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The effectiveness of interventions to reduce COVID-19 transmission in a large urban jail

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ABSTRACT

Objectives: We aim to estimate the impact of various mitigation strategies on COVID-19 transmission in a U.S. jail beyond those offered in national guidelines.

Design: We developed a stochastic dynamic transmission model of COVID-19.

Setting: One anonymous large urban U.S. jail.

Participants: Several thousand staff and incarcerated individuals

Interventions: There were four intervention phases during the outbreak: the start of the outbreak, depopulation of the jail, increased proportion of people in single cells, and asymptomatic testing.

Primary and Secondary Outcome Measures: The next generation method estimated the basic reproduction ratio, R_0 , in each phase. The fraction of new cases, hospitalizations, and deaths averted by these interventions along with the standard measures of sanitization, masking, and social distancing interventions are reported.

Results: For the first outbreak phase, the estimated R_0 was 8.23 (95% CrI: 5.01 to 12.90), and for the subsequent phases, $R_{0,phase\ 2} = 3.58$ (95% CrI: 2.46 to 5.08), $R_{0,phase\ 3} = 1.72$ (95% CrI: 1.41 to 2.12), and $R_{0,phase\ 4} = 0.45$ (95% CrI: 0.32 to 0.59). In total, the jail's interventions prevented approximately 83% of projected cases and hospitalizations and 89% of deaths over 83 days.

Conclusions: Depopulation, single celling, and asymptomatic testing within jails can be effective strategies to mitigate COVID-19 transmission in addition to standard public health measures. Decision-makers should prioritize reductions in the jail population, single celling, and testing asymptomatic populations, as additional measures to manage COVID-19 within correctional settings.

Strengths and limitations of this study

- COVID-19 has entered hundreds of correctional facilities in the United States, yet we identified only two past empirical studies which are focused on COVID-19 transmission in correctional facilities.
- A stochastic dynamic transmission model describes the spread of COVID-19 in a large urban jail in the United States.
- We calibrated the model to a moving average of the daily incidence of COVID-19 reported by the jail.
- We identified three major interventions – depopulation, single celling, and asymptomatic testing – undertaken by the jail and quantify the reduction in transmission rate as a result of these interventions.

INTRODUCTION

COVID-19, the disease caused by the SARS-CoV-2 virus, has affected millions of people worldwide, with disproportionate impact on some communities such as those inside correctional facilities. In the United States (U.S.), approximately 2.2 million people are incarcerated in any given day in over 5,000 facilities,¹ where the built environment and activities of daily living make physical distancing exceedingly difficult to implement.²⁻⁴ As of the third week of April 2020, 420 U.S. correctional facilities had at least one diagnosed case of COVID-19, accounting for a total of 4,893 cases among incarcerated individuals and 2,778 cases among staff members.³ As of June, correctional facilities account for eight out of ten of the largest COVID-19 outbreaks nationally, surpassing nursing homes and food processing plants, and 26 states now have a higher rate of COVID-19 infection in their correctional population than in their general population.^{5,6} Cook County Jail currently has one of the largest outbreaks in the country, and the infection rate at Rikers Island is nearly five times that of New York City.^{7,8}

Despite the severity of outbreaks in correctional facilities, national guidance surrounding the prevention and management of COVID-19 within such settings has been limited. In the weeks after the first major outbreak in a U.S. jail, the U.S. Centers for Disease Control and Prevention (CDC) published policy guidelines for correctional facilities to help mitigate COVID-19 transmission, which included limiting transfer of incarcerated people between facilities, restricting the number of visitors entering facilities, promoting personal hygiene and environmental sanitization, maximizing the space between those incarcerated (i.e. arranging bunks so individuals sleep head to toe), and screening staff for symptoms.⁹

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3 However, CDC guidelines then and still now do not account for the difficulty that many facilities
4 face in managing COVID-19 and creating physical distance within jails. Even among those jails
5 which are not crowded, physical distancing is challenging given use of congregate living
6 arrangements, shared meals, and exercise and recreation programming. In the absence of more
7 targeted guidelines, there is wide variance in how correctional facilities are managing COVID-
8 19, especially regarding depopulation efforts that may mitigate COVID-19 and approaches to
9 testing (symptomatic only vs. asymptomatic, viral testing vs. antibody testing). As an example,
10 Attorney General Barr has ordered that medically frail individuals in federal prisons be released
11 to home quarantine, whereas many U.S. state prison systems have no stated policies for larger
12 scale release. Some correctional systems have implemented systemwide testing of all
13 incarcerated individuals, including those who are asymptomatic, while others are only testing
14 those who are symptomatic.
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33 The effectiveness of such measures, which fall outside of CDC guidance, in reducing the
34 transmission of COVID-19 within correctional facilities has yet to be established. In this study,
35 we estimate the effectiveness of measures to mitigate the spread of COVID-19 beyond standard
36 CDC recommendations in a large urban jail. We focus on policies with large potential impact for
37 which there is variability in practice, namely depopulation (cessation of new detentions and
38 release of incarcerated individuals), single celling (percentage of the total incarcerated
39 population in a single cell), and testing asymptomatic individuals with the aim of providing
40 guidance to correctional policymakers and public health agencies.
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METHODS

We developed a stochastic dynamic transmission model of COVID-19 which we calibrated to the outbreak in the jail. We combined data on cases in incarcerated people and correctional staff because they interact very closely and regularly as an ecosystem behind the walls of the jail. We divided the outbreak timeline into four intervention phases marked by the start of the outbreak, start of depopulation efforts, increased single celling, and large-scale asymptomatic testing of incarcerated individuals. We estimated the initial basic reproduction ratio, R_0 , and the effective reproduction ratio, R_t , in each phase, for the entire jail. We also estimated the fraction of new cases, hospitalizations, and deaths averted by the combined interventions.

Model description

We modified a traditional SEIR model to represent the disease states of COVID-19. These disease states included susceptible (S), exposed (E), infected symptomatic (I_{sym}), infected asymptomatic (I_{asym}), quarantined (Q), hospitalized (H), and recovered (Rec) individuals (Figure 1). To model these interacting populations, we developed a mass-action mixing model described by the following equations:

$$\frac{dS}{dt} = bS - \frac{\beta S}{N}(I_{sym} + I_{asym}) \quad (1)$$

$$\frac{dE}{dt} = bE + \frac{\beta S}{N}(I_{sym} + I_{asym}) - \varepsilon E \quad (2)$$

$$\frac{dI_{sym}}{dt} = (1 - \alpha)\varepsilon E - I_{sym} \quad (3)$$

$$\frac{dI_{asym}}{dt} = bI_{asym} + \alpha\varepsilon E - \gamma I_{asym} \quad (4)$$

$$\frac{dQ}{dt} = I_{sym} - (1 - \eta)\gamma Q - \eta\left(\frac{1}{\gamma} - \frac{1}{\mu}\right)^{-1} Q \quad (5)$$

$$\frac{dH}{dt} = \eta \left(\frac{1}{\gamma} - \frac{1}{\mu} \right)^{-1} Q - \mu H \quad (6)$$

$$\frac{dRec}{dt} = (1 - d_I)(1 - \eta)\gamma Q + (1 - d_I)\mu H + \gamma I_{asym} \quad (7)$$

$$\frac{dDead}{dt} = d_I(1 - \eta)\gamma Q + d_I\mu H \quad (8)$$

$$N = S + E + I_{sym} + I_{asym} + Q + H + Rec \quad (9)$$

The susceptible, exposed, and asymptomatic infected populations grew at rate b which represented the overall growth or reduction in jail population. We assume that symptomatic infected individuals are not removed from the jail during general depopulation and would be admitted directly to quarantine. For the time horizon of the model, the population was generally shrinking. Susceptible individuals were exposed to COVID-19 at transmission rate β . We recalibrated this transmission rate for each of the four outbreak phases. We assumed that asymptomatic and symptomatic infected individuals could transmit the disease.^{10 11} Exposed individuals were infected but not yet infectious and become asymptomatic or symptomatic infected at rate ε , which corresponded to the incubation period of COVID-19. A certain proportion, α , of these individuals stayed asymptomatic, while remaining individuals became symptomatic. Based on the jail's report, we assumed that symptomatic infected individuals were identified one day after symptoms presented and placed in quarantine after identification. We assumed that individuals once quarantined did not transmit COVID-19, as they were isolated from the susceptible population. A fraction, η , of quarantined individuals were hospitalized and recovered from hospitalization at rate μ . All infected individuals recovered or died at rate γ regardless of symptomatic or asymptomatic status. Symptomatic infected individuals died with probability d_I .

Interventions

The jail implemented various measures over time in an attempt to mitigate the spread of COVID-19. We divide the outbreak into four intervention phases, corresponding to the initiation of key measures of interest which fell outside the guidance of the CDC. During Phase 1 (days 1-11), the jail implemented a broad array of strategies that were consistent with CDC guidance including: basic screening for flu-like symptoms in incarcerated people; new detainees quarantined for at least 7 days and basic screening for flu-like symptoms for visitors, vendors, attorneys, and community members entering the facility; staff required to report symptoms as well as contact with known COVID-19 positive cases and any travel outside of the U.S.; suspension of all tours, large gatherings, in-person visitation. During phase 2 (days 12-17), the jail population started to decrease by 1.41% each day through a combination of measures which included a marked decrease in new detentions given changes in the court and judicial system procedures and large community organized bail outs (Figure 2). The jail also began taking the temperature of all employees each day. During phase 3 (days 18-36), the jail began increasing the proportion of the population in single-occupancy cells from 26% on day 18 to 54% on day 36. During this period, they began requiring all staff to wear surgical masks and allotted new masks to those incarcerated each day. They also continued to isolate confirmed and suspected COVID-19 cases among incarcerated individuals but given the number of individuals, they identified a different building for segregating patients which provided a larger space for the growing number of confirmed cases. Lastly, they started on-site voluntary testing for employees and a two-week COVID-19 paid leave policy for all employees. During phase 4 (days 37-83), the jail began testing for asymptomatic cases in divisions with high numbers of cases identified during contact tracing at a rate of approximately 50-75 people per day.

Model Instantiation and Calibration

We estimated some model parameter values from previous literature (Table 1). The rate at which exposed individuals became asymptotically or symptomatically infected, ϵ , was the inverse of the incubation period. The incubation period of COVID-19 was previously described with a lognormal distribution with mean 5.1 days and standard deviation 0.89 days.¹² We assumed that the proportion of infections that are asymptomatic, α , was uniformly distributed over the range 0.25 to 0.56.^{13 14} The average recovery rate was previously estimated to be 0.1, the inverse of the 10-day mean infection period.¹⁵ We assumed that the infection period followed a truncated normal distribution with mean 10 days, standard deviation 6.25 days, minimum 5 days, and maximum 20 days. Additionally, the length of hospitalization from COVID-19 has been estimated to be 5 days, making the daily recovery probability from the hospital 0.2.¹⁶ We assumed that the length of hospitalization followed a lognormal distribution with a mean of 5 days and standard deviation of 1 day.

The jail provided demographic data about the size of the incarcerated population per day, as well as epidemiological data about confirmed COVID-19 cases over the course of 83 days. We assumed an average reporting delay of six days from first exposure to reported incidence. This accounts for the mean incubation period and a minor delay between symptom onset and COVID-19 test result and isolation. The jail provided data on the age of the infected person, date of positive COVID-19 test, the work or incarceration location of the infected individual, and whether the individual was hospitalized or died as a result of the COVID-19 infection. We used these data to calculate the proportion of symptomatic infections that were hospitalized or died.

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3 For each intervention phase, we used the epidemiological data to determine the growth rate, b , as
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5 the average rate of growth for the entire facility.
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10 We calibrated the transmission rate, β , for each intervention phase. We first pseudo-randomly
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12 selected values for parameters ε , α , γ , and μ based on our assumed distributions (Table 1). Then,
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14 we calculated b for the intervention phase. To find the best-fitting value of β for the given
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16 parameter set, we implemented an exhaustive search over the range $[0,4]$ in increments of 0.01.
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18 We chose the value of β which minimized the sum of mean squared error between the reported
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20 daily incidence of confirmed COVID-19 cases among incarcerated people and staff in the jail to
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22 the daily incidence of symptomatic infected cases in the model for that phase. We calculated the
23
24 incidence of symptomatic cases using the raw reported incidence before asymptomatic testing.
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26 Select asymptomatic testing for incarcerated people began on day 31 and for staff began on day
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28 21. After asymptomatic testing began, we took the minimum of the jail-provided data on the
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30 number of symptomatic tests multiplied by the average percentage of positive results of
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32 symptomatic tests between days 16-30 (89%) and the raw reported incidence. Based on this
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34 estimate, on average, 82% of the reported daily incidence among the incarcerated population was
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36 symptomatic after asymptomatic testing began. Because we did not have testing data available
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38 for staff, we assumed that 82% of reported new staff cases were symptomatic after on-site testing
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40 became available for staff.
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49 We used a simple moving average of the previous five days of incidence to smooth the
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51 calibration targets. We assumed that the reported incidence corresponded to the number of
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53 incarcerated individuals and staff members who showed symptoms of COVID-19. For each
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intervention phase, we ran 1,000 Monte Carlo simulations and defined the 95% credible interval of β as the range into which 95% of calibrated values of β fell.

Calculation of R_0 and R_t

To calculate R_0 and R_t , we used the next generation method.¹⁷ This method utilizes two matrices of partial derivatives of compartments with infected individuals.¹⁸ In our model, this included exposed, asymptomatic infected, symptomatic infected, quarantined, and hospitalized individuals. The first matrix, F , is the rate of appearance of new infections for each compartment. Each element, f_{ij} , of F is the partial derivative of any term in which new infections appear in compartment i with respect to compartment j where $i, j \in [E, I_{asym}, I_{sym}, Q, H]$.

$$F = \begin{matrix} E \\ I_{sym} \\ I_{asym} \\ Q \\ H \end{matrix} \begin{bmatrix} 0 & \frac{\beta S_0}{N} & \frac{\beta S_0}{N} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (10)$$

The second matrix, V , is the rate of transfer of individuals out of a compartment minus the rate of transfer of individuals into a compartment. Therefore, each element, v_{ij} , of V is the partial derivative of the additive inverse of any term other than the appearance of new infections in compartment i with respect to compartment j . The matrix V and its inverse are as follows:

$$V = \begin{matrix} E \\ I_{sym} \\ I_{asym} \\ Q \\ H \end{matrix} \begin{bmatrix} \varepsilon - b & 0 & 0 & 0 & 0 \\ -(1 - \alpha)\varepsilon & 1 & 0 & 0 & 0 \\ -\alpha\varepsilon & 0 & \gamma - b & 0 & 0 \\ 0 & -1 & 0 & (1 - \eta)\gamma + \eta\left(\frac{1}{\gamma} - \frac{1}{\mu}\right)^{-1} & 0 \\ 0 & 0 & 0 & -\eta\left(\frac{1}{\gamma} - \frac{1}{\mu}\right)^{-1} & \mu \end{bmatrix} \quad (11)$$

$$V^{-1} = \begin{bmatrix} (\varepsilon - b)^{-1} & 0 & 0 & 0 & 0 \\ \alpha + 1 & 1 & 0 & 0 & 0 \\ \frac{\alpha}{\gamma} & 0 & (\gamma - b)^{-1} & 0 & 0 \\ -\frac{(\alpha + 1)(\gamma - \mu)}{\gamma(\eta - 1) + \mu} & \frac{\mu - \gamma}{\gamma(\eta - 1) + \mu} & 0 & \frac{\mu - \gamma}{\gamma(\eta - 1) + \mu} & 0 \\ \frac{(\alpha + 1)\eta}{\gamma(\eta - 1) + \mu} & \frac{\eta}{\gamma(\eta - 1) + \mu} & 0 & \frac{\eta}{\gamma(\eta - 1) + \mu} & \mu^{-1} \end{bmatrix} \quad (12)$$

The next generation method calculates R_0 as the dominant eigenvalue of the next generation matrix. The next generation matrix is defined as FV^{-1} :

$$FV^{-1} = \begin{bmatrix} \frac{\beta S_0(\alpha + 1)}{N} + \frac{\alpha \beta S_0}{\gamma N} & \frac{\beta S_0}{N} & \frac{\beta S_0}{(\gamma - b)N} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (13)$$

In our model, FV^{-1} has only one nonzero eigenvalue, $\lambda = \frac{-\beta S_0(b - \gamma)(\alpha\gamma + \alpha + \gamma)}{\gamma N(\gamma - b)}$. Therefore, $R_0 = \max(0, \lambda)$, and since $\lambda \geq 0$, $R_0 = \lambda$. Since R_0 is directly proportional to β , we can calculate the values of R_0 of other phases simply by using phase 1 starting conditions combined with the reduced transmission rate.

