiJin/mpox_SEIR.[27]

Patient and public involvement

None.

RESULTS

Susceptibility profiles of the 37 territories

The size of the susceptible population varied substantially across the 37 territories. Under the assumption of an 80.7% vaccine effectiveness, 34 territories had higher immunity levels due to smallpox vaccines compared with the DRC, with 27 having 75–90% of their population remaining susceptible to MPXV. Territories in East Asia, including China, Hong Kong SAR, Japan, South Korea and Taiwan, had the lowest percentages of susceptible population, at 60–70%. Nevertheless, the proportion of high-risk susceptible individuals was relatively larger in these territories, with at least 1.5% belonging to this subpopulation. Several Southeast Asian territories, such as Thailand, Cambodia, Laos and Singapore, also had relatively high proportions of high-risk susceptible subpopulations, accounting for over 2% of the total population. This was particularly true in Thailand, where the proportion reached a high value of 2.9%. In contrast, the high-risk susceptible subpopulation was relatively small in many territories in Central and West Asia, hovering around or even below 1% (figure 2).

Outbreak scale under the scenario involving one initial local infection

When the index local infection with Clade Ib MPXV occurred in the low-risk group, Phnom Penh and Vientiane were identified as the two cities with the highest risk of large-scale outbreaks, with projected case counts exceeding 50 within 1 year following the index local infection. A significantly larger outbreak size would be expected were the index local infection a high-risk individual, with over 200 cases expected in any of the 37 cities within the same timeframe. Four cities—Phnom Penh, Dubai, Vientiane and Manila—were projected to experience outbreaks with over 1500 cases, while a few other cities in East and Southeast Asia, such as Taipei, Hong Kong and Jakarta, would be relatively less affected (figure 3). However, the ultimate scale of the outbreak by the end of the wave was minimally influenced by whether the initial local infection occurred in the high-risk or low-risk group (online supplemental figure S14).

Impact of importation size on local transmission

The risk of experiencing large-scale outbreaks remained consistent across scenarios with varying initial local infection sizes, with the number of infections, cases or deaths in 1 year linearly correlated with the number of initial local infections. Specifically, in any city, an outbreak triggered by five initial local infections would result in approximately five times the number of infections within

