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Vaccination and testing of the border workforce for COVID-19 and risk of community outbreaks: a modelling study

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Executive Summary

- Vaccination of New Zealand's frontline border workforce is a priority in order to protect this high-exposure group from the health impacts of COVID-19.
- Although vaccines are highly effective in preventing disease, their effectiveness in preventing transmission of COVID-19 is less certain.
- There is a danger that vaccination could prevent or reduce symptoms of COVID-19 but not prevent transmission. Counterintuitively, this means that vaccinating frontline border workers could *increase* the risk of a community outbreak.
- In a scenario where the vaccine reduces transmission by 50%, vaccinating border workers could increase the risk of a significant community outbreak from around 7% per seed case to around 9% per seed case.
- Until more is known about the effect of the vaccine on transmission, we recommend increasing the routine testing of vaccinated border workers to mitigate this risk. Regular saliva testing may be a good way to achieve this.
- Careful attention should be paid to any groups, such as frontline workers' family members, who may be vaccinated but who are not undergoing routine testing to ensure they do not become asymptomatic spreaders.

Abstract

Australia and New Zealand have a strategy to eliminate community transmission of COVID-19 and require overseas arrivals to quarantine in government-managed facilities at the border. In both countries, community outbreaks of COVID-19 have been sparked following infection of a border worker. This workforce is rightly being prioritised for vaccination. However, although vaccines are highly effective in preventing disease, their effectiveness in preventing transmission of COVID-19 is less certain. There is a danger that vaccination could prevent symptoms of COVID-19 but not prevent transmission. Here, we use a stochastic model of COVID-19 transmission and testing to investigate the effect that vaccination of border workers has on the risk of an outbreak in an unvaccinated community. We simulate the model starting with a single infected border worker and measure the number of people who are infected before the first case is detected by testing. We show that if a vaccine reduces transmission by 50%, vaccination of border workers increases the risk of a major outbreak from around 7% per seed case to around 9% per seed case. The lower the vaccine effectiveness against transmission, the higher the risk. The increase in risk as a result of vaccination can be mitigated by increasing the frequency of routine testing for high-exposure vaccinated groups.

Introduction

Australia and New Zealand have a strategy to eliminate community transmission of COVID-19 and to prevent reintroductions by requiring overseas arrivals to spend a period of time in government-managed isolation and quarantine facilities. Since October 2020, the majority of cases in both countries have been in overseas arrivals and have been contained at the border. The managed isolation and quarantine facilities and other border operations are supported by a large and varied workforce. In New Zealand in the period from July 2020 to early March 2021, there have been 12 known border breaches resulting in an active case of COVID-19 entering the community. Of these 12 breaches, 5 have been caused by a quarantine worker becoming infected and 3 have been associated with transmission between recent arrivals within quarantine facilities. The remaining 4 known breaches either started from a non-quarantine border worker (e.g. port worker, aircrew) or have an unknown cause. Australia experienced 7 border breaches in the period up to 31 January 2021, all associated with infection of a border worker (Grout et al., 2021).

While there is no community transmission, frontline border workers are the group with the highest risk of being infected with SARS-CoV-2. Border workers and their household contacts are therefore rightly being prioritised for vaccination in Australia and New Zealand (Department of Health Australia, 2021; Ministry of Health New Zealand, 2021b). Approved vaccines are proven to be effective in preventing symptomatic disease, so vaccinating high-exposure groups will protect them from the health impacts of COVID-19. However, it remains unknown how effective vaccines will be in reducing infection with and transmission of SARS-CoV-2. If the vaccine is effective in preventing frontline workers from becoming infected with or transmitting SARS-CoV-2, vaccination of frontline workers will provide an additional buffer that will help protect the wider community against border reincursions. However, if the vaccine does not prevent infection or transmission, there is counterintuitively a danger that vaccinating frontline workers could increase the risk of community outbreaks, by making the initial infection in a frontline worker harder to detect. This danger could be mitigated by increased testing of frontline workers.

In this report, we use a model for COVID-19 transmission and testing to investigate the risk of a community outbreak under various border workforce vaccination and testing scenarios. The border

workforce is varied and different groups have different frequencies of routine testing depending on their level of exposure. For simplicity, we focus on the highest-exposure group of quarantine workers who are currently on a weekly testing schedule.