To find the effective reproduction ratio, R_t , at time t , we used the next generation method with the same matrices but updated the values of S and β as appropriate. Because the number of susceptible individuals, S , is a function of time, we recalculate R_t each day. The functional form of R_t for our model is as follows:

$$R_t = \frac{-\beta S_t(b - \gamma)(\alpha\gamma + \alpha + \gamma)}{\gamma N(\gamma - b)} \quad (14)$$

We computed the 95% credible interval of R_t as the range into which 95% of calibrated values of R_t fell. This study was deemed exempt from IRB review by the Yale Human Investigation Committee as we received completely anonymized data from the jail.

Role of the funding source

The funding sources had no role in the study design, collection, analysis, and interpretation of data, writing the report, nor the decision to submit the paper for publication.

RESULTS

Daily reported incidence of COVID-19 in the jail was highly variable, ranging from 0 to 67. The mean absolute error of the model compared to the simple moving average was 19% (Figure 3).

Transmission Rates

In following the initial CDC recommendations for correctional facilities (phase 1), the baseline transmission rate (β) was 1.89 (95% Credible Interval (CrI): 1.44-2.44) (Figure 4). After depopulation began (phase 2), the transmission rate was $\beta = 0.83$ (95% CrI: 0.66-1.06). This represents a 56% decrease in the transmission rate from phase 1. After the increase in single-occupancy cells (phase 3), the transmission rate was $\beta = 0.41$ (95% CrI: 0.30-0.56), a 51% decrease from phase 2. Finally, the transmission rate after testing of asymptomatic individuals began (phase 4) was $\beta = 0.11$ (95% CrI: 0.06-0.20), a 73% decrease from phase 3. All of these reductions are statistically significant.

Reproduction Ratios

The estimated value of R_0 was highest in phase 1, during the first 11 days of the outbreak (Table 2). For this phase, we estimate $R_0 = 8.23$ (95% CrI: 5.01-12.90) (Table 2). We estimate R_0 of each phase in a completely susceptible population as if the outbreak had begun with the values for β which correspond to each phase: $R_{0,phase 2} = 3.58$ (95% CrI: 2.46-5.08), $R_{0,phase 3} = 1.72$

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3 (95% CrI: 1.41-2.12), and $R_{0,phase\ 4} = 0.45$ (95% CrI: 0.32-0.59). The effective reproduction
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5 ratio, R_t , decreased over time as the susceptible population shrank, the transmission rate
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7 changed, and different interventions were implemented (Figure 5). For the entire jail, we
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9 estimate that the interventions may have reduced the effective reproduction ratio R_t below 1
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11 about five weeks after the outbreak began (on day 37).
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16 17 *Averted Infections, Hospitalizations, and Deaths*

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19 Table 2 shows the expected total symptomatic cases on day 83 and expected total cases on day
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21 200, assuming that the estimated transmission rate for a particular outbreak phase holds over all
22
23 subsequent days. Over the first 83 days of the outbreak, the jail reported 778 symptomatic cases
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25 among incarcerated individuals and staff. Our model predicts 642 symptomatic cases (95% CrI:
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27 592-692), 90 hospitalizations (95% CrI: 83-97), and 4 deaths (95% CrI: 3.6-4.1) over this same
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29 time period (Figure 6). Our estimate is 17% less than the number of reported cases that were
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31 symptomatic. Compared to what could have happened with only the implemented CDC
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33 recommended interventions of phase one, the model predicts a reduction of over 3,200
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35 symptomatic cases, 450 hospitalizations, and 30 deaths over 83 days. This suggests that the
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37 combination of interventions (depopulation, increased single celling, and large-scale
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39 asymptomatic testing of incarcerated individuals) in addition to standard CDC COVID-19
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41 mitigation strategies led to an 83% reduction in predicted symptomatic cases and hospitalizations
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43 and an 89% reduction in predicted deaths.
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51 **DISCUSSION**

52 53 *Principal findings*

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3 Using a stochastic compartmental model, we estimate that depopulation efforts, single celling
4 and asymptomatic testing are important interventions, in addition to those recommended by the
5 CDC to reduce COVID-19 transmission in jails. We estimate that the actions taken by the jail
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7 reduced potential new cases by approximately 83% over 83 days, and this may have averted over
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9 450 hospitalization and 30 deaths among those who work and live in jails.
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14 *Policy Implications*

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16 Given these findings, depopulation efforts should be a primary strategy for COVID-19
17 mitigation in jails. Reductions in detained populations to prevent disease transmission is best
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19 achieved by both decreasing the number of new intakes and increasing the number of releases.
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21 This requires that authorities that control jail admissions (including police departments, judges,
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23 and in some cases correctional departments) and jail releases (including judges, lawyers and
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25 community bail funds) both focus on promoting depopulation efforts to mitigate COVID-19
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27 transmission.
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35 Our data also suggest that jails should focus on single celling to mitigate COVID-19. To be clear,
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37 single celling does not imply solitary confinement but rather placing one person in a 6 x 9-foot
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39 cell to increase physical distancing in correctional facilities.¹⁹ Given physical crowding in many
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41 facilities is difficult, even when overall incarcerated populations are at record lows, increasing
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43 access to single-occupancy cells will not be feasible without depopulation efforts, and as
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45 supported by our model, will not lead to a contained transmission rate alone. Facilities unable to
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47 appropriately place individuals in single cell without relying on solitary confinement should
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49 consider depopulation as a preferred strategy. Implementing all of these measures will require
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51 interagency coordination to achieve the full public health impact. Further, by enacting these
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3 measures, correctional facilities may contribute to managing transmission in the surrounding
4 community as well, as several recent studies have documented jails as drivers of community
5 spread of COVID-19.^{20 21}
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12 Lastly, asymptomatic testing is an important component to COVID-19 mitigation strategies. In
13 this jail, they focused on asymptomatic testing through contact tracing of people who tested
14 positive, but much more research needs to be conducted on who should be tested and under what
15 circumstances, including whether mass testing is effective, when individuals should be tested
16 (upon entry, upon release, only for contact tracing, or in regular intervals), and whether certain
17 community rates should guide whether asymptomatic people warrant testing in corrections.
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22 While widespread asymptomatic testing may not be indicated in a jail without community cases,
23 when community cases are present, asymptomatic testing should be strongly recommended.
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27 National and international health agencies, such as the CDC and the World Health Organization,
28 should address depopulation, single celling, and asymptomatic testing in future guidance for
29 detention facilities and how best to implement these measures. Correctional facility
30 administrators will need to also consider how to best mitigate the challenges that come with any
31 of these strategies. For example, coordination of health care and social services organizations
32 prior to release should be prioritized and considerations of testing when releasing individuals as
33 part of depopulation efforts.⁴
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38 *Limitations*

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40 Our analysis has several limitations. We used a compartmental model which assumes
41 homogeneous mixing among the entire population. Correctional facilities in reality do not exhibit
42 homogeneous mixing, especially across divisions. Our model does not have the granularity to
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3 capture the influence of individuals on transmission dynamics. Our model assumes a relatively
4 stationary population and only accounts for mixing within the jail. In reality, jail populations are
5 highly variable with frequent intakes and releases. Jailed individuals also have variable daily
6 routines, such as where they eat or exercise, which are not accounted for in our model. We did
7 not account for possible false positives, misdiagnosis, overreporting, or underreporting in the
8 dataset. Finally, the many interventions undertaken by the jail make it difficult to determine the
9 causal influence of any one particular intervention.
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21 Importantly, these limitations influence our estimates of β and R_0 . We model the jail as a closed
22 system and thus neglect exogenous infection (e.g., staff or new intake incarcerated individuals
23 who contracted the disease in the community) that likely entered the jail before large-scale
24 testing efforts. Because our analysis assumed that all new infections arise from internal
25 transmission, we likely overestimate the true values of β and R_0 , particularly in the early phases
26 of the epidemic in the jail. Thus, conclusions resulting from our analysis should focus on the
27 relative reductions of β and R_0 rather than the precise estimates of these values.
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38 *Conclusions*

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40 Despite the limitations of our analysis, we conclude that it is possible to mitigate the spread of
41 COVID-19 even in correctional settings, where standard social distancing practices are difficult
42 to achieve, by implementing depopulation strategies, promoting increased single celling, and
43 asymptomatic testing with appropriate isolation. The large estimated reduction in the
44 transmission rate ($\geq 50\%$) from these three intervention strategies is comparable to standard
45 social distancing measures in a community setting.²² As states and the federal government are
46 focused on re-opening economies, strategies should be devised to protect those who are
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3 incarcerated and those who work in corrections by further limiting population increases so that
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5 future outbreaks are averted.
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10 **Declaration of interests**

11 All authors have completed the ICMJE uniform disclosure form at
12
13 www.icmje.org/coi_disclosure.pdf and declare: no support from any organization for the
14
15 submitted work; no financial relationships with any organizations that might have an interest in
16
17 the submitted work in the previous three years; no other relationships or activities that could
18
19 appear to have influenced the submitted work.
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24 **Contributions**

25
26 GM contributed to model design, creation, and implementation, data analysis and manipulation,
27
28 analysis of results, figure creation, and writing. LP contributed to writing, editing, data
29
30 collection, study design, and literature review. MB contributed to model design, writing, and
31
32 editing. TH contributed to writing, editing, and literature search. EW contributed to writing,
33
34 editing, data collection, study design, and literature search.
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38 **Transparency declaration**

39
40 G.M. affirms that this manuscript is an honest, accurate, and transparent account of the study
41
42 being reported; that no important aspects of the study have been omitted; and that any
43
44 discrepancies from the study as planned (and, if relevant, registered) have been explained.
45
46

47 **Acknowledgments**

48
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50
51 providing detailed data on COVID-19 transmission. At the time that this work was conducted,
52
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3 and Quality and L.P. was partially supported by the Veterans Health Administration. The content
4
5 is solely the responsibility of the authors and does not necessarily represent the policy or views
6
7 of the Agency of Healthcare Research and Quality, the Veterans Health Administration or the
8
9 United States Government.
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11 **Data Sharing Statement**

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14 Whenever possible, in accordance with previously signed data usage agreements, we will make
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16 the data used in this study available upon reasonable request to GM.
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Figures

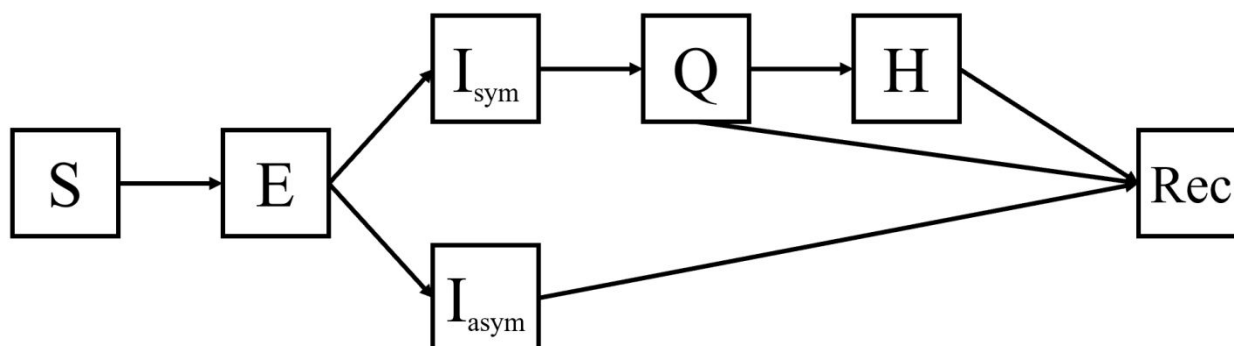


Figure 1. Structure of the disease transmission model. These disease states included susceptible (S), exposed (E), infected symptomatic (I_{sym}), infected asymptomatic (I_{asym}), quarantined (Q), hospitalized (H), and recovered (Rec) individuals.

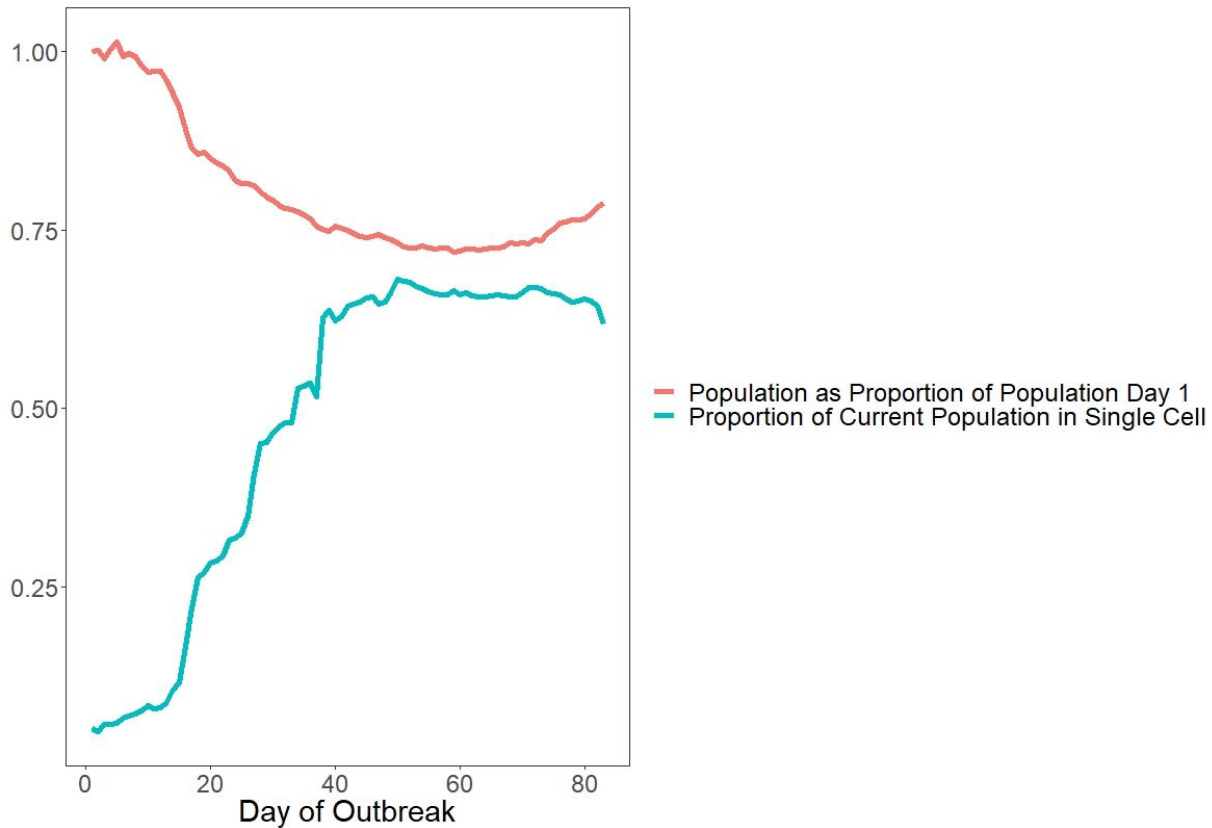


Figure 2. Change in the total population of the jail and the portion of the population in single-occupancy cells over the course of the outbreak. As depopulation increases, the overall population as a proportion of the population on day 1 of the outbreak decreases. Additionally, the proportion of incarcerated people in single-occupancy cells increases over time.