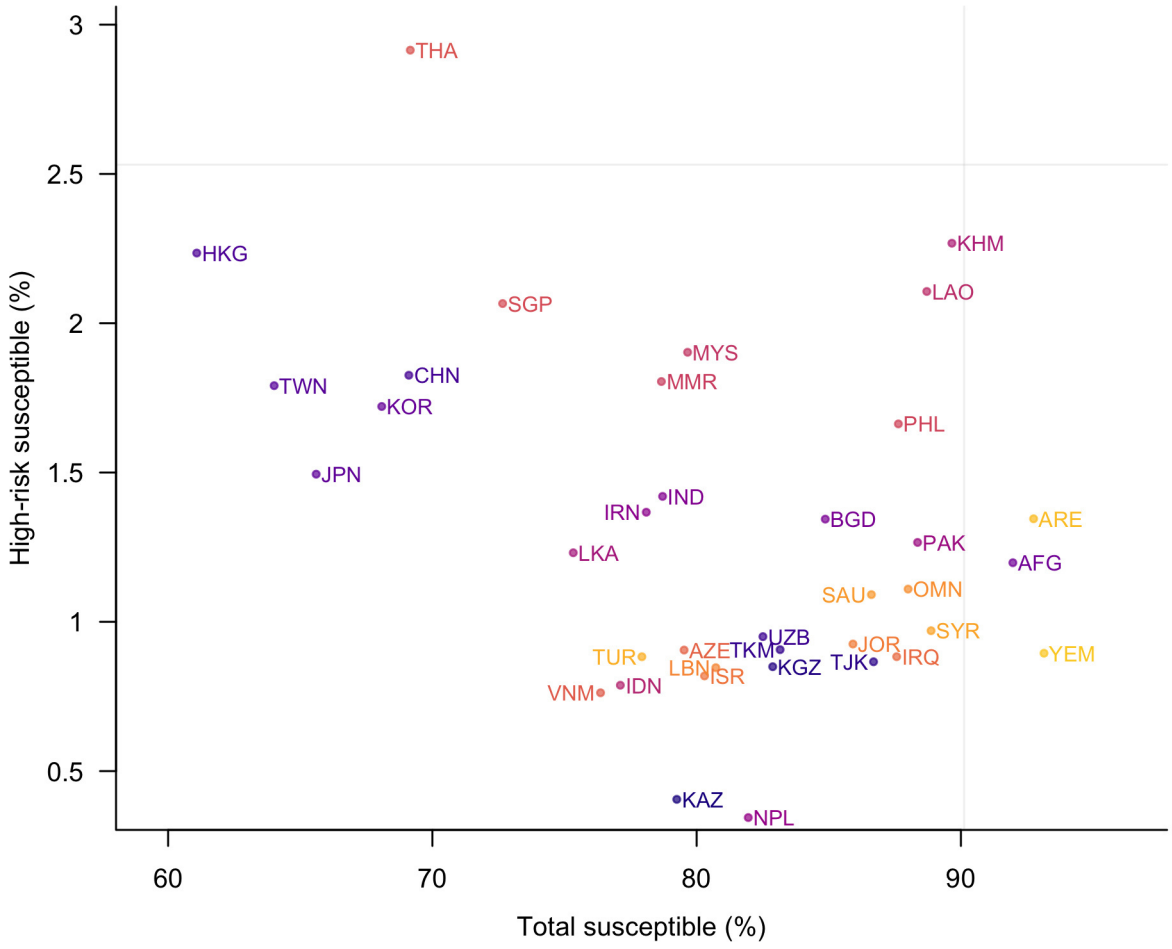

Figure 2 Proportion of total susceptible population (x-axis) and that of high-risk susceptible individuals (y-axis) in each territory. A vaccine effectiveness rate of 80.7% was assumed for smallpox vaccines. Territories within the same subregion (Central, East, Southeast, Southern or West Asia) are represented by similar colours. The grey horizontal and vertical lines indicate the respective statistics in the Democratic Republic of the Congo. Please refer online supplemental table S2 for the full names of the territories.

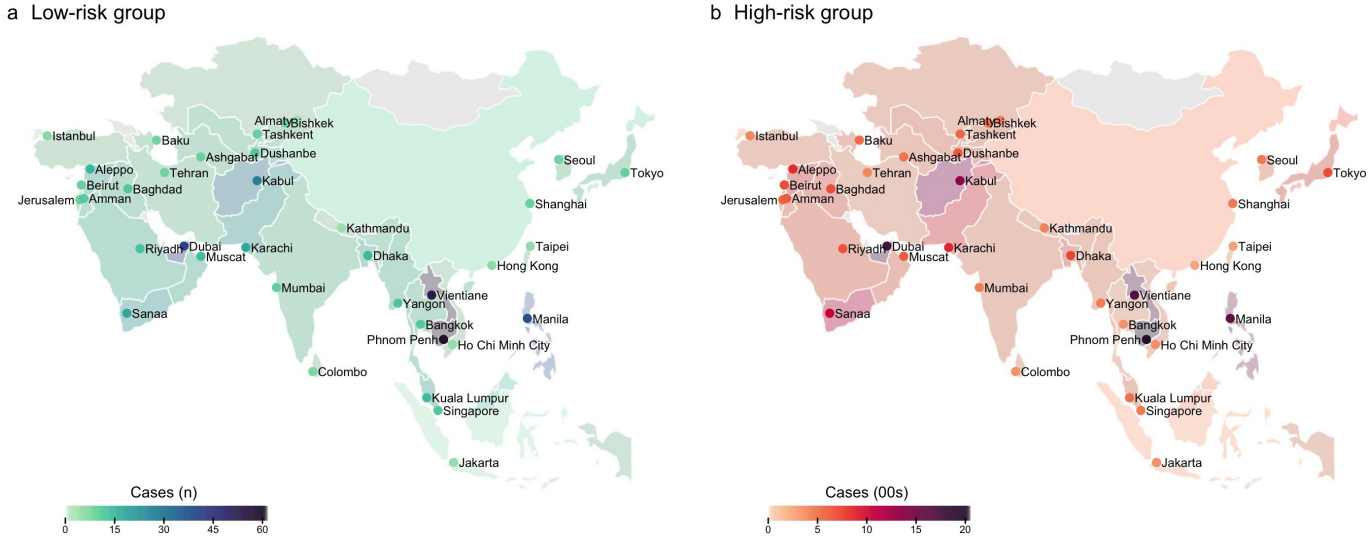

Figure 3 Outbreak sizes in 1 year. They are measured by total number of infections in 1 year following the initial local infection when the infection belonged to either the (a) low- or (b) high-risk group, across the 37 cities.