Methods

We use a stochastic branching process model for the spread of COVID-19, seeded with a single infected frontline worker. The following is a non-technical summary of the main model assumptions; see Appendix for full model specification. The model includes heterogeneity in the number of secondary infections caused by a single infected individual (i.e. superspreading) with dispersion parameter $k = 0.5$. We run the model for two different values of the basic reproduction number: $R_0 = 2.5$ representing pre-existing variants of SARS-CoV-2 that were dominant for most of 2020; and $R_0 = 3.75$ representing a newer variant that is 50% more transmissible (e.g. Davies et al., 2021). For simplicity, we assume that frontline border workers and the general population have the same mean reproduction number and the same superspreading parameter $k = 0.5$. We assume that 33% of SARS-CoV-2 infections in unvaccinated individuals are subclinical (see Appendix Table S3 for sensitivity analysis on this parameter), meaning that they do not develop clinical symptoms at any time during the infection. We assume subclinical infections have 50% of the transmission rate of clinical cases.

All frontline border workers undergo regular scheduled nasopharyngeal PCR tests with symptom checks. The border worker seed case is assumed to be infected at a random time relative to their routine testing schedule. We assume that for routine tests, the probability of a positive result being returned is a function of time since infection, using the data of Kucirka et al. (2020). We assume that symptom checks by health professionals help to provide a very low probability that clinical cases are missed by testing after symptom onset. For example, symptomatic individuals may be retested and/or diagnosed as probable cases in the absence of a positive PCR test result. We assume that routine tests in subclinical infections have a probability of returning a positive result that is 65% of that for clinical cases (Chau et al., 2020; Clifford et al., 2020). We assume that time-dependence of the probability of testing positive is the same for all individuals, and that multiple tests in the same individual are statistically independent. These are model simplifications and could be generalised, for example by explicitly modelling heterogeneity in magnitude and timing of peak viral load (Quilty et al., 2021), but at the expense of increased model complexity. We assume there is no routine testing in the general population. In addition to routine testing, cases may also be detected as a result of symptom-triggered testing. When border workers are vaccinated, this only occurs in the general population. We assume that clinical cases in the general population have a 30% probability of detection by symptom-triggered testing, with a mean time from symptom onset to detection of 6 days. Neither vaccinated individuals nor subclinical infections can receive a symptom-triggered test.

We investigate how vaccinating the border workforce affects the risk of a community outbreak under various vaccine effectiveness and testing scenarios. Approved vaccines are known to be effective in preventing symptomatic disease caused by SARS-CoV-2. However, it is still uncertain how effective they are in reducing infection with or transmission of the virus. If a vaccine prevents or reduces symptoms of COVID-19 in frontline border workers but does not prevent them from transmitting the virus, there is counterintuitively a danger this could increase the risk of community outbreaks by making it harder to detect the virus in the seed cases, and therefore more likely that the outbreak could spread into the community before being detected.

In all scenarios, we assume that 100% of the frontline border workforce has been fully vaccinated, and that the vaccine is 100% effective in preventing symptoms of COVID-19. This is a simplifying assumption, but it is a conservative one for the purposes of this study, which is to estimate the risk of asymptomatic transmission from border workers. If the vaccine coverage or effectiveness against symptoms is less than 100%, results will be closer to the baseline scenario in which there is no vaccination. Early uptake of the vaccine amongst New Zealand's border workers has been high, with approximately 91% having received their first dose as of 17 March 2021 (Ministry of Health New Zealand, 2021a). And the Pfizer vaccine being rolled out has been shown to have high effectiveness (>90%) against symptoms so the assumption (Polack et al., 2020; Dagan et al., 2021), although conservative, is not unreasonable.

We first investigate a worst-case scenario in which the vaccine does not reduce infection or transmission of the virus at all. This scenario is not intended to be a realistic vaccine model, but rather to illustrate the nature of the risks involved, and their potential magnitude in a worst-case scenario. In this scenario, all infected individuals transmit the virus at the same rate as if they were unvaccinated. Secondly, we investigate a more realistic scenario in which the vaccine is partially effective in preventing transmission. To model this, we assume that the vaccine is 50% effective in reducing transmission (i.e. the average reproduction number for vaccinated individuals is 50% of that in unvaccinated individuals). Thirdly, we investigate an optimistic scenario where the vaccine is 75% effective in reducing transmission.

Prevention of symptomatic disease in vaccinated border workers has two effects on the testing model. Firstly, it means that border workers only get routine scheduled tests (e.g. weekly tests) and do not get additional symptom-triggered tests that they may get if they were unvaccinated. Secondly, it means that cases cannot be flagged for repeat testing or diagnosed as a probable case as a result of symptom checks. This increases the likelihood of an infected individual being missed by a PCR test.