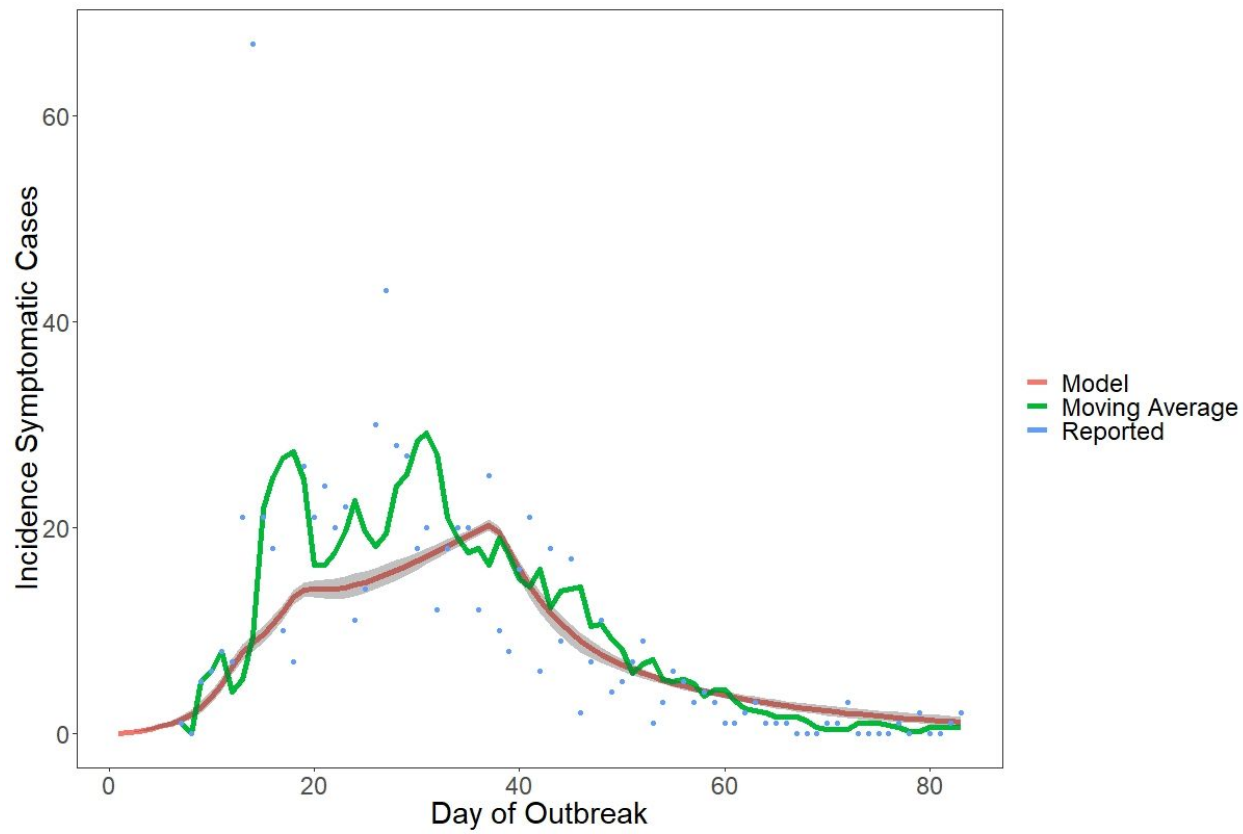


Figure 3. Comparison of the incidence of symptomatic cases in the model with reported COVID-19 incidence at the jail.

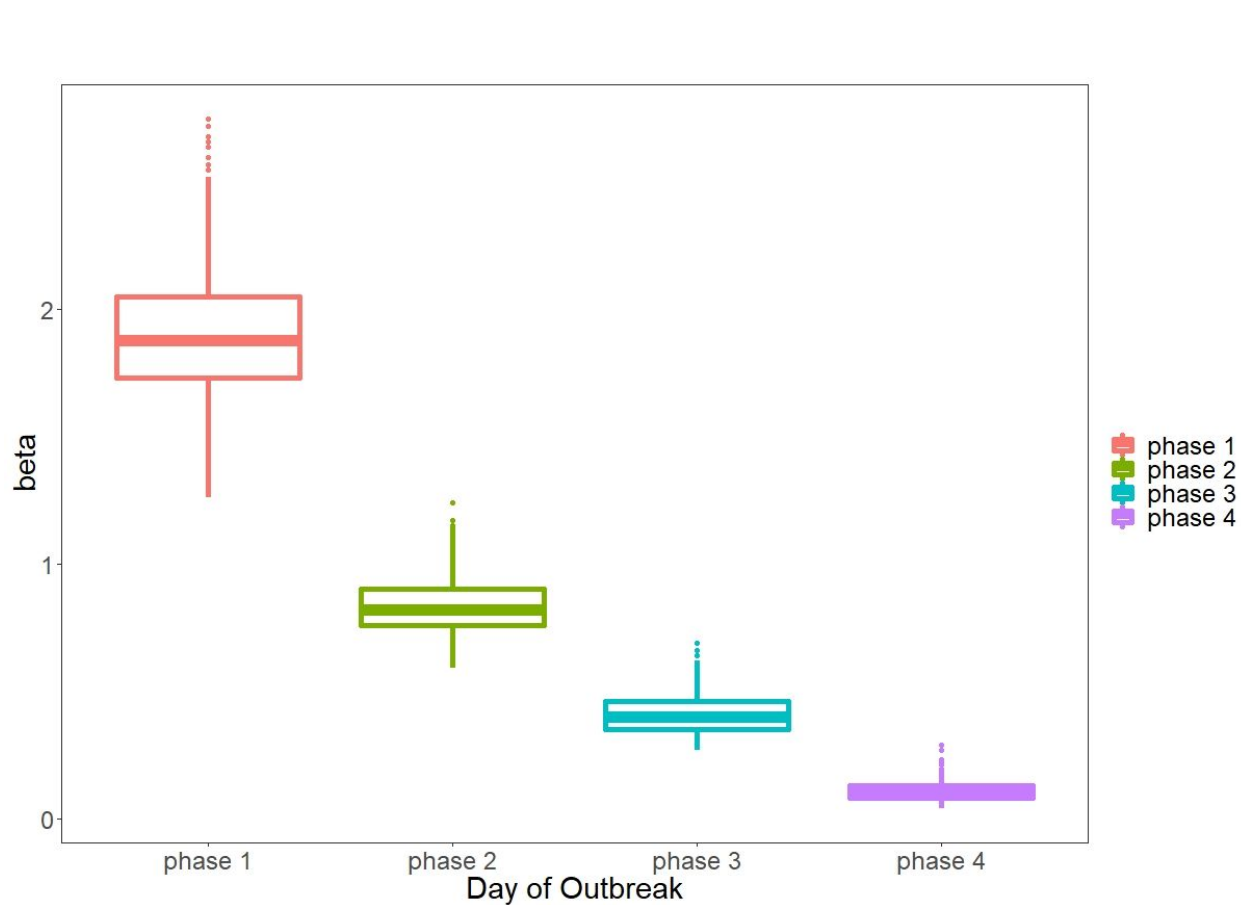


Figure 4. Calibrated values of the transmission rate β for different outbreak phases (Phase 1: initial outbreak, Phase 2: depopulation began, Phase 3: increased single celling, Phase 4: widespread testing of asymptomatic incarcerated individuals).

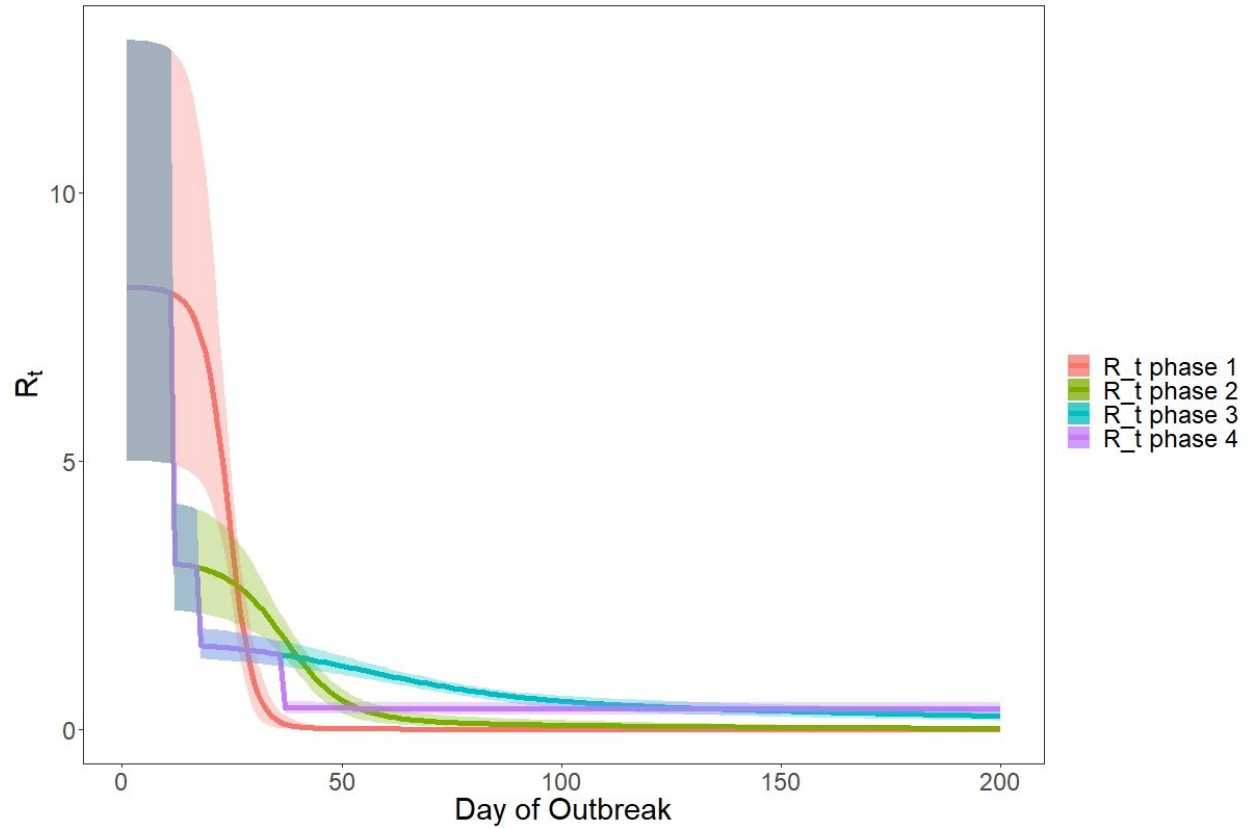


Figure 5. Calculated values of the effective reproduction ratio R_t for all intervention phases (Phase 1: initial outbreak, Phase 2: depopulation began, Phase 3: increased single celling, Phase 4: widespread testing of asymptomatic incarcerated individuals).

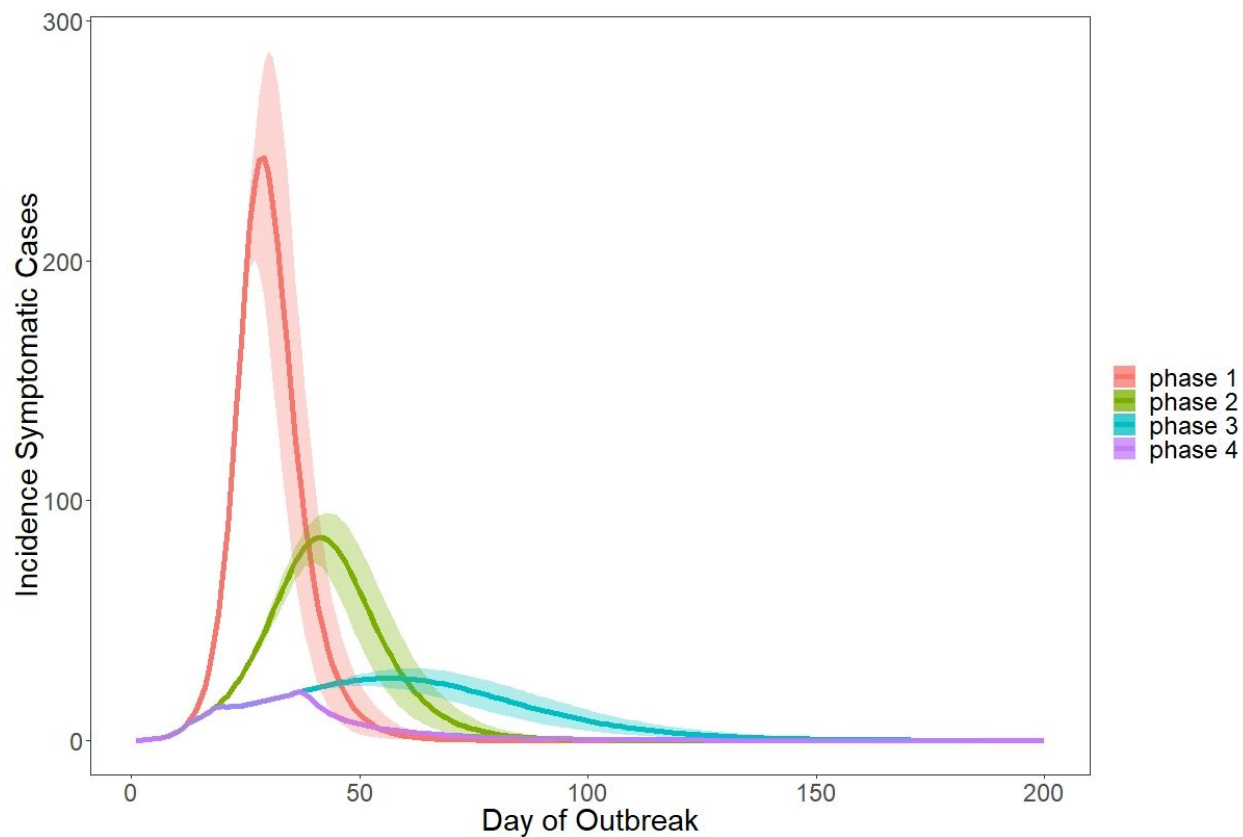


Figure 6. Projected incidence of symptomatic cases for all intervention phases (Phase 1: initial outbreak, Phase 2: depopulation began, Phase 3: increased single celling, Phase 4: widespread testing of asymptomatic incarcerated individuals).