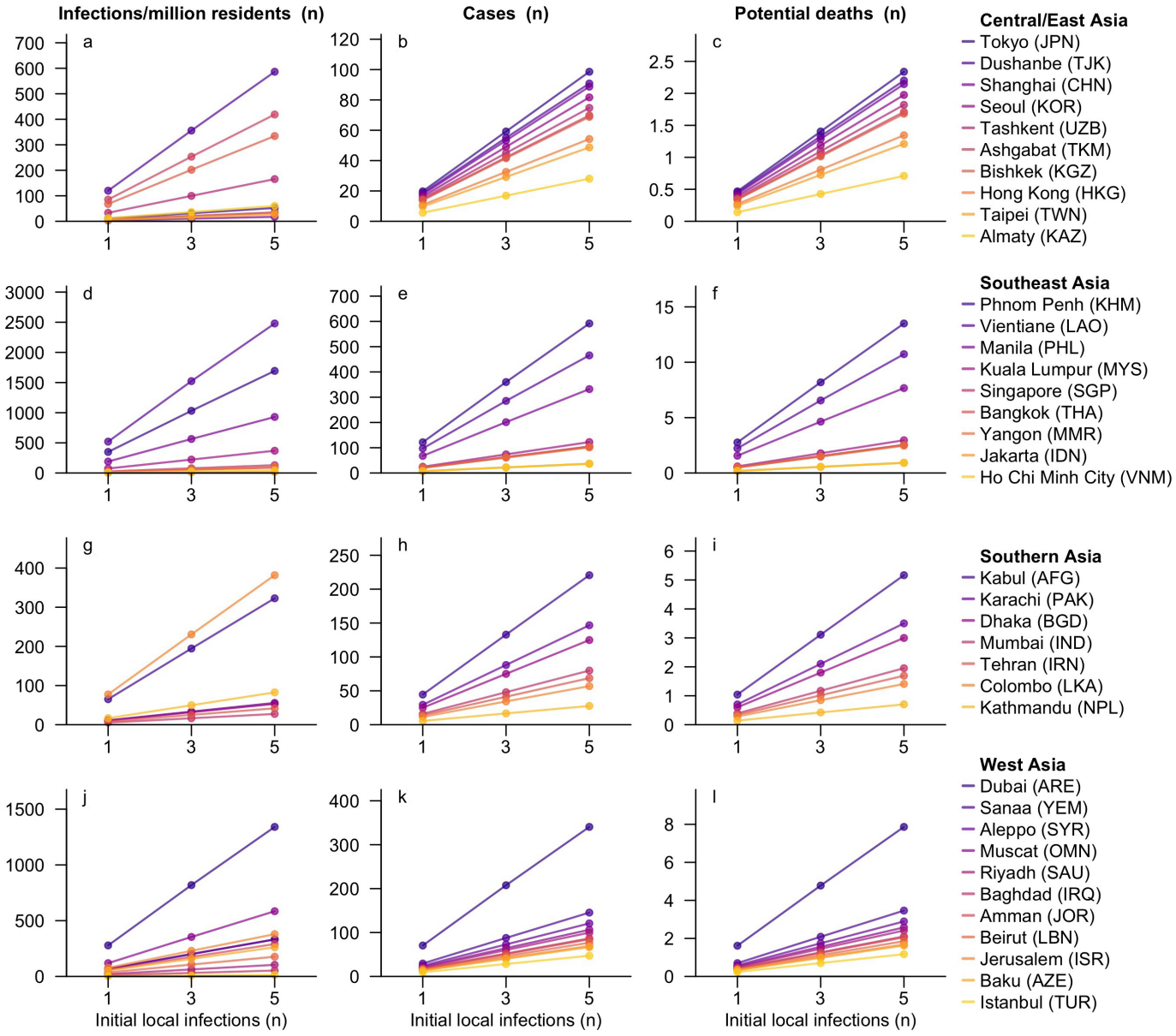

Figure 4 Summary statistics for simulated outbreaks in 37 Asian cities. The three statistics reported are number of infections (column 1; a, d, g, h), confirmed cases (column 2; b, e, h, k) and individuals at risk of dying (column 3; c, f, i, l) per million residents within 1 year following the initial local infections caused by a single importation event. The scenarios considered for each city include one, three and five initial local infections. Cities within each subregion were ordered by potential death counts in the scenario with five initial local infections.

1 year compared with an outbreak initiated by a single local infection (figure 4).

In three cities in Southeast and West Asia, including Vientiane, Phnom Penh and Dubai, five initial local infections would lead to over 1000 infections per million residents within 1 year after the importation event that caused these infections. In contrast, significantly smaller proportions of the population would be affected in East Asian cities, with no more than 60 infections per million residents during the same period. Even under this hypothetical worst-case scenario, mortality would remain low in the first year, with no more than five infections per million residents at risk of dying projected in 34 of the 37 Asian cities (figure 4). However, it is worth noting that surges in case counts were not observed in countries until over 1 year after the initial local infections, and that the final outbreak size in one city by the end of the epidemic wave was marginally affected by the initial local infection sizes. Municipals with large populations or considerable numbers of high-risk individuals, such as Shanghai and Bangkok, were likely to experience high case counts during the wave, even if the outbreak appeared relatively modest in the first year (online supplemental figure S15).