Finally, we consider a scenario modelling vaccination of frontline workers and their close family members. To model this, we assume that 50% of the cases infected by a frontline worker are vaccinated. This is a simplifying assumption designed to give an indication of the qualitative effect of vaccinating frontline workers' family members. A more detailed model stratified into household and non-household contacts could be used to provide a more accurate result.

For each scenario, we examine the risk of community outbreaks under different routine testing frequencies for border workers. We calculate the proportion of simulations, each seeded with a single infected border worker, in which the outbreak is (i) never detected, (ii) first detected in the seed case (generation 1 detection), or (iii) first detected in a secondary case or later (generation 2+ detection). We also calculate the size of the outbreak (total number of people infected) at the time it is first detected.

Results

Table 1 shows the proportion of 5000 independent realisations initialised with a single infected frontline border worker in which the outbreak: (i) dies out without being detected; (ii) is detected in generation 1 (i.e. in the seed case representing the border worker); or (iii) is detected in generation 2 or later (i.e. a non-seed case), with $R_0 = 2.5$. Note we do not present confidence intervals for these

probabilities as these would account only for the relative small amount of stochasticity in a multinomial random variable over 5000 trials and would ignore other sources of model uncertainty.

Undetected outbreaks typically occur when the seed case does not infect any other individuals, or only causes a very small number of additional infections. These outbreaks therefore do not represent a significant public health risk. For outbreaks detected in generation 1 or in generation 2+, Table 1 shows the median number of infected individuals at the time of detection (referred to as outbreak size). There is some variability between simulations of the model, due to the timing of the seed cases becoming infected relative to their routine testing schedule, as well as the inherent stochasticity in the testing and transmission models. To capture this variability, Table 1 also shows the interquartile range (IQR) of outbreak size.

In all scenarios, outbreaks detected are generation 2+ are significantly larger than those detected at generation 1, which typically involve fewer than 5 infections at time of detection. Consistent with previous modelling studies (Steyn et al., 2021), this shows that if a case is detected outside the frontline worker group, it is likely that there are much larger number of people already infected. We therefore focus on the proportion of generation 2+ detections as the primary model output quantifying the risk of a major community outbreak. The average size of generation 2+ detections is a secondary output indicating the potential size of these outbreaks.

In a baseline scenario with no vaccination and with scheduled weekly testing of frontline workers (representing the current situation in early February 2021), approximately 7% of simulations result in an outbreak detected at generation 2+ and these have median outbreak size 19.5 (IQR 9 – 40). In the worst-case scenario of a vaccine that does not reduce transmission, and with scheduled weekly testing, approximately 14% of simulations result in an outbreak detected at generation 2+ and these have a median outbreak size of 22 (IQR 10 – 44). This shows that in a worst-case scenario, vaccinating border workers could approximately double the frequency of generation 2+ detections and slightly increase the average outbreak size. If the frequency of routine testing is increased to once every 4 days, approximately 5% of simulations result in an outbreak detected at generation 2+, with median outbreak size is 18 (IQR 9 – 35). This shows that in the worst-case scenario, the risk of community outbreaks due to vaccine-induced symptom prevention in frontline workers can be completely mitigated by increasing the testing frequency from weekly to once every 4 days.

A more realistic scenario is one where the vaccine provides at least some reduction in transmission, although the size of the reduction is unknown at this time. If the vaccine reduces transmission by 50%, the risk of community outbreaks is not as great as when the vaccine does not reduce transmission. With weekly testing, the probability of a generation 2+ detection is around 9%, compared to 7% in the baseline no-vaccine scenario. Increasing the testing frequency from once every 7 days to once every 4 days more than compensates for this increased risk, reducing the probability of a generation 2+ detection to around 4%, which is lower than baseline scenario. Under an optimistic scenario where the vaccine is 75% effective in reducing transmission, the proportion of simulations resulting in a generation 2+ detections is 5%, which is lower than in the baseline no-vaccine scenario (7%), even without additional testing of frontline workers.