Table 1. Parameter Estimates

Name	Description	Value	Source
b	Net rate of entrance into the jail, phase 1 [1/day]	-0.004	Jail dataset
	Net rate of entrance into the jail, phase 2 [1/day]	-0.0141	
	Net rate of entrance into the jail, phase 3 [1/day]	-0.0076	
	Net rate of entrance into the jail, phase 4 [1/day]	0.0005	
β	Transmission rate [1/day]		Calibrated
ε	Incubation period ¹ [1/day]	0.18	12
		Incubation period: <i>Lognormal</i> (5.1, 0.89)	
α	Proportion of cases that are asymptomatic	0.405	13 14
		<i>uniform</i> (0.25, 0.56)	
γ	Recovery rate [1/day]	0.1	15 16
		Infection period: <i>Truncated N</i> (10, 6.25, <i>min</i> = 5, <i>max</i> = 20)	
η	Proportion of symptomatic infections that are hospitalized	0.14	Jail dataset
λ	Recovery rate from hospital [1/day]	0.2	16
		Length of hospitalization: <i>Lognormal</i> (5,1)	

Table 2. Intervention Effects: Estimated Transmission Rates (β), Effective Reproduction Ratios (R_0), and Disease Cases for each Outbreak Phase

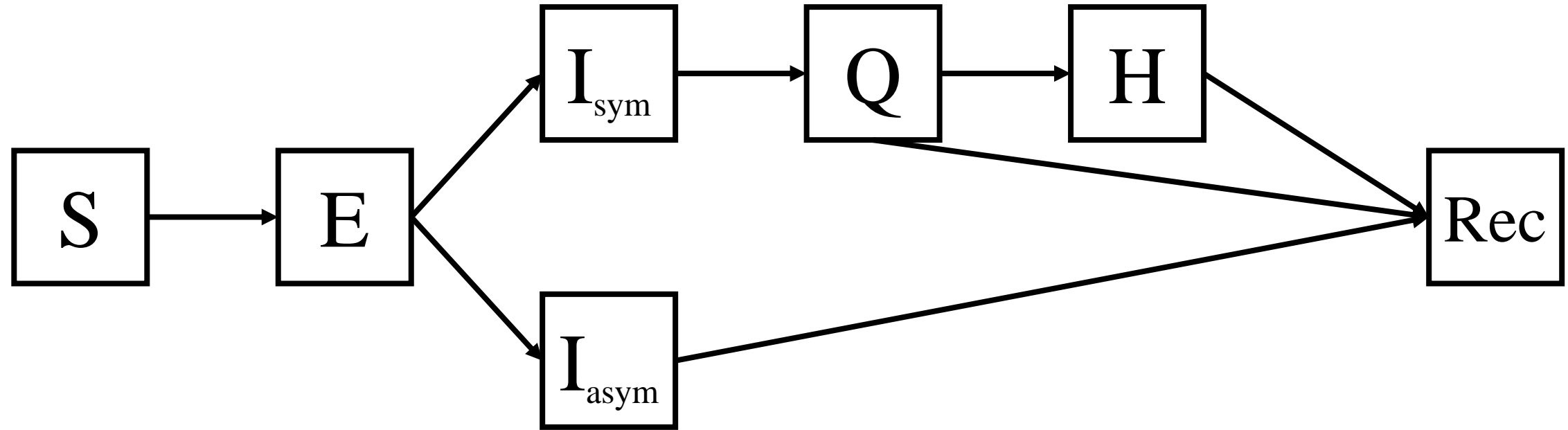
Phase	Time Range in Days	β (95% CrI)	R_0 (95% CrI)	Reduction in β and R_0 from Previous Phase	Expected Total Symptomatic Cases, Day 83* (95% CrI)	Expected Total Hospitalizations, Day 83* (95% CrI)	Expected Total Deaths, Day 83* (95% CrI)	Expected Total Cases, Day 200* (95% CrI)
1: Initial outbreak	1 – 11	1.89 (1.44 - 2.44)	8.25 (5.01 - 12.90)		3,867 (2,742 - 5,044)	541 (384 - 706)	38 (29 - 47)	6,372 (6,318 - 6,437)
2: Depopulation	12 – 17	0.83 (0.66 - 1.06)	3.58 (2.46 - 5.08)	56%	2,520 (1,940 - 3,088)	353 (272 - 432)	24 (20 - 28)	4,055 (3,666 - 4,294)
3: Increased single celling	18 – 36	0.41 (0.30 - 0.56)	1.72 (1.41 - 2.12)	51%	1,447 (1,224 - 1,654)	203 (171 - 232)	12 (11 - 13)	2,950 (2,331 - 3,521)
4: Widespread testing of asymptomatic incarcerated individuals	37 – 83	0.11 (0.06 - 0.20)	0.45 (0.32 - 0.59)	73%	642 (592 - 692)	90 (83 - 97)	3.9 (3.6 - 4.1)	1,121 (904 - 1,433)

* Assuming the value of β estimated for this intervention phase occurs during all subsequent days.

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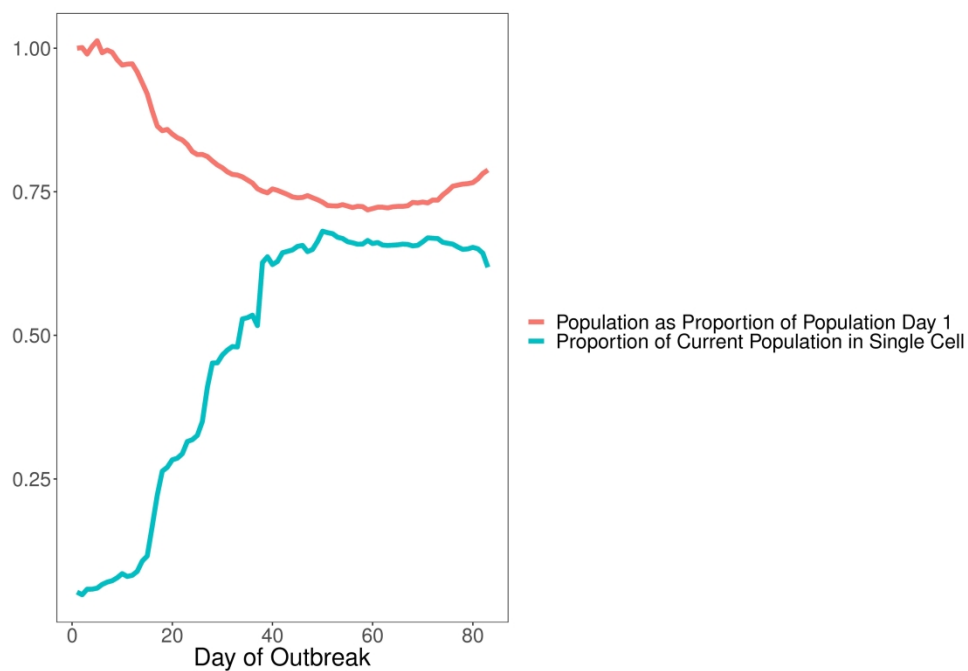


Figure 2. Change in the total population of the jail and the portion of the population in single-occupancy cells over the course of the outbreak. As depopulation increases, the overall population as a proportion of the population on day 1 of the outbreak decreases. Additionally, the proportion of incarcerated people in single-occupancy cells increases over time.

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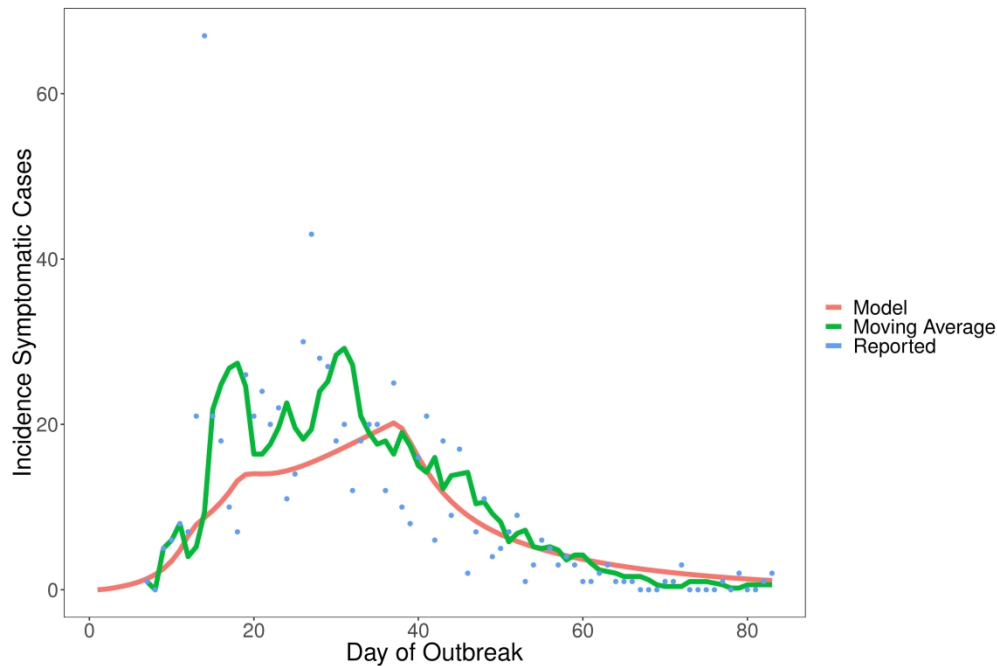


Figure 3. Comparison of the incidence of symptomatic cases in the model with reported COVID-19 incidence at the jail.

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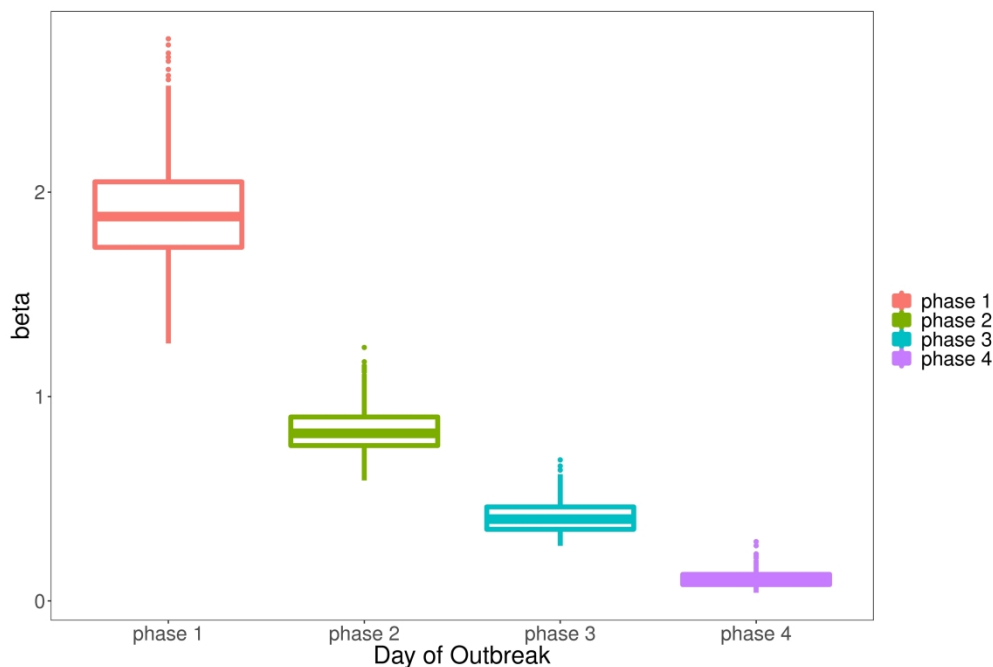


Figure 4. Calibrated values of the transmission rate β for different outbreak phases (Phase 1: initial outbreak, Phase 2: depopulation began, Phase 3: increased single celling, Phase 4: widespread testing of asymptomatic incarcerated individuals).

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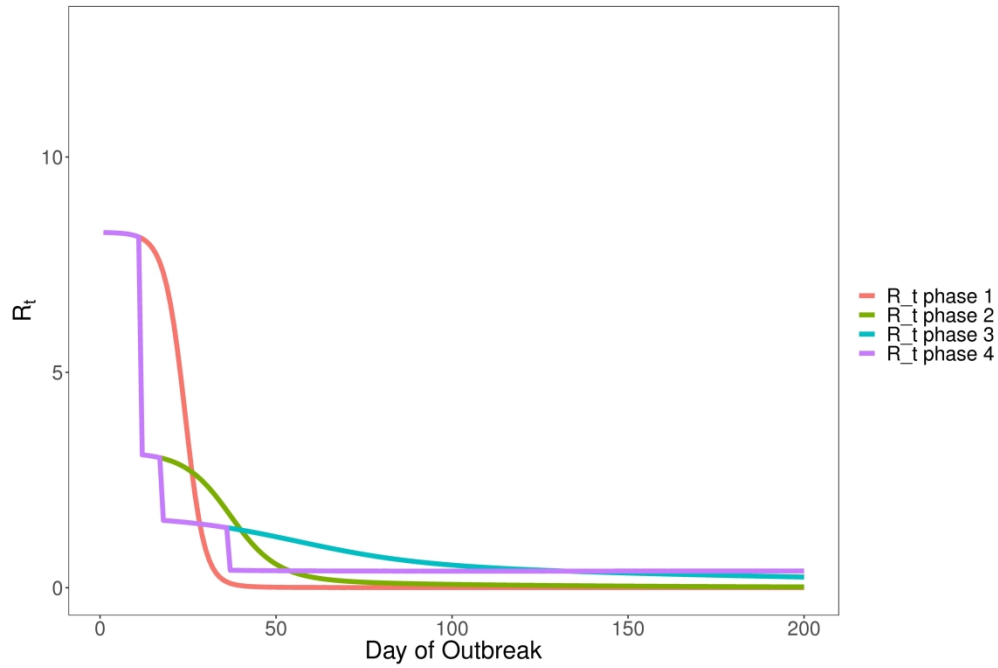


Figure 5. Calculated values of the effective reproduction ratio R_t for all intervention phases (Phase 1: initial outbreak, Phase 2: depopulation began, Phase 3: increased single celling, Phase 4: widespread testing of asymptomatic incarcerated individuals).

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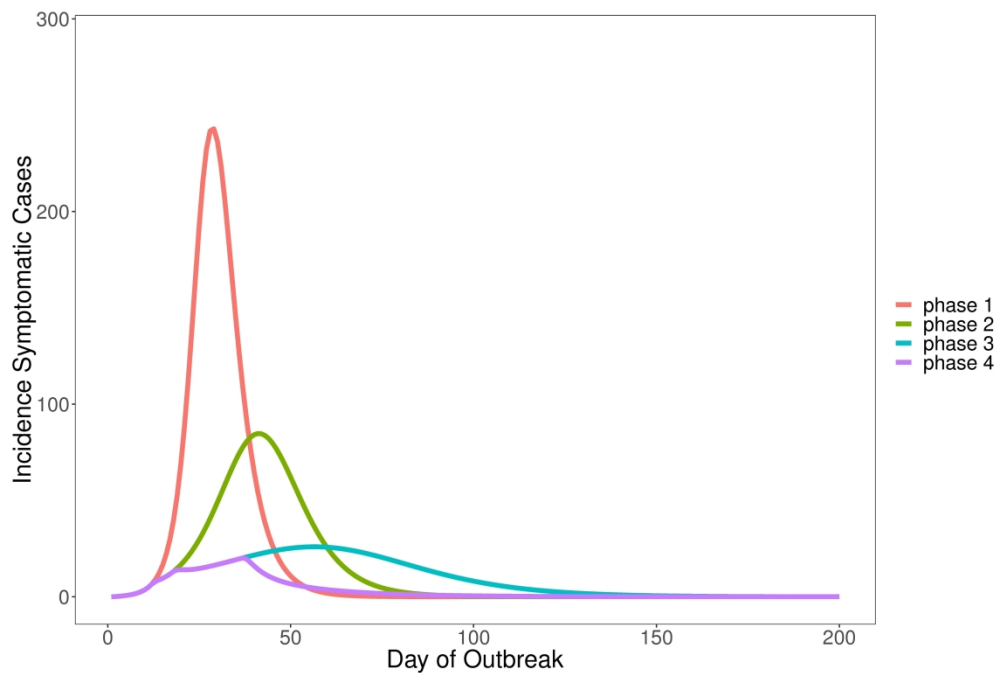


Figure 6. Projected incidence of symptomatic cases for all intervention phases (Phase 1: initial outbreak, Phase 2: depopulation began, Phase 3: increased single celling, Phase 4: widespread testing of asymptomatic incarcerated individuals).