Note that the projected epidemic trajectories might vary substantially if alternative high-risk population sizes were assumed instead of the values reported in literature (online supplemental figures S8–S10). Furthermore, the sensitivity analyses also show that the outbreak size

in 1 year following the initial local infections would be affected by the number of initial infections in the high-risk population, where a higher proportion of infections falling in this group would substantially increase the outbreak scale (online supplemental figures S11–S13). Modelling the smallpox vaccine as an all-or-nothing mechanism, rather than a leaky vaccine as assumed in the main analysis, would also result in more infections over the first year (online supplemental figures S5 and S6). However, a potentially shortened infectious period among asymptomatic or mild infections could delay outbreaks and reduce the scale across the Asian cities (online supplemental figures S1 and S2). Please refer to online supplemental file 1 for further details on the simulated outbreaks under these alternative scenarios.

Effectiveness of NPIs on outbreak control

Both isolation and quarantine would contribute to significant reductions in confirmed cases for the 37 cities. In the scenario with three initial local infections, compared with the baseline without NPIs, isolation alone would bring a 43.8% (IQR: 42.8–44.7%), 67.8% (IQR: 66.5–68.9%), 80.8% (IQR: 79.5–82.0%) and 88.0% (IQR: 86.8–89.1%) reduction to the cumulative cases within 1 year following the initial local infection events, when it decreased the interpersonal contacts by 25%, 50%, 75% and 100%, respectively. Adding quarantine would further lower the cumulative cases by 22.0 (IQR: 21.8–22.1), 19.9 (IQR: 19.6–20.0), 13.5 (IQR: 13.1–13.7) and 8.4 (IQR: 8.0–8.8) percentage points for the four levels of isolation effectiveness (figure 5). Nevertheless, the impact of isolation substantially diminished when the assessment window was extended to 5 years, while a significant increase was observed in the effectiveness of quarantine, potentially due to the delayed outbreak surge caused by interventions (online supplemental figures S16 and S17, table S5).

The impacts of NPIs also varied greatly across the 37 cities. Cities experiencing larger outbreaks within the first year tended to benefit more from NPIs. For example, in Phnom Penh, isolation alone could decrease 48.0%, 73.2%, 86.2% and 92.8% of confirmed cases at the four effectiveness levels, respectively. Conversely, in cities like Kathmandu and Almaty, where fewer than 20 cases were expected in the first year, reductions were lower by at least 9 percentage points at each effectiveness level (figure 5, online supplemental figure S18). Nevertheless, this strong association between intervention effectiveness and local outbreak size was less evident when the assessment period was extended to 5 years (online supplemental figures S16 and S19).

DISCUSSION

In this study, we simulated localised mpox outbreaks triggered by a single importation event to project the potential spread of Clade Ib MPXV in 37 Asian cities with varying population sizes, levels of immunity from smallpox vaccination and proportions of sexually active population at higher transmission risk. In the scenario involving three initial local infections, an outbreak of up to 340 cases per million residents was anticipated within 1 year in the absence of interventions, while the implementation of potent isolation and quarantine measures could lower the incidence to fewer than four per million.