Scenario	Test freq.	Detection type			Outbreak size gen. 1	Outbreak size gen. 2+
		Undet.	Gen. 1	Gen. 2+		
No vaccine	**7 days**	**5.8%**	**87.4%**	**6.8%**	**2 [1, 4]**	**19.5 [9, 40]**
No vaccine	4 days	2.1%	94.1%	3.8%	1.5 [1, 4]	17 [7, 31]
No vaccine	2 days	0.2%	98.5%	1.4%	1 [1, 4]	8 [5, 18]
Vaccine 0% eff	7 days	9.2%	76.6%	14.2%	2 [1, 6]	22 [10, 44]
Vaccine 0% eff	4 days	3.1%	91.6%	5.3%	2 [1, 5]	18 [9, 35]
Vaccine 0% eff	2 days	0.3%	98.2%	1.5%	2 [1, 5]	11 [6, 22]
Vaccine 50% eff	7 days	10.4%	81.1%	8.5%	1 [1, 4]	17 [8, 35]
Vaccine 50% eff	4 days	3.7%	92.5%	3.8%	1 [1, 3]	14 [6, 32]
Vaccine 50% eff	2 days	0.4%	98.8%	0.8%	1 [1, 2]	9.5 [4, 16]
Vaccine 75% eff	7 days	13.3%	81.7%	5.0%	1 [1, 2]	15 [5, 37]
Vaccine 75% eff	4 days	3.9%	94.4%	1.7%	1 [1, 2]	12 [4, 37]
Vaccine 75% eff	2 days	0.5%	99.1%	0.4%	1 [1, 2]	4 [3, 16]

Table 1. Model results for four vaccination scenarios (no vaccination of frontline workers, a vaccine that is 0%, 50% and 75% effective at preventing transmission) different frequencies of routine testing of frontline workers, with $R_0 = 2.5$. Row with bold font indicates the status quo prior to vaccination of border workers. The "Detection type" columns show the proportion of model simulations that result in: an outbreak that dies out without being detected (Undet.); an outbreak that is first detected in the seed case (Gen. 1); and an outbreak that is first detected in a secondary case or later (Gen. 2+). The "Outbreak size" columns show the median [IQR] number of infected individuals at the time the first case is detected. Results are from 5000 independent simulations of the model, each initialised with a single seed case in a frontline worker.

Table 2 shows corresponding results for a SARS-COV-2 variant that is 50% more transmissible ($R_0 = 3.75$). This increases the probability of generation 2+ detections and results in larger outbreaks across all scenarios investigated. As for the pre-existing variant, a vaccine that reduces transmission by 50% requires an increase in testing frequency to avoid increasing the risk of generation 2+ detections relative to the baseline no-vaccine scenario. Under the realistic and optimistic vaccine scenarios, testing border workers once every four days is sufficient to reduce the risk of community outbreaks from the more transmissible variant to a level similar to or below that from the pre-existing variant.

Table 3 shows results of the model for vaccinating frontline workers and their close family members. Overall, the results are similar to those where only frontline workers are vaccinated (Table 1). In the worst-case scenario of a vaccine that does not prevent transmission, outbreaks detected at generation 2+ tend to be larger if frontline workers family members are vaccinated than if they are not. This is because family members do not get routine testing and, if they are vaccinated, will not develop symptoms. There is therefore a danger of them continuing to transmit the virus asymptomatically, allowing the outbreak to grow larger before detection. If the vaccine is 50% effective in reducing transmission, this danger is much smaller.

Scenario	Test freq.	Detection type			Outbreak size gen. 1	Outbreak size gen. 2+
		Undet.	Gen. 1	Gen. 2+		
No vaccine	**7 days**	**5.2%**	**86.7%**	**8.0%**	**2 [1, 7]**	**33 [15, 71]**
No vaccine	4 days	1.8%	93.4%	4.8%	2 [1, 6]	28 [11, 57]
No vaccine	2 days	0.3%	98.0%	1.7%	2 [1, 5]	16 [7, 33]
Vaccine 0% eff	7 days	7.4%	76.1%	16.6%	3 [1, 11]	39 [17, 80]
Vaccine 0% eff	4 days	1.8%	90.0%	8.3%	3 [1, 9]	33 [14, 66]
Vaccine 0% eff	2 days	0.2%	97.1%	2.7%	2 [1, 7]	24 [9, 41]
Vaccine 50% eff	7 days	9.4%	78.7%	11.9%	1 [1, 6]	29 [11, 62]
Vaccine 50% eff	4 days	2.9%	91.7%	5.4%	1 [1, 5]	25.5 [10, 54]
Vaccine 50% eff	2 days	0.3%	98.2%	1.5%	1 [1, 4]	15 [6, 37]
Vaccine 75% eff	7 days	11.2%	80.7%	8.0%	1 [1, 3]	26 [8, 64]
Vaccine 75% eff	4 days	3.4%	93.7%	2.9%	1 [1, 2]	25 [9, 60]
Vaccine 75% eff	2 days	0.3%	99.0%	0.8%	1 [1, 2]	5.5 [3, 17]

Table 2. Model results for four vaccination scenarios (no vaccination of frontline workers, a vaccine that is 0%, 50% and 75% effective at preventing transmission) different frequencies of routine testing of frontline workers, and a SARS-COV-2 variant with $R_0 = 3.75$. Results are from 5000 independent simulations of the model, each initialised with a single seed case in a frontline worker.