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BMJ Open

The effectiveness of interventions to reduce COVID-19 transmission in a large urban jail: A model-based analysis

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3 1 **The effectiveness of interventions to reduce COVID-19 transmission in a large urban jail:**

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5 2 **A model-based analysis**

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3 28 **ABSTRACT**
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5 29 **Objectives:** We aim to estimate the impact of various mitigation strategies on COVID-19
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8 30 transmission in a U.S. jail beyond those offered in national guidelines.
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10 31 **Design:** We developed a stochastic dynamic transmission model of COVID-19.
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12 32 **Setting:** One anonymous large urban U.S. jail.
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14 33 **Participants:** Several thousand staff and incarcerated individuals.
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17 34 **Interventions:** There were four intervention phases during the outbreak: the start of the
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19 35 outbreak, depopulation of the jail, increased proportion of people in single cells, and
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21 36 asymptomatic testing. These interventions were implemented incrementally and in concert with
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23 37 one another.
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26 38 **Primary and Secondary Outcome Measures:** The basic reproduction ratio, R_0 , in each phase,
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28 39 as estimated using the next generation method. The fraction of new cases, hospitalizations, and
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30 40 deaths averted by these interventions (along with the standard measures of sanitization, masking,
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32 41 and social distancing interventions).
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35 42 **Results:** For the first outbreak phase, the estimated R_0 was 8.44 (95% CrI: 5.00 to 13.10), and
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37 43 for the subsequent phases, $R_{0,phase\ 2} = 3.64$ (95% CrI: 2.43 to 5.11), $R_{0,phase\ 3} = 1.72$ (95% CrI:
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39 44 1.40 to 2.12), and $R_{0,phase\ 4} = 0.58$ (95% CrI: 0.43 to 0.75). In total, the jail's interventions
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41 45 prevented approximately 83% of projected cases, hospitalizations, and deaths over 83 days.
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45 46 **Conclusions:** Depopulation, single celling, and asymptomatic testing within jails can be
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47 47 effective strategies to mitigate COVID-19 transmission in addition to standard public health
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49 48 measures. Decision makers should prioritize reductions in the jail population, single celling, and
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51 49 testing asymptomatic populations as additional measures to manage COVID-19 within
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53 50 correctional settings.
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3 51 **Strengths and limitations of this study**

- 4 52
- 5 53 • COVID-19 has entered hundreds of correctional facilities in the United States, yet few empirical studies have focused on COVID-19 transmission in correctional facilities.
 - 6 54 • We developed a stochastic dynamic transmission model describing the spread of COVID-19 in a large urban jail in the United States and calibrated the model to a moving average of the daily incident cases of COVID-19 reported by the jail.
 - 7 55 • We identified three major interventions – depopulation, single celling, and asymptomatic testing – undertaken by the jail and quantified the reduction in transmission rate as a result of these interventions.
 - 8 56 • We report the estimated reduction in predicted cases, hospitalizations, and deaths as a result of the jail interventions among both incarcerated people and correctional staff.
 - 9 57 • The model assumes homogeneous mixing and does not capture transmission to and from the surrounding community.
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65 INTRODUCTION

66 COVID-19, the disease caused by the SARS-CoV-2 virus, has affected millions of people
67 worldwide, with disproportionate impact on some communities including those inside
68 correctional facilities. In the United States (U.S.), approximately 2.2 million people are
69 incarcerated in any given day in over 5,000 facilities,¹ where the built environment and activities
70 of daily living make physical distancing exceedingly difficult to implement.²⁻⁴ As of the third
71 week of April 2020, 420 U.S. correctional facilities had at least one diagnosed case of COVID-
72 19, accounting for a total of 4,893 cases among incarcerated individuals and 2,778 cases among
73 staff members.³ As of June, correctional facilities accounted for eight out of ten of the largest
74 COVID-19 outbreaks nationally, surpassing nursing homes and food processing plants, and 26
75 states had a higher rate of COVID-19 infection in their correctional population than in their
76 general population.^{5, 6} In spring 2020, Cook County Jail had one of the largest outbreaks in the
77 country, and the infection rate at Rikers Island was nearly five times that of New York City.^{7, 8}
78
79 Despite the severity of outbreaks in correctional facilities, national guidance surrounding the
80 prevention and management of COVID-19 within such settings has been limited. In the weeks
81 after the first major outbreak in a U.S. jail, the U.S. Centers for Disease Control and Prevention
82 (CDC) published policy guidelines for correctional facilities to help mitigate COVID-19
83 transmission; these included limiting transfer of incarcerated people between facilities,
84 restricting the number of visitors entering facilities, promoting personal hygiene and
85 environmental sanitization, maximizing the space between those incarcerated (i.e., arranging
86 bunks so individuals sleep head to toe), and screening staff for symptoms.⁹

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3 88 However, CDC guidelines then and still now do not account for the difficulty that many facilities
4
5 89 face in managing COVID-19. Even among those facilities which are not crowded, physical
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7 90 distancing is challenging given use of congregate living arrangements, shared meals, and
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9 91 exercise and recreation programming. In the absence of more targeted guidelines, there is wide
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11 92 variance in how correctional facilities are managing COVID-19, especially regarding
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13 93 depopulation efforts that may mitigate COVID-19 and approaches to testing (symptomatic only
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15 94 vs. asymptomatic, viral testing vs. antibody testing). As an example, Attorney General Barr has
16
17 95 ordered that medically frail individuals in federal prisons be released to home quarantine,
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19 96 whereas many U.S. state prison systems have no stated policies for larger scale release. Some
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21 97 correctional systems have implemented a one-time systemwide testing of all incarcerated
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23 98 individuals, including those who are asymptomatic, while others are only testing those who are
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25 99 symptomatic.
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33 101 The effectiveness of various mitigation measures, many of which fall outside of CDC guidance,
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35 102 in reducing the transmission of COVID-19 within correctional facilities has yet to be established.
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37 103 In this study, we estimate the effectiveness of measures beyond standard CDC recommendations
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39 104 to mitigate the spread of COVID-19 in a large urban jail. With the aim of providing guidance to
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41 105 correctional policymakers and public health agencies, we focus on policies that could have large
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43 106 impact and are highly variable in implementation, namely depopulation (cessation of new
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45 107 detentions and release of incarcerated individuals), single celling (percentage of the total
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47 108 incarcerated population in a single cell), and testing asymptomatic individuals.
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109 METHODS

110 We developed a stochastic dynamic transmission model of COVID-19 which we calibrated to
111 the outbreak in the jail. We combined data on cases among incarcerated people and correctional
112 staff because they interact very closely and regularly as an ecosystem behind the walls of the jail.
113 Cases were confirmed using SARS-CoV-2 nasal swab PCR tests. We divided the outbreak
114 timeline into four intervention phases marked by the start of the outbreak, start of depopulation
115 efforts, increased single celling, and large-scale asymptomatic testing of incarcerated individuals.
116 We estimated the initial basic reproduction ratio, R_0 , and the effective reproduction ratio, R_t , in
117 each phase, for the entire jail. We also estimated the fraction of new cases, hospitalizations, and
118 deaths averted by the combined interventions in addition to the standard CDC recommended
119 guidance.

120

121 *Model description*

122 We modified a traditional SEIR model to represent the disease states of COVID-19. These
123 disease states included susceptible (S), exposed (E), infected symptomatic (I_{sym}), infected
124 asymptomatic (I_{asym}), infected asymptomatic undetected ($I_{asym,undetected}$), quarantined
125 symptomatic (Q), quarantined asymptomatic (Q_{asym}), hospitalized (H), and recovered (Rec)
126 individuals (Figure 1). Individuals in the infected states (I_{sym} , I_{asym} , $I_{asym,undetected}$) are assumed
127 to be infectious, whereas individuals in the exposed state (E) are not yet infectious. Some
128 correctional systems distinguish between quarantining exposed groups together and isolating
129 confirmed cases. In this model, the quarantined state includes both.

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3 131 To model these interacting populations, we developed a mass-action mixing model described by
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5 132 the following equations:

$$6 \quad 133 \quad \frac{dS}{dt} = bS - \frac{\beta S}{N}(I_{sym} + I_{asym} + I_{asym,undetected}) \quad (1)$$

$$7 \quad 134 \quad \frac{dE}{dt} = bE + \frac{\beta S}{N}(I_{sym} + I_{asym} + I_{asym,undetected}) - \varepsilon E \quad (2)$$

$$8 \quad 135 \quad \frac{dI_{sym}}{dt} = (1 - \alpha)\varepsilon E - I_{sym} \quad (3)$$

$$9 \quad 136 \quad \frac{dI_{asym}}{dt} = bI_{asym} + \alpha\varepsilon E - I_{asym} \quad (4)$$

$$10 \quad 137 \quad \frac{dI_{asym,undetected}}{dt} = bI_{asym,undetected} + (1 - p_{detected})I_{asym} - \gamma I_{asym,undetected} \quad (5)$$

$$11 \quad 138 \quad \frac{dQ}{dt} = I_{sym} - (1 - \eta)\gamma Q - \eta\left(\frac{1}{\gamma} - \frac{1}{\mu}\right)^{-1} Q \quad (6)$$

$$12 \quad 139 \quad \frac{dQ_{asym}}{dt} = p_{detected}I_{asym} - \gamma Q_{asym} \quad (7)$$

$$13 \quad 140 \quad \frac{dH}{dt} = \eta\left(\frac{1}{\gamma} - \frac{1}{\mu}\right)^{-1} Q - \mu H \quad (8)$$

$$14 \quad 141 \quad \frac{dRec}{dt} = (1 - d_I)(1 - \eta)\gamma Q + (1 - d_I)\mu H + \gamma I_{asym,undetected} + \gamma Q_{asym} \quad (9)$$

$$15 \quad 142 \quad \frac{dDead}{dt} = d_I(1 - \eta)\gamma Q + d_I\mu H \quad (10)$$

$$16 \quad 143 \quad N = S + E + I_{sym} + I_{asym} + I_{asym,undetected} + Q + Q_{asym} + H + Rec \quad (11)$$

17 144 The susceptible, exposed, and asymptomatic infected populations grew at rate b which
18 145 represented the overall growth or reduction in jail population. We assume that symptomatic
19 146 infected individuals are not removed from the jail during general depopulation and would be
20 147 admitted directly to quarantine. For the time horizon of the model, the population was generally
21 148 shrinking. Susceptible individuals were exposed to COVID-19 at transmission rate β . We re-
22 149 calibrated this transmission rate for each of the four outbreak phases. We assumed that
23 150 asymptomatic and symptomatic infected individuals could transmit the disease.^{10, 11} Exposed

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3 151 individuals were not yet infectious and become asymptomatic or symptomatic infected at rate ε ,
4
5 152 which corresponded to the incubation period of COVID-19. A certain proportion, α , of these
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7 153 individuals stayed asymptomatic, while remaining individuals became symptomatic. Based on
8
9 154 the jail's report, we assumed that symptomatic infected individuals and a fraction, $p_{detected}$, of
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11 155 asymptomatic infected individuals were identified one day after symptoms presented and placed
12
13 156 in quarantine after identification. We assumed that individuals once quarantined did not transmit
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15 157 COVID-19, as they were isolated from the susceptible population. A fraction, η , of quarantined
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17 158 individuals were hospitalized and recovered from hospitalization at rate μ . All infected
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19 159 individuals recovered or died at rate γ regardless of symptomatic or asymptomatic status.
20
21
22 160 Symptomatic infected individuals died with probability d_I .
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29 162 *Interventions*

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31 163 The jail implemented various measures over time to mitigate the spread of COVID-19. We
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33 164 divide the outbreak into four intervention phases, corresponding to the initiation of key measures
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35 165 of interest which fell outside the guidance of the CDC. The interventions were implemented
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37 166 incrementally and in an additive manner, with depopulation first added, then single-celling
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39 167 added, then asymptomatic testing added. The days when these interventions were added are
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42 168 shown in Figure 2.
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47 170 During Phase 1 (days 1-11), the jail implemented a broad array of strategies that were consistent
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49 171 with CDC guidance including: basic screening for flu-like symptoms in incarcerated people; new
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51 172 detainees quarantined for at least 7 days; basic screening for flu-like symptoms for visitors,
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54 173 vendors, attorneys, and community members entering the facility; staff required to report
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3 174 symptoms, as well as contact with known COVID-19 positive cases and any travel outside of the
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5 175 U.S.; suspension of all tours, large gatherings, and in-person visitation. Sanitation techniques
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7 176 continued to follow CDC guidance for the duration of the outbreak and no significant new
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10 177 techniques were introduced during any other phases. A total of 23 SARS-Co-V-2 tests were
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12 178 performed in this phase; 19 were positive (positivity rate 82.6%).
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17 180 During phase 2 (days 12-17), the jail population started to decrease by 1.41% each day through a
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19 181 combination of measures which included a marked decrease in new detentions given changes in
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21 182 court and judicial system procedures and large community organized bail outs (Figure 2). The
22
23 183 jail also began taking the temperature of all employees each day. Lastly, they started on-site
24
25 184 voluntary testing for employees and a two-week COVID-19 paid leave policy for all employees.
26
27 185 A total of 149 SARS-Co-V-2 tests were performed in this phase; 139 were positive (positivity
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29 186 rate 93.2%).
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35 188 During phase 3 (days 18-36), the jail began increasing the proportion of the population in single-
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37 189 occupancy cells from 26% on day 18 to 54% on day 36. During this period, they began requiring
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39 190 all staff to wear surgical masks and allotted new masks to those incarcerated each day. They also
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41 191 continued to isolate confirmed and suspected COVID-19 cases among incarcerated individuals.
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43 192 At this time, given the growing number of individuals, they identified a different building for
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45 193 segregating patients which provided a larger space for confirmed cases. A total of 455 SARS-
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47 194 Co-V-2 tests were performed in this phase; 253 were positive (positivity rate 55.6%).
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3 196 During phase 4 (days 37-83), the jail began testing for asymptomatic cases at a rate of
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5 197 approximately 50-75 people per day in divisions with high numbers of cases identified during
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7 198 contact tracing. A total of 2741 SARS-Co-V-2 tests were performed in this phase; 523 were
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9 199 positive (positivity rate 19.5%).
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14 201 *Model Instantiation and Calibration*