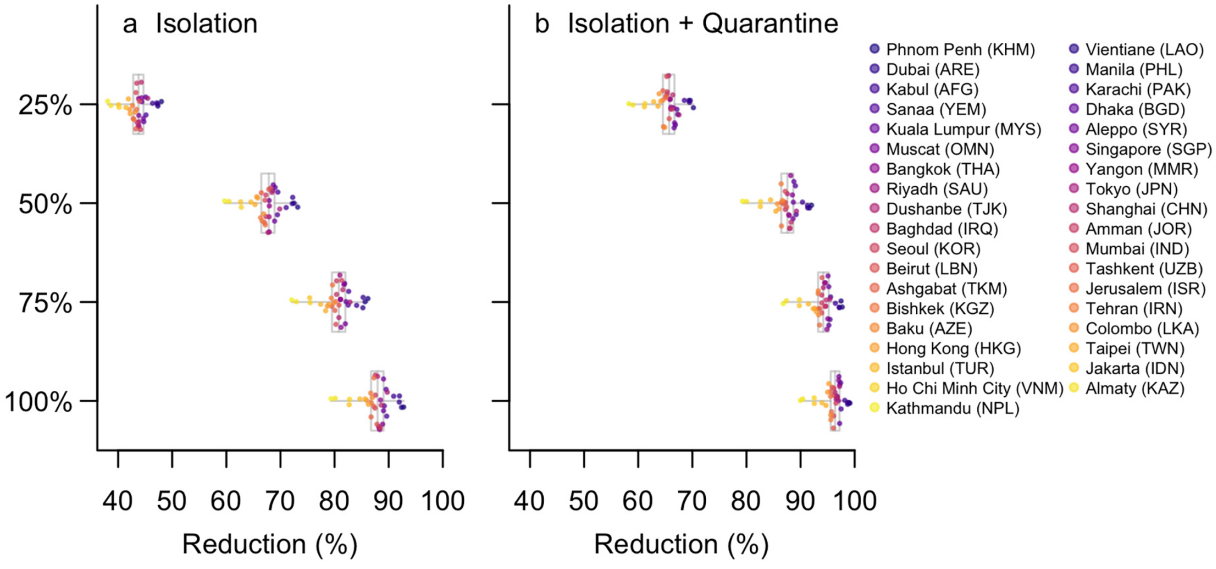

Figure 5 Projected reduction in confirmed cases in 1 year following the initial three local infections due to the (a) isolation or (b) isolation combined with quarantine. The reduction proportions were calculated for each level of isolation effectiveness (25%, 50%, 75% and 100% reduction in interpersonal contacts) Compared with the baseline scenario with no non-pharmaceutical interventions (NPIs) and three initial local infections per city. Grey box plots display the median, IQRs and ranges of reductions across the 37 cities. In the legend bar on the right, these cities were ordered by confirmed case counts in 1 year in the scenario without NPIs, with a darker colour indicating a greater decrease.

Our simulation results revealed positive correlations between outbreak sizes and both the proportion of sexually active individuals at high transmission risk and the level of immunity due to smallpox vaccination in each city. While the large-scale outbreaks in Dubai were mainly attributed to the low vaccine-induced (7%), the substantial number of infections projected for Thailand, where smallpox vaccines were estimated to protect over 30% of the population from MPXV infections, was primarily the result of the high proportion of high-risk individuals in the community.[21] Specifically, over 10% of males aged 15–49 years were documented to engage with sex workers,[25] leading to an estimated 2.9% of the population being unvaccinated and categorised as high-risk in our study (figure 2). This finding is further supported by the results of the sensitivity analysis, where Bangkok was predicted to be among the cities with the lowest outbreak risks under the assumption of a uniform high-risk proportion among individuals aged 15–49 years across different cities (online supplemental figures S7–S10).

Both NPIs assessed in our analysis—case isolation and quarantining of close contacts—demonstrated promising potential in mitigating the outbreaks across all Asian cities. While the median reduction in the total case counts over 1 year was expected to approach roughly 90% in the ideal scenario where isolation was 100% effective in preventing contacts between susceptible and isolated infectious individuals, the rate of case reduction would diminish per 25% increment in isolation effectiveness. The actual effectiveness would depend on the stringency of isolation policies, the isolation facilities required (eg, home or designated healthcare centres) and compliance of affected individuals, which may vary between countries. Nevertheless, the moderate simulated outbreak sizes in most cities suggest the feasibility of less restrictive isolation measures, such as home isolation for confirmed cases, since even with 50% isolation effectiveness, our model projected fewer than 100 confirmed cases per million residents in any Asian city in 1 year following three initial local infections (online supplemental figures S17 and S18). Furthermore, given the significantly longer infectious period of mpox compared with COVID-19,[15] extended isolation in healthcare facilities could easily strain pre-existing infrastructure with a surge in case counts.

The added benefits of quarantining close contacts, beyond isolation alone, were consistently projected to slow the disease spread, contributing to an additional reduction of at least 5 percentage points in the case counts over 1 year. This aligns with its extensive use during the COVID-19 pandemic.[28 29] However, delays in contact tracing may affect quarantine effectiveness. In our analysis, we assumed a uniform 3-day interval between the diagnosis of index cases and the identification of their close contacts,[30] but longer delays in contact tracing could result in additional secondary infections caused by the infectious close contacts. It is also important to note that effective contact tracing would require substantial human resources for identifying close contacts, which may not always be readily available. As such, isolation is recommended as the primary intervention strategy for containing all potential outbreaks, with contact tracing and quarantining serving as supplementary measures in scenarios involving relatively large outbreak scales.

It is worth highlighting that our estimates of outbreak sizes and disease burden were based on simulated epidemic trajectories initiated by a one-time importation, whose outcomes were modelled through a fixed size of initial local infections in the fully susceptible local population for each city. It should be noted that our simulations assumed these initial infections were contracted through community contact. This assumption may underestimate the number of infections over 1 year should the initial local transmission occur through sexual contact within the high-risk group (online supplemental figures S11–S13). Moreover, we did not account for recurring importation events due to the observation of single imported cases in individual affected countries outside the African continent by September 2024. Challenges also exist in quantifying the infectivity of incoming infectious travellers on local residents as MPXV is mainly transmitted through close contacts[10] and contact patterns between travellers and the local population might differ significantly from those within the local community. Nevertheless, given the high disease transmissibility, especially through sexual transmission, the role of importation would likely be minimal in influencing the epidemic curve once the virus begins to circulate within the city.