Scenario	Test freq.	Detection type			Outbreak size gen. 1	Outbreak size gen. 2+
		Undet.	Gen. 1	Gen. 2+		
No vaccine	**7 days**	**5.7%**	**87.8%**	**6.6%**	**1 [1, 4]**	**21 [9, 44]**
No vaccine	4 days	2.1%	94.2%	3.6%	2 [1, 4]	16 [7, 35]
No vaccine	2 days	0.2%	98.8%	1.0%	1 [1, 4]	8.5 [5, 18]
Vaccine 0% eff	7 days	9.0%	79.7%	11.3%	2 [1, 7]	27 [13, 55]
Vaccine 0% eff	4 days	2.7%	92.7%	4.6%	2 [1, 5]	22 [12, 44]
Vaccine 0% eff	2 days	0.2%	98.7%	1.1%	2 [1, 5]	13 [7, 26]
Vaccine 50% eff	7 days	11.4%	82.5%	6.1%	1 [1, 3]	20 [9, 42]
Vaccine 50% eff	4 days	3.5%	93.8%	2.7%	1 [1, 3]	14 [7, 33]
Vaccine 50% eff	2 days	0.4%	99.0%	0.5%	1 [1, 2]	10 [6, 16]
Vaccine 75% eff	7 days	13.3%	83.0%	3.7%	1 [1, 2]	13.5 [6, 34]
Vaccine 75% eff	4 days	4.0%	94.7%	1.3%	1 [1, 2]	13 [6, 26]
Vaccine 75% eff	2 days	0.5%	99.3%	0.2%	1 [1, 2]	9 [5, 29]

Table 3. Model for vaccination of front workers and their family members under four vaccination scenarios (no vaccination, a vaccine that is 0%, 50% and 75% effective at preventing transmission) different frequencies of routine testing of frontline workers, with $R_0 = 2.5$. Results are from 5000 independent simulations of the model, each initialised with a single seed case in a frontline worker.

Discussion

We used a stochastic model of COVID-19 transmission and testing to assess the risk of community outbreaks under various frontline worker vaccination and testing scenarios. Preliminary results for the effectiveness of the Pfizer vaccine being rolled out to New Zealand's border workforce on transmission are promising. There is preliminary data showing that the Pfizer vaccine reduces viral load in infected individuals (Levine-Tiefenbrun et al., 2021; Petter et al., 2021), reduces incidence of document symptomatic or asymptomatic infection (Hall et al., 2021), and reduces transmission to close contacts (Shah et al., 2021). There are also encouraging results from other mRNA vaccines that vaccination reduces asymptomatic infection (FDA, 2021; Hall et al., 2021). Together, this evidence suggests that vaccination will reduce transmission substantially. However, until more data is available and studies have been through the peer review process, a precautionary approach is warranted and this means planning for a scenario where the vaccine has relatively low effectiveness at reducing transmission.

Under a worst-case scenario of a vaccine that prevents symptoms but does not reduce transmission at all, vaccination of frontline workers could approximately double the risk of a large community outbreak. This risk can be mitigated by increasing the frequency of routine testing of frontline workers from once per week to once every 4 days. Under a more realistic scenario of a vaccine that is 50% effective in preventing transmission, the increase in risk due to vaccination of frontline workers is smaller, but increased testing frequency is still required to avoid increasing the risk. Under an optimistic scenario where the vaccine is 75% effective in preventing transmission, vaccination of border workers reduces the risk of community outbreaks without the need for increased testing frequency.

Some of the recently identified variants of SARS-COV-2 are thought to be more transmissible. For example, the B.1.1.7 variant first identified in the UK has been estimated to have a 43-90% higher reproduction number than pre-existing variants (Davies et al., 2021). Contact tracing data from England suggested B.1.1.7 has a 10 - 70% higher secondary attack rate (Public Health England, 2020). We reran our model with a 50% increase in transmissibility ($R_0 = 3.75$). Overall, this increases the expected frequency and size of community outbreaks across all scenarios. Testing frontline border workers every 4 days is sufficient to mitigate this risk in all but the worst-case scenario of a vaccine that does not reduce transmission at all.