16 202 We estimated some model parameter values from previous literature (Table 1). The rate at which
17
18 203 exposed individuals became asymptotically or symptomatically infected, ϵ , was the inverse of
19
20 204 the incubation period. The incubation period of COVID-19 was previously described with a
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22 205 lognormal distribution with mean 5.1 days and standard deviation 0.89 days.¹² We assumed that
23
24 206 the proportion of infections that are asymptomatic, α , was uniformly distributed over the range
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26 207 0.25 to 0.56.^{13, 14} The average recovery rate was previously estimated to be 0.1, the inverse of the
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28 208 10-day mean infection period.¹⁵ We assumed that the infection period followed a truncated
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30 209 normal distribution with mean 10 days, standard deviation 6.25 days, minimum 5 days, and
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32 210 maximum 20 days. Additionally, the average length of hospitalization from COVID-19 has been
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34 211 estimated to be 5 days, making the daily recovery probability from the hospital 0.2.¹⁶ We
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36 212 assumed that the length of hospitalization followed a lognormal distribution with a mean of 5
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38 213 days and standard deviation of 1 day.
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46 215 The jail provided demographic data about the size of the incarcerated population per day, as well
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48 216 as epidemiological data about confirmed COVID-19 cases over the course of 83 days. We
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50 217 assumed an average reporting delay of six days from first exposure to reported incident cases.
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52 218 This accounts for the mean incubation period and a minor delay between symptom onset and
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3 219 COVID-19 test result and isolation. The jail provided data on the age of the infected person, date
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5 220 of positive COVID-19 test, the work or incarceration location of the infected individual, and
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7 221 whether the individual was hospitalized or died as a result of the COVID-19 infection. Testing
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9 222 was performed upon admission to the jail and through symptom onset or contact tracing. We
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11 223 used these data to calculate the proportion of symptomatic infections that were hospitalized or
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13 224 died. For each intervention phase, we used the epidemiological data to determine the growth rate,
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15 225 b , as the average rate of growth for the entire facility.
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21 227 We calibrated the transmission rate, β , for each intervention phase. We first pseudo-randomly
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23 228 selected values for parameters ε , α , γ , and μ based on our assumed distributions (Table 1). Then,
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25 229 we calculated b for the intervention phase. To find the best-fitting value of β for the given
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27 230 parameter set, we implemented an exhaustive search over the range $[0,4]$ in increments of 0.01.
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29 231 We chose the value of β which minimized the sum of mean squared error between the reported
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31 232 daily incident cases of confirmed COVID-19 cases among incarcerated people and staff in the
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33 233 jail to the daily incident cases of symptomatic infected cases in the model for that phase. We
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35 234 calculated incident symptomatic cases using the raw reported incident cases before
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37 235 asymptomatic testing. Select asymptomatic testing for incarcerated people began on day 31 and
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39 236 for staff began on site on day 21. After asymptomatic testing began, we took the minimum of the
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41 237 jail-provided data on the number of symptomatic tests multiplied by the average percentage of
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43 238 positive results of symptomatic tests between days 16-30 (89%) and the raw reported incident
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45 239 cases. Based on this estimate, on average, 82% of the reported daily incident cases among the
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47 240 incarcerated population was symptomatic after asymptomatic testing began. Because we did not
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241 have testing data for staff, we assumed that 82% of reported new staff cases were symptomatic
 242 after on-site testing became available for staff.

243
 244 We used a simple moving average of the previous five days of symptomatic incident cases to
 245 smooth the calibration targets. We assumed that the reported incident cases corresponded to the
 246 number of incarcerated individuals and staff members who showed symptoms of COVID-19. For
 247 each intervention phase, we ran 1,000 Monte Carlo simulations and defined the 95% credible
 248 interval of β as the range in which 95% of calibrated values of β fell.

249

250 *Calculation of R_0 and R_t*

251 To calculate R_0 and R_t , we used the next generation method.¹⁷ This method utilizes two matrices
 252 of partial derivatives of compartments with infected individuals.¹⁸ In our model, this included
 253 exposed, asymptomatic infected, symptomatic infected, quarantined, and hospitalized
 254 individuals. The first matrix, F , is the rate of appearance of new infections for each
 255 compartment. Each element, f_{ij} , of F is the partial derivative of any term in which new
 256 infections appear in compartment i with respect to compartment j where $i, j \in$
 257 $[E, I_{sym}, I_{asym}, I_{asym,undetected}, Q, Q_{asym}, H]$.

$$258 \quad F = \begin{matrix} E \\ I_{sym} \\ I_{asym} \\ I_{asym,undetected} \\ Q \\ Q_{asym} \\ H \end{matrix} \begin{bmatrix} 0 & \frac{\beta S}{N} & \frac{\beta S}{N} & \frac{\beta S}{N} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (10)$$

259 The second matrix, V , is the rate of transfer of individuals out of a compartment minus the rate of
 260 transfer of individuals into a compartment. Therefore, each element, v_{ij} , of V is the partial

261 derivative of the additive inverse of any term other than the appearance of new infections in
 262 compartment i with respect to compartment j . The matrix V and its inverse are as follows:

$$263 \quad V = \begin{matrix} E \\ I_{sym} \\ I_{asym} \\ I_{asym,undetected} \\ Q \\ Q_{asym} \\ H \end{matrix} \begin{bmatrix} \varepsilon - b & 0 & 0 & 0 & 0 & 0 & 0 \\ -(1 - \alpha)\varepsilon & 1 & 0 & 0 & 0 & 0 & 0 \\ -\alpha\varepsilon & 0 & 1 - b & 0 & 0 & 0 & 0 \\ 0 & 0 & -(1 - p_{detected}) & \gamma - b & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & (1 - \eta)\gamma + \eta\left(\frac{1}{\gamma} - \frac{1}{\mu}\right)^{-1} & 0 & 0 \\ 0 & 0 & -p_{detected} & 0 & 0 & \gamma & 0 \\ 0 & 0 & 0 & 0 & -\eta\left(\frac{1}{\gamma} - \frac{1}{\mu}\right)^{-1} & 0 & \mu \end{bmatrix} \quad (11)$$

$$264 \quad V^{-1} = \begin{matrix} E \\ I_{sym} \\ I_{asym} \\ I_{asym,undetected} \\ Q \\ Q_{asym} \\ H \end{matrix} \begin{bmatrix} (\varepsilon - b)^{-1} & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{(\alpha - 1)\varepsilon}{b - \varepsilon} & 1 & 0 & 0 & 0 & 0 & 0 \\ \frac{\alpha\varepsilon}{(b - \varepsilon)(b - 1)} & 0 & (1 - b)^{-1} & 0 & 0 & 0 & 0 \\ \frac{\alpha(p_{detected} - 1)\varepsilon}{(b - \varepsilon)(b - 1)(b - \gamma)} & 0 & \frac{1 - p_{detected}}{(b - 1)(b - \gamma)} & (\gamma - b)^{-1} & 0 & 0 & 0 \\ \frac{-(\alpha - 1)\varepsilon(\gamma - \mu)}{\gamma(b - \varepsilon)(\gamma(\eta - 1) + \mu)} & \frac{\mu - \gamma}{\gamma(\gamma(\eta - 1) + \mu)} & 0 & 0 & \frac{\mu - \gamma}{\gamma(\gamma(\eta - 1) + \mu)} & 0 & 0 \\ \frac{\alpha p_{detected}\varepsilon}{(b - \varepsilon)(b - 1)\gamma} & 0 & \frac{p_{detected}}{\gamma - \gamma b} & 0 & 0 & \gamma^{-1} & 0 \\ \frac{(\alpha - 1)\eta\varepsilon}{(b - \varepsilon)(\gamma(\eta - 1) + \mu)} & \frac{\eta}{\gamma(\eta - 1) + \mu} & 0 & 0 & \frac{\eta}{\gamma(\eta - 1) + \mu} & 0 & \mu^{-1} \end{bmatrix} \quad (12)$$

265 The next generation method calculates R_0 as the dominant eigenvalue of the next generation
 266 matrix. The next generation matrix is defined as FV^{-1} :

$$267 \quad FV^{-1} = \begin{bmatrix} \frac{\beta S\varepsilon(ab^2 - aby + \alpha p_{detected} - \alpha - b^2 + b\gamma + b - \gamma)}{N(b - \varepsilon)(b - 1)(b - \gamma)} & \frac{\beta S}{N} & \frac{\beta S(\gamma - b - p_{detected} + 1)}{N(b - 1)(b - \gamma)} & \frac{\beta S}{N(\gamma - b)} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (13)$$

268 In our model, FV^{-1} has only one nonzero eigenvalue, $\lambda =$

$$269 \quad \frac{\beta S\varepsilon(ab^2 - aby + \alpha p_{detected} - \alpha - b^2 + b\gamma + b - \gamma)}{N(b - \varepsilon)(b - 1)(b - \gamma)}. \text{ Therefore, } R_0 = \max(0, \lambda), \text{ and since } \lambda \geq 0, R_0 = \lambda.$$

270 Since R_0 is directly proportional to β , we can calculate the values of R_0 of other phases simply
 271 by using phase 1 starting conditions combined with the reduced transmission rate.

272

273 To find the effective reproduction ratio, R_t , at time t , we used the next generation method with
 274 the same matrices but updated the values of S and β as appropriate. Because the number of
 275 susceptible individuals, S , is a function of time, we recalculate R_t each day. The functional form
 276 of R_t for our model is as follows:

$$277 \quad R_t = \frac{\beta S_t \varepsilon (\alpha b^2 - \alpha b \gamma + \alpha p_{\text{detected}} - \alpha - b^2 + b \gamma + b - \gamma)}{N(b - \varepsilon)(b - 1)(b - \gamma)} \quad (14)$$

278 We computed the 95% credible interval of R_t as the range in which 95% of calibrated values of
 279 R_t fell.

281 *Sensitivity Analysis*

282 We assumed that the average length of time in the exposed state (i.e., the incubation period) was
 283 5.1 days based on a study of 181 cases in Wuhan, China.¹² Two recent studies estimated that 44-
 284 48% of transmission can come from presymptomatic individuals, suggesting that the mean
 285 length of time in the exposed state could be shorter than we assumed.^{19, 20} Given this recent
 286 evidence, we performed sensitivity analysis where we reduced the mean length of time in the
 287 exposed state by 2.1 days, and correspondingly increased the mean length of time in the
 288 infectious state by 2.1 days. The mean value of ε was updated accordingly to $\frac{1}{3}$. The model
 289 otherwise remained unchanged.

291 *Human subjects*

292 This study was deemed exempt from IRB review by the Yale Human Investigation Committee as
 293 we received completely anonymized data from the jail.

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3 295 *Role of the funding source*
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5 296 The funding sources had no role in the study design, collection, analysis, and interpretation of
6
7 297 data, writing the report, nor the decision to submit the paper for publication.
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9

10 298

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12 299 *Patient and public involvement*
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14 300 No patients were involved.
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19 302 **RESULTS**
20

21 303 The number of daily reported incident cases of COVID-19 in the jail was highly variable,
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23 304 ranging from 0 to 67. The mean absolute error of the model compared to the simple moving
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25 305 average was 29% (Figure 3).
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31 307 *Transmission Rates*
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33 308 When following the initial CDC recommendations for correctional facilities (phase 1), the
34
35 309 baseline transmission rate (β) was 1.79 (95% Credible Interval (CrI): 1.35-2.22) (Figure 4).
36

37 310 After depopulation began (phase 2), the transmission rate was $\beta = 0.78$ (95% CrI: 0.61-0.97).
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39
40 311 This represents a 56% decrease in the transmission rate from phase 1. After the increase in
41
42 312 single-occupancy cells (phase 3), the transmission rate was $\beta = 0.38$ (95% CrI: 0.28-0.52), a 51%
43
44 313 decrease from phase 2. Finally, the transmission rate after testing of asymptomatic individuals
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46 314 began (phase 4) was $\beta = 0.13$ (95% CrI: 0.07-0.24), a 66% decrease from phase 3. All of these
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48 315 reductions are statistically significant.
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317 *Reproduction Ratios*

318 The estimated value of R_0 was highest in phase 1, during the first 11 days of the outbreak (Table
319 2). For this phase, we estimate $R_0 = 8.44$ (95% CrI: 5.00-13.10) (Table 2). We estimate R_0 of
320 each phase in a completely susceptible population as if the outbreak had begun with the values of
321 β which correspond to each phase: $R_{0,phase\ 2} = 3.64$ (95% CrI: 2.43-5.11), $R_{0,phase\ 3} = 1.72$ (95%
322 CrI: 1.40-2.12), and $R_{0,phase\ 4} = 0.58$ (95% CrI: 0.43-0.75). Figure 5 shows the effective
323 reproduction ratio, R_t , over time for all intervention phases. R_t decreased as the susceptible
324 population shrank, the transmission rate changed, and different interventions were implemented.
325 For the entire jail, we estimate that the interventions may have reduced the effective reproduction
326 ratio R_t below 1 about five weeks after the outbreak began (on day 37).

328 *Averted Infections, Hospitalizations, and Deaths*

329 Table 2 shows the expected total symptomatic cases on day 83 and expected total cases on day
330 200, assuming that the estimated transmission rate for a particular outbreak phase holds over all
331 subsequent days. Over the first 83 days of the outbreak, the jail reported 778 symptomatic cases,
332 67 hospitalizations, and 10 deaths among incarcerated individuals and staff. Our model predicts
333 635 symptomatic cases (95% CrI: 506-821), 89 hospitalizations (95% CrI: 71-115), and 6 deaths
334 (95% CrI: 5.8-6.7) over this same time period (Figure 6). Our estimate is 18% less than the
335 number of reported cases that were symptomatic. Compared to what could have happened with
336 only the implemented CDC-recommended interventions of phase 1, the model predicts a
337 reduction of approximately 3,100 symptomatic cases, 435 hospitalizations, and 30 deaths over 83
338 days. This suggests that the combination of interventions (depopulation, increased single celling,
339 and large-scale asymptomatic testing of incarcerated individuals) in addition to standard CDC

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3 340 COVID-19 mitigation strategies led to an 83% reduction in predicted symptomatic cases,
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5 341 hospitalizations, and predicted deaths.
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10 343 *Sensitivity Analysis*

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12 344 In sensitivity analysis, when we assumed an incubation period that was 2.1 days shorter, the
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14 345 calibrated baseline transmission rate was $\beta=1.31$ (95% CrI: 1.00-1.71). After depopulation began
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16 346 (phase 2), the transmission rate was $\beta=0.64$ (95% CrI: 0.41-0.83). This represents a 51%
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18 347 decrease in the transmission rate from phase 1 (compared to a 56% decrease in the base case
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20 348 results). After the increase in single-occupancy cells (phase 3), the transmission rate was $\beta=$
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22 349 0.36 (95% CrI: 0.25-0.49), a 44% decrease from phase 2 (compared to a 51% decrease in the
23
24 350 base case results). Finally, the transmission rate after testing of asymptomatic individuals began
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26 351 (phase 4) was $\beta=0.17$ (95% CrI: 0.09-0.30), a 53% decrease from phase 3 (compared to 66% in
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28 352 the base case). We estimate the following basic reproduction ratios: $R_0 = 6.22$ (95% CrI: 3.56-
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30 353 9.98), $R_{0,phase\ 2} = 3.02$ (95% CrI: 1.95-4.32), $R_{0,phase\ 3} = 1.64$ (95% CrI: 1.33-2.02), and
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32 354 $R_{0,phase\ 4} = 0.75$ (95% CrI: 0.59-0.92).
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41 356 Over the first 83 days of the outbreak, the sensitivity analysis predicts 637 symptomatic cases
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43 357 (95% CrI: 502-827), 89 hospitalizations (95% CrI: 70-116), and 6 deaths (95% CrI: 5.8-6.8),
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45 358 values very close to those predicted in the base case analysis. Thus, even assuming a shorter
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47 359 incubation period, we estimate that the mitigation strategies led to an 83% reduction in predicted
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49 360 symptomatic cases, hospitalizations, and deaths.
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54 362 **DISCUSSION**