In this study, we employed a deterministic model to project the average outcome of disease transmission across diverse scenarios. The model's lack of stochasticity limits its capability to capture the uncertainties in the epidemic trajectories. Particularly, in low-incidence scenarios with fewer than five infections over an extended period, stochastic effects in reality could lead to the extinction of infections, while a deterministic model allows for fractional infections and prevents the transmission from dying out as long as the effective reproduction number is at least one. This poses challenges in quantifying the probability of extinction and interpreting predictions during the early stages of an outbreak. Therefore, we alternatively focused on infection sizes over an extended simulation period, during which the outbreak sizes were generally sufficiently large. In this context, the consistent, predictable outcomes generated by the deterministic model offer a more intuitive quantification of the potential outbreak scales in the investigated cities, supporting comparisons across settings and facilitating informed decision-making.

A further simplification of real-world scenarios in our study lies in the modelling of vaccination effectiveness. We assumed a leaky vaccine model for historical smallpox vaccines, representing their impact as a population-level reduction in disease transmissibility. Compared with an all-or-nothing assumption, this assumption led to slower outbreak progression but a larger final outbreak size

(online supplemental figures S5 and S6).[31] Meanwhile, we did not account for the reducing population immunity due to ageing over the long simulation window, which may have caused an underestimation of the final outbreak sizes.

In addition, it should be noted that our approximation of high-risk population sizes was based on reported numbers of sex workers and their clients.[23–25] Although consistent data sources were used for most territories and the same calculation method was applied to enhance the comparability across territories, relevant statistics were unavailable for certain territories, especially those in the Middle East. Consequently, we extrapolated the figures using subregional average proportions, which were lower than the reported values for other parts of Asia. Possibilities also exist that the number of individuals engaging with sex workers was under-reported in surveys due to strict cultural norms in some Asian territories and the stigma associated with acknowledging commercial sex.[25 32] Both factors could lead to an underestimation of the high-risk population sizes and hence an underestimation of outbreak size as sexual transmission was a key driver of disease spread in our simulations.

Another major limitation of our study pertains to the large uncertainty surrounding transmission-related model parameters. The co-circulation of multiple MPXV clades in Africa,[33] along with a lack of comprehensive sequencing data, complicates efforts to pinpoint the transmissibility of MPXV Clade Ib. The disparities in transmission dynamics across regions with reported Clade Ib MPXV infections introduced additional unsureness regarding the contribution of sexual transmission to the overall outbreak.[16] In this study, we stratified the population according to their sexual activity levels and based the transmissibility estimates for these two groups on disease surveillance data from South Kivu, assuming that transmission in the province was predominately driven by Clade Ib MPXV. These parameter estimates were derived using a next-generation matrix approach, accounting for the impacts of heterogeneous sexual networks and the age-specific contact patterns,[16] but our population-level model did not fully capture the detailed network structure. Since the cases identified outside the African continent primarily consisted of importations and data on local transmission remained scarce by September 2024, we extrapolated these estimates from the outbreak data in the DRC to the Asian urban setting without validating against context-specific observations. We characterised the heterogeneity in effective reproduction number across individual cities using territory-specific smallpox immunity profiles and high-risk population sizes. However, several other driving factors of the transmission potential were not included due to the limited available data and challenges in quantifying their exact impacts on shaping the transmissibility of Clade Ib MPXV. Particularly, geospatial differences are likely to exist in the number and frequency of close contacts across the 37 Asian cities, including both sexual interactions and physical contacts within households stemming from discrepancies in family sizes, demographical structures, living habits, cultural norms and other social and economic factors. This limits the generalisability of our results. Given the relatively smaller household sizes in many Asian cities compared with those in the DRC,[34] the number of infections might have been overestimated. The shortened viral shedding duration among asymptomatic or mild infections,[35] coupled with their potentially reduced frequencies of contacts owing to self-isolation, may also contribute to an overestimation of their infectivity and hence an overestimation of outbreak sizes (online supplemental figures S1 and S2). Furthermore, the reliance on surveillance data sourcing from Africa, where healthcare and monitoring systems may face constraints, might have led to an underestimation of infection sizes and an overestimation of disease severity. Consequently, the projected potential death counts based on African data in our study may far exceed reality in many Asian cities. With the availability of more case data and epidemiological parameters, our model may require updating.