The vaccine rollout will initially prioritise frontline border workers and their close family members. Since family members are not necessarily undergoing routine regular testing, there is a danger that a vaccine that prevented symptoms could turn family members into asymptomatic spreaders. A model scenario where 50% of secondary cases from frontline workers were vaccinated showed that this could potentially increase the size of outbreaks detected at the second generation or later. This suggests that careful attention should be paid to any groups who are vaccinated because of their proximity to groups like border workers with high levels of exposure to the virus, but who are not themselves undergoing routine testing.

For simplicity, we assumed that all tests have the same time-dependent sensitivity curve (Kucrika et al., 2020), representing a PCR nasopharyngeal swab test. Increasing the frequency of nasopharyngeal swabbing of frontline border workers may not be practical and would be onerous for those being tested. Regular saliva testing in combination with a weekly nasopharyngeal swab test may be an alternative method to achieve the routine testing coverage needed to mitigate the risk of a community outbreak. A review found that a range of saliva tests had comparable sensitivity and specificity to nasopharyngeal swabbing (Butler-Laporte et al., 2021). Even if saliva tests had lower

sensitivity, this could be compensated for by increased testing frequency provided sufficient processing capacity was available.

Rolling out a rapid mass vaccination programme to as many people as possible is the best way to prevent the potentially devastating health impacts of COVID-19. Countries such as New Zealand, Australia and Taiwan have largely eliminated community transmission of the virus and have strategy of quarantining incoming travellers to prevent re-establishment (Summers et al., 2020). In such countries, people working in border quarantine facilities have the highest exposure to the virus of any population group. Our results should not be used to suggest that border workers should not be vaccinated as a priority. Protecting them from the health impacts of COVID-19 at the earliest opportunity is an national ethical obligation. However, care needs to be taken to ensure this group does not inadvertently become a silent source of transmission into a community that is largely unvaccinated at present. Regular routine testing is a good safeguard against this. If, in future, vaccines are demonstrated to be highly effective against transmission, the danger will be much smaller. Until then, or until high levels of vaccine coverage are achieved in the general population, increased routine testing of border workers is recommended.

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Appendix

A. Model specification

Transmission model

The model is a stochastic branching process model, simulated in time steps of $\delta t = 1$ day. The number of secondary infection caused by infected individual i on day t is a Poisson distributed random variable with mean

$$\lambda_i(t) = R_i v_i \int_t^{t+\delta t} W(\tau - T_{I,i}) d\tau, \quad (1)$$

where $W(\tau)$ is the probability density function of the generation time distribution, R_i is the individual reproduction number for individual i if unvaccinated, and v_i is the relative transmission reduction due to vaccination for individual i.

The generation time distribution is assumed to be a Weibull distribution with mean 5.0 days and standard deviation 1.9 days (Ferretti et al., 2020). The model does not explicitly include a latent period or pre-symptomatic infectious period. However, the shape of the Weibull generation time distribution captures these phases, giving a low probability of a short generation time between infections and with 90% of transmission occurring between 2.0 days and 8.4 days after infection.

Infected individuals are grouped into two categories: (i) those who show clinical symptoms at some point during their infection; and (ii) those who are subclinical throughout their infection. Each new infection is randomly assigned as subclinical with probability $p_{sub} = 0.33$ and clinical with probability $1 - p_{sub}$, independent of who infected them. Once assigned as clinical or subclinical, individuals remain in this category for the duration of their infectious period.

The average reproduction number R_{sub} of subclinical individuals was assumed to be 50% of the average reproduction number R_{clin} of clinical individuals. This reflects lower infectiousness of subclinical cases (Davies et al., 2020). Individual heterogeneity in transmission rates was included by setting the individual reproduction number R_i for individual i to be $R_i = R_{clin} Y_i$ for clinical cases and $R_i = R_{sub} Y_i$ for subclinical infections, where Y_i is a gamma distribution with mean 1 and variance $1/k$. In the absence of case isolation measures (see below), each infected individual i causes a randomly generated number $N_i \sim Poisson(R_i)$ of new infections. This means that the number of people infected by a randomly selected clinical [subclinical] individual has distribution $NegBin(R_{clin[sub]}, k)$.

We assume that vaccination causes the same relative reduction in transmission for all vaccinated individuals, so $v_i = 1$ for unvaccinated individuals and $v_i = 1 - VE_T$ where VE_T is the vaccine effectiveness against transmission. We assume that all frontline workers are vaccinated and so $v_i = 1 - VE_T$ for the seed case in each simulation. In most scenarios, we assume that the general community is completely unvaccinated and so $v_i = 1$ for all non-seed cases. In the scenario investigating the effects of vaccinating border workers' household members, we assume that 50% of cases infected by the seed case are household members so for second generation cases, we set $v_i = 1 - VE_T$ with probability 0.5 and $v_i = 1$ with probability 0.5, independent of all other individuals. We set $v_i = 1$ for any third or higher generation cases.