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3 363 *Principal findings*
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5 364 Using a stochastic compartmental model, we estimate that depopulation efforts, single celling
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7 365 and asymptomatic testing are important interventions to reduce COVID-19 transmission in jails.
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10 366 We estimate that these actions taken by the jail, in addition to those recommended by the CDC
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12 367 including sanitation and masking, reduced potential new cases by approximately 83% over 83
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14 368 days, and this may have averted more than 435 hospitalizations and 30 deaths among those who
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16 369 live and work in the jail. Taken together, these measures not only have bearing for the
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18 370 correctional facility, but also for the community health systems that surround the jail.
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24 372 *Policy Implications*
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26 373 Our findings suggest that depopulation efforts should be a primary strategy for COVID-19
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28 374 mitigation in jails. Reduction in detained populations to prevent disease transmission is best
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30 375 achieved by both decreasing the number of new intakes and increasing the number of releases.
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32 376 This requires that authorities controlling jail admissions (including police departments, judges,
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34 377 and in some cases correctional departments) and jail releases (including judges, lawyers, and
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36 378 community bail funds) focus on promoting depopulation efforts to mitigate COVID-19
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38 379 transmission.
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44 381 By creating smaller populations within correctional institutions, other mitigation strategies,
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46 382 including physical distancing and the ability to quarantine and medically isolate the incarcerated
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48 383 population that remains when necessary, are easier to implement. Our analysis suggests that
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50 384 single celling, in concert with depopulation, was effective in mitigating COVID-19 transmission.
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53 385 To be clear, single celling does not imply solitary confinement but rather placing one person in a
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3 386 6×9-foot cell to increase physical distancing in correctional facilities.²¹ Given physical crowding
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5 387 in many facilities, even when overall incarcerated populations are at record lows, increasing
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7 388 access to single-occupancy cells will not be feasible without depopulation efforts, and as
8
9 389 supported by our model, will not lead to a contained transmission rate alone. Depopulation
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11 390 should continue in concert with single celling, as depopulation reduces density of shared spaces
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13 391 in common areas. Facilities unable to appropriately place individuals in single cells without
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15 392 relying on solitary confinement should embrace depopulation as a preferred strategy.
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17 393 Decarceration will require interagency coordination to achieve the full public health impact,
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19 394 including testing people prior to release.²² Without testing and ensuring opportunities for
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21 395 community quarantine, correctional facilities may contribute to ongoing transmission in the
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23 396 surrounding community.^{23, 24}
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31 398 Lastly, asymptomatic testing is an important component of COVID-19 mitigation strategies. This
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33 399 jail focused on asymptomatic testing through contact tracing of people who tested positive,
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35 400 medically vulnerable populations, and upon admission. However, more research needs to be
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37 401 conducted on who should be tested and under what circumstances, including whether mass
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39 402 testing is effective, when individuals should be tested, and at what intervals.
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44 404 National and international health agencies, such as the CDC and the World Health Organization,
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46 405 should address depopulation, single celling, and asymptomatic testing in future guidance for
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48 406 detention facilities and should consider how to best implement these measures. Correctional
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50 407 facility administrators will need to consider how to best mitigate the challenges that come with
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52 408 these strategies. For example, coordination of health care and social services organizations prior
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3 409 to release should be prioritized, as should considerations of testing when releasing individuals as
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5 410 part of depopulation efforts.^{4, 22}
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10 412 *Limitations*

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12 413 Our analysis has several limitations. We used a compartmental model which assumes
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14 414 homogeneous mixing among the entire population. Correctional facilities in reality do not exhibit
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16 415 homogeneous mixing, especially across divisions, buildings, or tiers within the facility. Our
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18 416 model does not have the granularity to capture the influence of individuals on transmission
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20 417 dynamics. Our model assumes a relatively stationary population and only accounts for mixing
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22 418 within the jail. Jail populations are highly variable with frequent intakes and releases. Jailed
23
24 419 individuals also have variable daily routines, such as where they eat or exercise, which are not
25
26 420 accounted for in our model. We did not account for possible false positives, misdiagnosis,
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28 421 overreporting, or underreporting in the dataset. Finally, the many interventions undertaken by the
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30 422 jail make it difficult to determine the causal influence of any one intervention.
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37 424 Importantly, these limitations influence our estimates of β and R_0 . We model the jail as a closed
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39 425 system and thus neglect exogenous infection (e.g., staff or new intake incarcerated individuals
40
41 426 who contracted the disease in the community) that likely entered the jail before large-scale
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43 427 testing efforts. Because our analysis assumed that all new infections arise from internal
44
45 428 transmission, we likely overestimate the true values of β and R_0 , particularly in the early phases
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47 429 of the epidemic in the jail. Thus, conclusions resulting from our analysis should focus on the
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49 430 relative reductions of β and R_0 rather than the precise estimates of these values.
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432 *Conclusions*

433 Despite the limitations of our analysis, we conclude that it is possible to mitigate the spread of
434 COVID-19 even in correctional settings, where standard physical distancing practices are
435 difficult to achieve, by implementing depopulation strategies, promoting increased single celling,
436 and asymptomatic testing with appropriate isolation. The large estimated reduction in the
437 transmission rate ($\geq 80\%$) from these three intervention strategies is comparable to standard
438 social distancing measures in a community setting.²⁵ Even when accounting for potential
439 additional pre-symptomatic transmission, the relative reductions in β and R_0 remain very high,
440 further reinforcing the effectiveness of depopulation, single celling, and asymptomatic testing.
441 As states and the federal government are focused on re-opening economies and resurging
442 numbers of cases in many states, strategies should be devised to protect those who are
443 incarcerated and those who work in corrections by further limiting population increases so that
444 future outbreaks are averted.

445

446 **Declaration of interests**

447 All authors have completed the ICMJE uniform disclosure form at
448 www.icmje.org/coi_disclosure.pdf and declare: no support from any organization for the
449 submitted work; no financial relationships with any organizations that might have an interest in
450 the submitted work in the previous three years; no other relationships or activities that could
451 appear to have influenced the submitted work.

452

453 **Contributions**

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2
3 454 GM contributed to model design, creation, and implementation, data analysis and manipulation,
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5 455 analysis of results, figure creation, and writing. LP contributed to writing, editing, data
6
7 456 collection, study design, and literature review. MB contributed to model design, writing, and
8
9 457 editing. TH contributed to writing, editing, and literature search. EW contributed to writing,
10
11 458 editing, data collection, study design, and literature search.
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16 17 460 **Transparency declaration**

18
19 461 GM affirms that this manuscript is an honest, accurate, and transparent account of the study
20
21 462 being reported; that no important aspects of the study have been omitted; and that any
22
23 463 discrepancies from the study as planned (and, if relevant, registered) have been explained.
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27 28 465 **Acknowledgments**

29
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31
32 467 providing detailed data on COVID-19 transmission.
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38
39 470 from the Agency for Healthcare Research and Quality, MB was supported by grant R37-
40
41 471 DA15612 from the National Institute on Drug Abuse, and LP was partially supported by the
42
43 472 Veterans Health Administration (grant number N/A). In the past 36 months, EW received
44
45 473 research support through Yale University from the Bureau of Justice Administration to study
46
47 474 reentry by linking correctional and community health system data (2015-RY-BX-K002) and the
48
49 475 Substance Abuse and Mental Health Services Administration to study how to improve the health
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51 476 of women just released from corrections. EW currently receives research support through Yale
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3 477 University from the National Cancer Institute of National Institute of Health (1R01CA230444),
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12
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16
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18
19 485 Clinic Network in California. The content is solely the responsibility of the authors and does not
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21 486 necessarily represent the policy or views of any of the funding agencies.
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28 489 **Data Sharing Statement**

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31 490 Whenever possible, in accordance with previously signed data usage agreements, we will make
32
33 491 the data used in this study available upon reasonable request to GM.
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3 **563 Figures**
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6 **564**

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8 **565** Figure 1. Structure of the disease transmission model. The disease states included susceptible (S)
9 **566**), exposed (E), infected symptomatic (I_{sym}), infected asymptomatic (I_{asym}), infected
10 **567** asymptomatic undetected ($I_{asym,undetected}$), quarantined (Q), quarantined asymptomatic (Q_{asym}),
11 **568** hospitalized (H), and recovered (Rec) individuals. Detection and subsequent quarantine of
12 **569** asymptomatic individuals are only considered after the start of asymptomatic testing in phase 4.
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14 **570**

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16 **572** Figure 2. Change in the total population of the jail and the portion of the population in single-
17 **573** occupancy cells over the course of the outbreak. As depopulation increases, the overall
18 **574** population as a proportion of the population on day 1 of the outbreak decreases. Additionally, the
19 **575** proportion of incarcerated people in single-occupancy cells increases over time. We denote the
20 **576** timing of each intervention phase on the graph. Phase 1: initial outbreak, Phase 2: depopulation
21 **577** began, Phase 3: increased single celling, Phase 4: widespread testing of asymptomatic
22 **578** incarcerated individuals.
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26 **580** Figure 3. Comparison of the daily number of incident symptomatic cases in the model with
27 **581** reported new symptomatic COVID-19 cases at the jail. Shaded gray area represents 95% credible
28 **582** interval of model runs. We denote the timing of each intervention phase on the graph. Phase 1:
29 **583** initial outbreak, Phase 2: depopulation began, Phase 3: increased single celling, Phase 4:
30 **584** widespread testing of asymptomatic incarcerated individuals.
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34 **586** Figure 4. Calibrated values of the transmission rate β for different outbreak phases (Phase 1:
35 **587** initial outbreak, Phase 2: depopulation began, Phase 3: increased single celling, Phase 4:
36 **588** widespread testing of asymptomatic incarcerated individuals). CDC guidelines were
37 **589** implemented during all four phases. Boxes denote 25th percentile, median, and 75th percentile.
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39 **590**

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41 **591** Figure 5. Calculated values of the effective reproduction ratio R_t for all intervention phases
42 **592** (Phase 1: initial outbreak, Phase 2: depopulation began, Phase 3: increased single celling, Phase
43 **593** 4: widespread testing of asymptomatic incarcerated individuals). CDC guidelines were
44 **594** implemented during all four phases. Shaded area around each line reflects the 95% credible
45 **595** interval.
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3 597 Figure 6. Projected number of incident symptomatic cases per day for all intervention phases
4 598 (Phase 1: initial outbreak, Phase 2: depopulation began, Phase 3: increased single ceiling, Phase
5 599 4: widespread testing of asymptomatic incarcerated individuals). CDC guidelines were
6 600 implemented during all four phases. Shaded area around each line reflects the 95% credible
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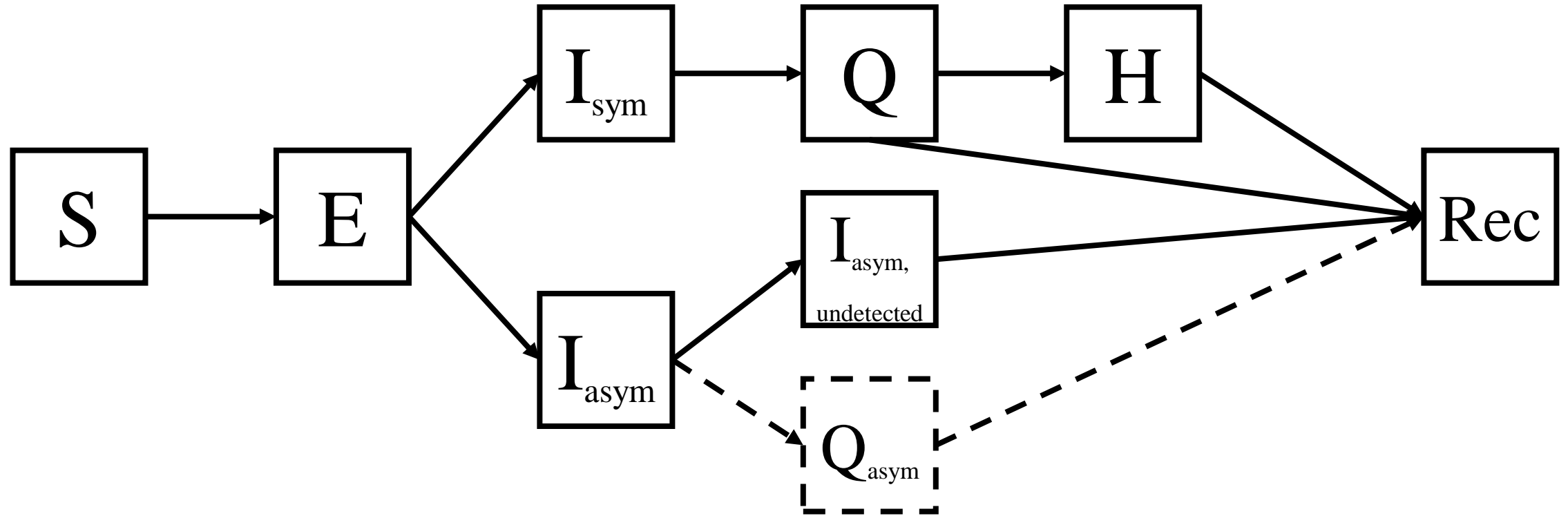
Table 1. Base Case Parameter Estimates

Name	Description	Value	Source
b	Net rate of entrance into the jail, phase 1 [1/day]	-0.004	Jail dataset
	Net rate of entrance into the jail, phase 2 [1/day]	-0.0141	
	Net rate of entrance into the jail, phase 3 [1/day]	-0.0076	
	Net rate of entrance into the jail, phase 4 [1/day]	0.0005	
β	Transmission rate [1/day]		Calibrated
ε	Incubation period ⁻¹ [1/day]	0.18	12
		Incubation period: <i>Lognormal</i> (5.1, 0.89)	
α	Proportion of cases that are asymptomatic	0.405	13, 14
		<i>uniform</i> (0.25, 0.56)	
γ	Recovery rate [1/day]	0.1	15, 16
		Infection period: <i>Truncated N</i> (10, 6.25, <i>min</i> = 5, <i>max</i> = 20)	
η	Proportion of symptomatic infections that are hospitalized	0.14	Jail dataset
μ	Recovery rate from hospital [1/day]	0.2	16
		Length of hospitalization: <i>Lognormal</i> (5,1)	
d_I	Probability of death due to symptomatic COVID-19 infection	0.01	Jail dataset

Table 2. Intervention Effects: Estimated Transmission Rates (β), Effective Reproduction Ratios (R_0), and Disease Cases for each Outbreak Phase

Phase	Time Range in Days	β (95% CrI)	R_0 (95% CrI)	Reduction in β and R_0 from Previous Phase	Expected Total Symptomatic Cases, Day 83* (95% CrI)	Expected Total Hospitalizations, Day 83* (95% CrI)	Expected Total Deaths, Day 83* (95% CrI)	Expected Total Cases, Day 200* (95% CrI)
1: Initial outbreak	1 – 11	1.79 (1.35 - 2.22)	8.44 (5.00 - 13.10)		3,758 (3,656 – 3,820)	526 (512 - 535)	38 (29 - 47)	6,365 (6,310 - 6,425)
2: Depopulation	12 – 17	0.78 (0.61 – 0.97)	3.64 (2.43 - 5.11)	56%	2,317 (2,106 - 2,495)	324 (295 - 349)	24 (20 - 28)	4,056 (3,660 - 4,280)
3: Increased single celling	18 – 36	0.38 (0.28 - 0.52)	1.72 (1.40 - 2.12)	51%	1,225 (998 - 1,508)	171 (140 - 211)	12.3 (11.5 – 13.0)	2,961 (2,315 - 3,513)
4: Widespread testing of asymptomatic incarcerated individuals	37 – 83	0.13 (0.07 - 0.24)	0.58 (0.43 - 0.75)	66%	635 (506 - 821)	89 (71 - 115)	6.3 (5.8 – 6.7)	1,144 (923 - 1,459)
Jail data: Day 83 of outbreak					778	67	10	