Despite these limitations, our simulations suggest that while mpox outbreaks triggered by importation could lead to substantial morbidity and mortality in an Asian city with large populations of sexually active individuals at risk, they would still remain controllable provided adequate preparation and a timely response from decision-makers, underscoring the significance of robust surveillance systems. In addition, the transmission model proposed in this study enables the quantification of the impacts of containment measures widely applied during the COVID-19 pandemic on mpox outbreaks, an area much less explored compared with the virus's transmission patterns.[1 36] Provided proper implementation, the NPIs evaluated in this study have the potential to suppress outbreak sizes and curb disease spread by up to 99%, offering evidence for adopting them to effectively manage new outbreaks with potentially high community transmissibility. Based on these findings, there exists an urgent need for strong surveillance systems, efficient contact tracing, quarantining of close contacts and institutional isolation of cases.

Contributors SJ, GG and BLD conceived and designed the study. SJ implemented the statistical analysis and created the figures and tables; and wrote the original draft of the manuscript. GG, AE, KP, RKJT, JTL, KE and BLD reviewed and edited the manuscript. BLD is the guarantor.

Funding This work was supported by the Singapore Ministry of Education Reimagine Research Grant (grant/award Number: not applicable); and PREPARE, Singapore Ministry of Health (grant/award number: not applicable). AE is supported by the Japan Science and Technology Agency (JST) (JPMJPR22R3), JSPS Grants-in-Aid KAKENHI (JP22K17329) and National University of Singapore Start-Up Grant (grant/award number: not applicable). The funding sources were not involved in the study design, in collection, analysis and interpretation of data, in the writing of the report or in the decision to submit the paper for publication.

remains solely that of the relevant source and is not endorsed by BMJ. Maps are provided without any warranty of any kind, either express or implied.

Competing interests None declared.

Patient and public involvement Patients and/or the public were not involved in the design, or conduct, or reporting, or dissemination plans of this research.

Patient consent for publication Not applicable.

Ethics approval Not applicable.

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement Data are available in a public, open access repository. Supplementary data and analytical codes used for this study are available at https://github.com/ShihuiJin/mpox_SEIR.