The effects of case isolation and contact tracing are not considered in this model because it is only used to simulate the early stages of an outbreak before any cases have been detected.

Parameter	Value
Generation time distribution (days)	$T_G \sim Weibull(5.67,2.83)$
Incubation period distribution (days)	$T_{onset} \sim Gamma(0.95,5.8)$
Mean reproduction number of clinical cases	$R_{clin} = 3$ (baseline) 4.5 (variant)
Mean reproduction number of subclinical infections	$R_{sub} = 0.5R_{clin}$
Superspreading dispersion parameter	$k = 0.5$
Proportion of subclinical infections	$p_{sub} = 0.33$ (see also sensitivity analysis)
Vaccine effectiveness against transmission	VE_T (see scenarios)

Table S1. Transmission model parameters and distributions. Weibull and gamma distribution parameters are specified as (scale,shape).

Testing model

Table S2 gives an overview of the testing model assumptions. Border workers have regular routine testing with a time-dependent probability of returning a positive result defined by the curves shown in Figure S1. Unvaccinated clinical cases (blue curve in Figure S1) are assumed to have a probability of returning a positive result that increases towards 1 following symptom onset. This represents symptom checks by health professionals for these individuals, which may result in either repeat testing or clinical diagnosis as a probable case in the absence of a positive PCR test. In vaccinated individuals (red curve in Figure S1), the probability of returning a positive test result peaks around 7 days after infection and then gradually declines. Subclinical infections (yellow curve in Figure S1) have a lower probability of returning a positive result, assumed to be 65% of the corresponding probability for clinical infections (Chau et al., 2020; Clifford et al., 2020).

In addition to routine testing of border workers, unvaccinated clinical cases in either border workers or the general population can be receive a symptom-triggered test. The probability of an unvaccinated clinical case being detected by a symptom-triggered test is assumed to be 1 in border workers and 0.3 in the general population. The time from symptom onset to a symptom-triggered test is drawn from an exponential distribution with mean 2 days for border workers and 6 days for the general population. The incubation period (time from infection to symptom onset) is drawn from a gamma distribution with mean 5.5 days and standard deviation 2.3 days (Lauer et al. 2020).

Type of individual		Routine testing [probability of positive result]	Symptom-triggered detection probability	Mean delay from symptom onset to detection
Border worker (seed case)	Unvaccinated clinical	Y [blue curve]	1	2 days
	Vaccinated	Y [red curve]	0	-
	Subclinical	Y [yellow curve]	0	-
General population (non-seed case)	Unvaccinated clinical	N	0.3	6 days
	Vaccinated	N	0	-
	Subclinical	N	0	-

Table S2. Testing models for different types of individual according to whether they are a border worker, vaccination status and clinical/subclinical infection. Border workers have regular routine testing with a time-dependent probability of returning a positive result defined by the curves shown in Figure S1. Unvaccinated clinical cases have a probability of being detected via a symptom-triggered test that is assumed to be 1 in border workers and 0.3 in the general population. The time from symptom onset to a symptom-triggered test is exponential distributed with mean 2 days for border workers and 6 days for the general population.

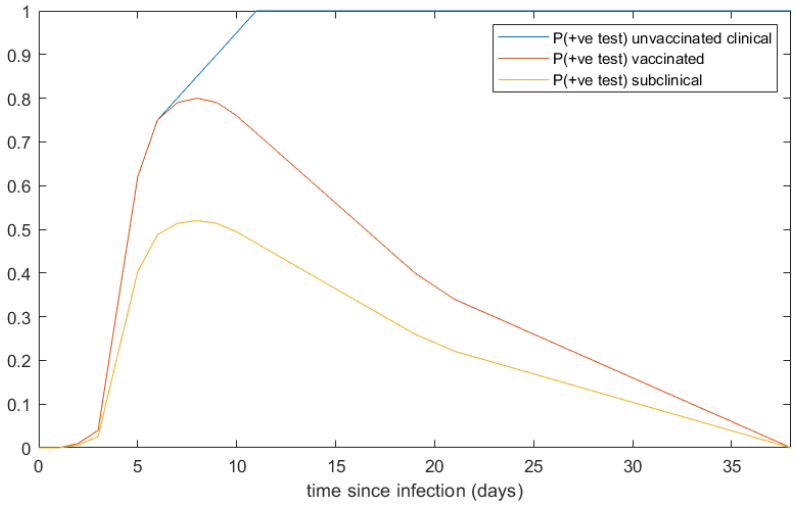

Figure S1. Probability of returning a positive result from a routine test as a function of time since infection for unvaccinated clinical individuals (blue), vaccinated individuals (red) and subclinical individuals (yellow). Note blue and red curves are overlapping up to $t = 6$ days.