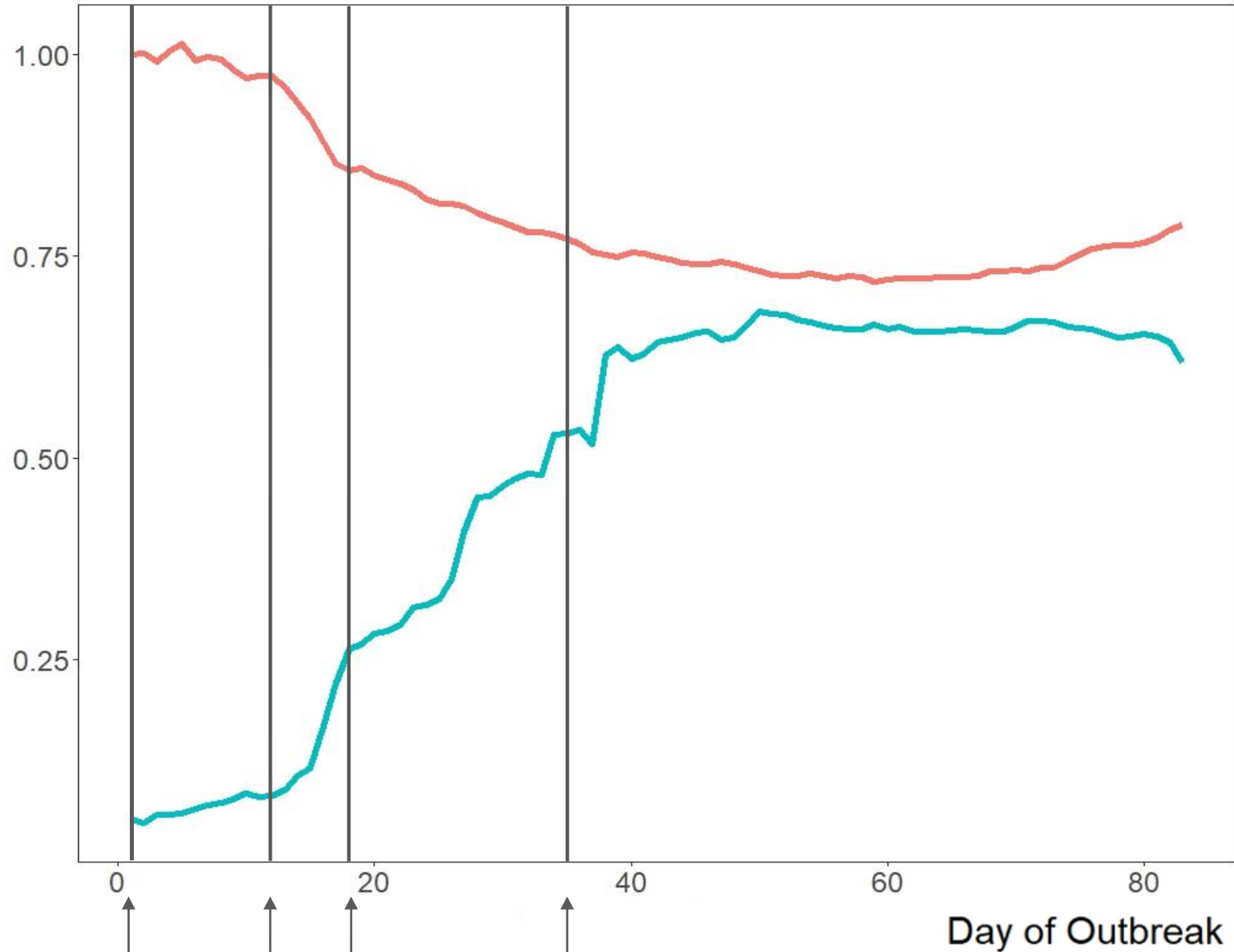
* Assuming the value of β estimated for this intervention phase occurs during all subsequent days



(After asymptomatic testing begins)

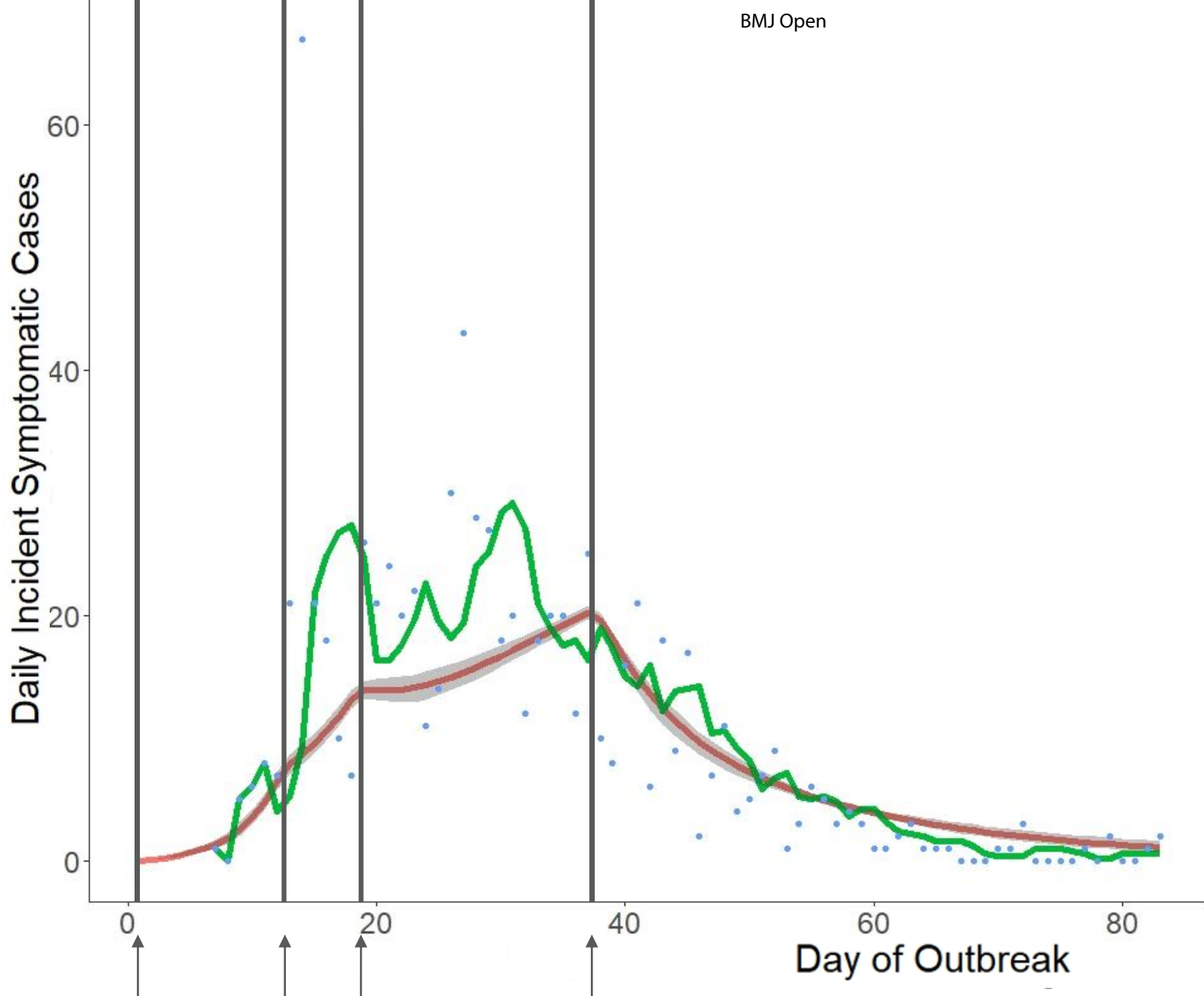
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BMJ Open
Population as Proportion of Population Day 1
Proportion of Current Population in Single Cell



Phase 1 begins Phase 2 begins Phase 3 begins Phase 4 begins
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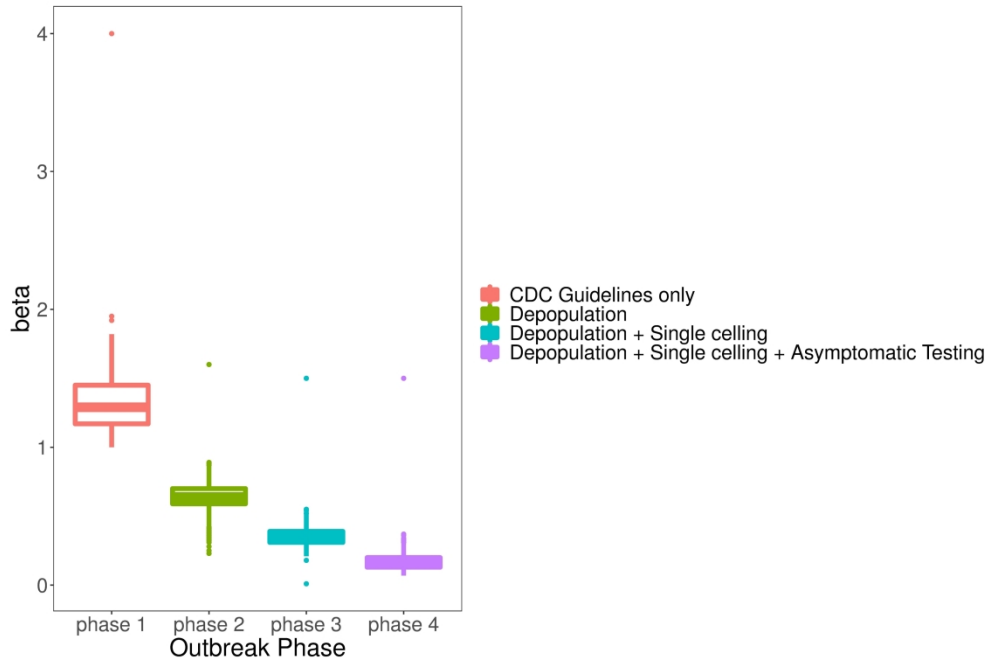


Figure 4. Calibrated values of the transmission rate β for different outbreak phases (Phase 1: initial outbreak, Phase 2: depopulation began, Phase 3: increased single celling, Phase 4: widespread testing of asymptomatic incarcerated individuals). CDC guidelines were implemented during all four phases. Boxes denote 25th percentile, median, and 75th percentile.

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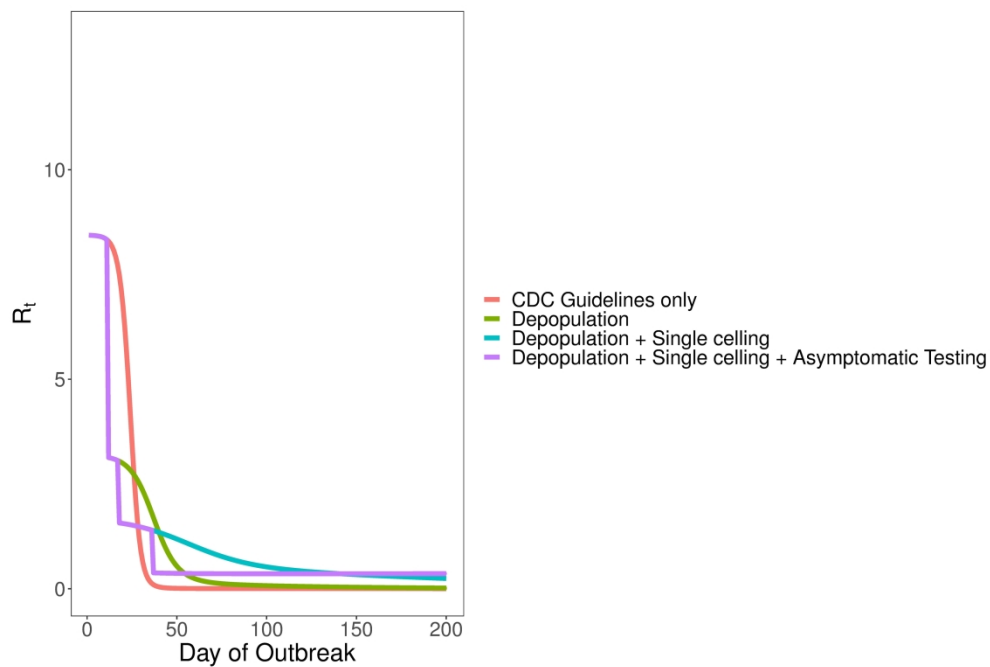


Figure 5. Calculated values of the effective reproduction ratio R_t for all intervention phases (Phase 1: initial outbreak, Phase 2: depopulation began, Phase 3: increased single celling, Phase 4: widespread testing of asymptomatic incarcerated individuals). CDC guidelines were implemented during all four phases. Shaded area around each line reflects the 95% credible interval.

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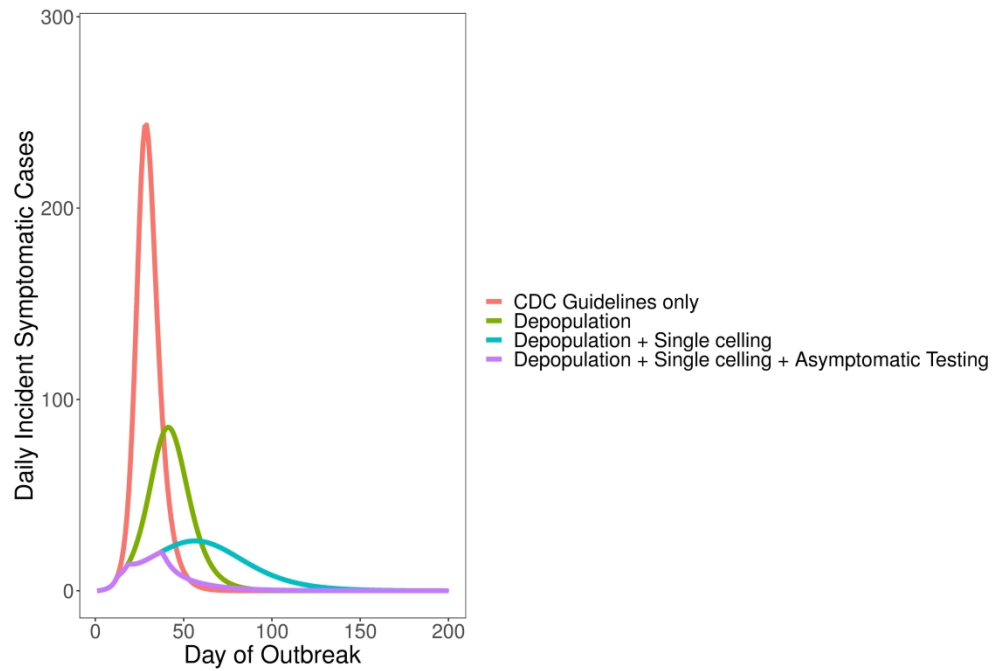


Figure 6. Projected number of incident symptomatic cases per day for all intervention phases (Phase 1: initial outbreak, Phase 2: depopulation began, Phase 3: increased single celling, Phase 4: widespread testing of asymptomatic incarcerated individuals). CDC guidelines were implemented during all four phases. Shaded area around each line reflects the 95% credible interval.

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