ORCID iD

Shihui Jin http://orcid.org/0000-0003-0079-7390

REFERENCES

1 Vakaniaki EH, Kacita C, Kinganda-Lusamaki E, *et al*. Sustained human outbreak of a new MPXV clade I lineage in eastern Democratic Republic of the Congo. *Nat Med* 2024;30:2791–5.
2 European Centre for Disease Prevention and Control. Epidemiological update: mpox due to monkeypox virus clade i. 2024 Available: https://www.ecdc.europa.eu/en/news-events/epidemiological-update-mpox-due-monkeypox-virus-clade-i
3 CIDRAP. India reports imported clade 1b mpox case. 2024. Available: https://www.cidrap.umn.edu/mpox/india-reports-imported-clade-1b-mpox-case
4 WHO. WHO director-general declares mpox outbreak a public health emergency of international concern. 2024. Available: https://www.who.int/news/item/14-08-2024-who-director-general-declares-mpox-outbreak-a-public-health-emergency-of-international-concern
5 Multi-country outbreak of mpox, external situation report#35. 2024 Available: https://www.who.int/publications/m/item/multi-country-outbreak-of-mpox--external-situation-report-35--12-august-2024
6 Chan ZYS, Chong SY, Niaupari S, *et al*. Receptiveness to monkeypox vaccines and public health communication strategies among gay, bisexual and other men who have sex with men in Singapore: cross-sectional quantitative and qualitative insights. *Sex Transm Infect* 2024;100:362–7.
7 Endo A, Murayama H, Abbott S, *et al*. Heavy-tailed sexual contact networks and monkeypox epidemiology in the global outbreak, 2022. *Science* 2022;378:90–4.
8 Rivers C, Watson C, Phelan AL. The Resurgence of Mpox in Africa. *JAMA* 2024;332:1045–6.
9 Risk assessment for the eu/eea of the mpox epidemic caused by monkeypox virus clade i in affected african countries. 2024. Available: https://www.ecdc.europa.eu/en/publications-data/risk-assessment-mpox-epidemic-monkeypox-virus-clade-i-africa
10 WHO. Mpox. 2024 Available: https://www.who.int/news-room/fact-sheets/detail/mpox
11 Yeoh EK, Chong KC, Chiew CJ, *et al*. Assessing the impact of non-pharmaceutical interventions on the transmissibility and severity of COVID-19 during the first five months in the Western Pacific Region. *One Health* 2021;12:100213.
12 El Guerche-Séblain C, Chakir L, Nageshwaran G, *et al*. Experience from five Asia-Pacific countries during the first wave of the COVID-19 pandemic: Mitigation strategies and epidemiology outcomes. *Travel Med Infect Dis* 2021;44:102171.
13 Fitzgerald DA, Wong GWK. COVID-19: A tale of two pandemics across the Asia Pacific region. *Paediatr Respir Rev* 2020;35:75–80.
14 Beeson A, Styczynski A, Hutson CL, *et al*. Mpox respiratory transmission: the state of the evidence. *Lancet Microbe* 2023;4:e277–83.
15 Byrne AW, McEvoy D, Collins AB, *et al*. Inferred duration of infectious period of SARS-CoV-2: rapid scoping review and analysis of available evidence for asymptomatic and symptomatic COVID-19 cases. *BMJ Open* 2020;10:e039856.
16 Murayama H, Asakura TR, Dickens BL, *et al*. Roles of community and sexual contacts as drivers of clade i mpox outbreaks. *Epidemiology* [Preprint] 2024. 10.1101/2024.10.15.24315554 Available: https://www.medrxiv.org/content/10.1101/2024.10.15.24315554v1
17 Branda F. African disease analysis and monitoring system (adams). 2024. Available: https://github.com/fbranda/ADAMS/tree/main
18 Matusali G, Petruccioli E, Cimini E, *et al*. Evaluation of Cross-Immunity to the Mpox Virus Due to Historic Smallpox Vaccination. *Vaccines (Basel)* 2023;11:1541.
19 Population and Population Structure. Population and population structure. 2024. Available: http://www.singstat.gov.sg/find-data/search-by-theme/population/population-and-population-structure/latest-data
20 Metzger WG, Köhler C, Mordmüller B. Lessons from a modern review of the smallpox eradication files. *J R Soc Med* 2015;108:473–7.
21 Taube JC, Rest EC, Lloyd-Smith JO, *et al*. The global landscape of smallpox vaccination history and implications for current and future orthopoxvirus susceptibility: a modelling study. *Lancet Infect Dis* 2023;23:454–62.
22 United Nations. World population prospects - population division. 2024. Available: https://population.un.org/wpp/Download/Standard/Population/
23 UNAIDS. AIDSinfo. 2024. Available: https://aidsinfo.unaids.org/
24 International Union of Sex Workers. Sex worker statistics by country. 2024. Available: https://iusw.org/sex-worker-statistics/
25 Carael M, Slaymaker E, Lyerla R, *et al*. Clients of sex workers in different regions of the world: hard to count. *Sex Transm Infect* 2006;82 Suppl 3:iii26–33.
26 R Core Team. R: a language and environment for statistical computing. R Foundation for Statistical Computing,Vienna, Austria; 2024. Available: https://www.R-project.org/
27 Shihui Jin. Mpox_SEIR. 2025. Available: https://github.com/ShihuiJin/mpox_SEIR
28 Shen M, Peng Z, Guo Y, *et al*. Assessing the effects of metropolitan-wide quarantine on the spread of COVID-19 in public space and households. *Int J Infect Dis* 2020;96:503–5.
29 Girum T, Lentiro K, Geremew M, *et al*. Global strategies and effectiveness for COVID-19 prevention through contact tracing, screening, quarantine, and isolation: a systematic review. *Trop Med Health* 2020;48:91.
30 Quilty BJ, Clifford S, Hellewell J, *et al*. Quarantine and testing strategies in contact tracing for SARS-CoV-2: a modelling study. *Lancet Public Health* 2021;6:e175–83.
31 Lee DI, Nande A, Anderson TL, *et al*. Vaccine failure mode determines population-level impact of vaccination campaigns during epidemics. *Epidemiology* [Preprint] 2024. 10.1101/2024.09.30.24314493 Available: https://www.medrxiv.org/content/10.1101/2024.09.30.24314493v1
32 Husson L. Who Are the Clients and What They Say about Prostitution in South-East Asia? *moussons* 2017;209–62.
33 Kuppalli K, Dunning J, Damon I, *et al*. The worsening mpox outbreak in Africa: a call to action. *Lancet Infect Dis* 2024;24:1190–2.
34 World Population Review. Family size by country. 2024. Available: https://worldpopulationreview.com/country-rankings/family-size-by-country
35 Mazzotta V, Nozza S, Lanini S, *et al*. Clinical and laboratory predictors of mpox severity and duration: an Italian multicentre cohort study (mpox-Icona). *EBioMedicine* 2024;107:105289.
36 Kibungu EM, Vakaniaki EH, Kinganda-Lusamaki E, *et al*. Clade I-Associated Mpox Cases Associated with Sexual Contact, the Democratic Republic of the Congo. *Emerg Infect Dis* 2024;30:172–6.