B. Sensitivity analysis results

We ran a sensitivity analysis on the proportion of infections that are subclinical. Table S1 shows results when 20% or 40% of infections are subclinical without vaccination. In most cases, these are similar to the results in Table 1 (33% subclinical), and within the bounds of uncertainty of the stochastic model. A lower subclinical fraction means there is a slightly smaller chance of generation 2+ detections without vaccination, because detection of clinical cases is easier. With a vaccine that is completely ineffective against transmission, a testing frequency slightly higher than every 4 days may be needed to mitigate risk of a community outbreak. However for the other vaccine scenarios, the results are similar to those in Table 1, and the qualitative conclusions are the same.

Scenario	Test freq.	Detection type			Outbreak size gen. 1	Outbreak size gen. 2+
		Undet.	Gen. 1	Gen. 2+		
20% subclinical						
No vaccine	**7 days**	**3.2%**	**92.0%**	**4.8%**	**1 [1, 4]**	**15.5 [8, 34]**
No vaccine	4 days	1.7%	95.3%	3.0%	1 [1, 4]	12.5 [6, 23]
No vaccine	2 days	0.2%	98.8%	1.0%	1 [1, 4]	12 [6, 22]
Vaccine 0% eff	7 days	6.5%	80.8%	12.8%	2 [1, 6]	20 [8, 40]
Vaccine 0% eff	4 days	2.1%	92.2%	5.7%	2 [1, 5]	15 [6, 32]
Vaccine 0% eff	2 days	0.2%	98.0%	1.8%	2 [1, 4]	12.5 [7, 22]
Vaccine 50% eff	7 days	8.4%	83.6%	8.0%	1 [1, 3]	16 [7, 34]
Vaccine 50% eff	4 days	2.4%	94.1%	3.4%	1 [1, 3]	10 [5, 24]
Vaccine 50% eff	2 days	0.2%	99.1%	0.7%	1 [1, 3]	10 [5, 19]
Vaccine 75% eff	7 days	11.1%	84.2%	4.8%	1 [1, 2]	12 [4, 28]
Vaccine 75% eff	4 days	2.2%	96.0%	1.7%	1 [1, 2]	9 [4, 16]
Vaccine 75% eff	2 days	0.3%	99.3%	0.4%	1 [1, 2]	5.5 [3, 8]
40% subclinical						
No vaccine	**7 days**	**6.9%**	**86.2%**	**6.8%**	**2 [1, 4]**	**22 [9, 44]**
No vaccine	4 days	2.8%	93.1%	4.1%	2 [1, 4]	20 [9, 41]
No vaccine	2 days	0.5%	98.2%	1.3%	1 [1, 4]	14 [6, 34]
Vaccine 0% eff	7 days	9.5%	77.9%	12.7%	2 [1, 7]	24 [10, 46]
Vaccine 0% eff	4 days	3.2%	90.4%	6.3%	2 [1, 6]	20 [10, 43]
Vaccine 0% eff	2 days	0.3%	98.2%	1.5%	2 [1, 5]	13.5 [5, 29]
Vaccine 50% eff	7 days	10.8%	80.9%	8.3%	1 [1, 3]	19 [7, 40]
Vaccine 50% eff	4 days	4.0%	92.3%	3.8%	1 [1, 3]	16 [8, 37]
Vaccine 50% eff	2 days	0.5%	98.4%	1.0%	1 [1, 3]	7 [4, 17]
Vaccine 75% eff	7 days	13.4%	81.8%	4.7%	1 [1, 2]	18 [6, 45]
Vaccine 75% eff	4 days	4.3%	93.1%	2.6%	1 [1, 2]	13 [5, 26]
Vaccine 75% eff	2 days	0.5%	99.1%	0.4%	1 [1, 2]	7 [4, 18]

Table S3. Sensitivity analysis for different subclinical fractions: either 20% of infections are subclinical without vaccination; or 40% of infections are subclinical without vaccination (compare with Table 1 where 33% are subclinical). Results are from 5000 independent simulations of the model with $R_0 = 2.5$, each initialised with a single seed case in a frontline worker.