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The effect of border controls on the risk of COVID-19 reincursion from international arrivals

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Executive Summary

- A 14-day period of managed isolation or quarantine (MIQ) with day 3 and day 12 testing reduces the risk of an infectious case being released into the community to a very low level.
- A five-day quarantine period is ineffective and would present a much greater risk to the community
- Any mixing of individuals in MIQ that could allow transmission of COVID-19 increases the risk of an infectious case being released into the community.
- Strict infection control and use of PPE by staff at MIQ is essential and close contact between individuals in MIQ and staff must be avoided.
- Provided the above guidelines are followed, special exemptions restricted to the second week of stay and after an additional negative test result has been returned pose little additional risk.
- The ratio of cases detected in the second week to cases detected in the first week can be used to estimate whether transmission within MIQ is occurring, although this requires a larger sample size than is currently available.

Introduction

Early in the COVID-19 outbreak New Zealand imposed strong border restrictions: the border has been closed to non-residents since 20 March and all arrivals have been required to spend 14 days in government-managed isolation/quarantine (MIQ) since 10 April. Together with very strong population-wide control measures imposed in late March, these restrictions have been successful in containing the virus and eliminating community transmission. As of 8 July 2020, there has been no reported transmission of COVID-19 outside government-managed quarantine facilities for more than six weeks and population-wide restrictions on domestic travel and large gatherings have been almost completely lifted. However, the strict border restrictions remain in place. In addition to the 14-day MIQ, travellers are checked for symptoms daily and are tested for COVID-19 on the 3rd and 12th day after arrival. Those that test positive and/or display symptoms are moved to a stricter MIQ facility until they recover. Individuals have the right to refuse to be tested; however, reports indicate this is rare, and those that do can be held in MIQ for up to an additional 14 days under the COVID-19 Public Health Response Act (New Zealand Government, 2020a).

Models of COVID-19 in New Zealand have so far not considered the rate of arrival of COVID-19 cases from overseas and the effect of various border measures in reducing the risk of these cases being released into the community. Assessment of the risk is critical because, now that domestic restrictions have been lifted, it is likely than any community transmission would grow into a large outbreak very rapidly, as seen recently in Melbourne for example. A model specifically designed for this purpose allows us to (a) determine which measurable variables may be useful to determine unmeasurable outcomes (e.g. whether there is transmission of COVID-19 within MIQ facilities) and (b) quantify the risk associated with different settings such as allowing special exemptions or better separating recent arrivals from those at the end of their stay.

In this study, we introduce a mathematical model of COVID-19 incubation, transmission and testing in border MIQ and explore the risk of releasing infectious individuals into the community under different scenarios. Key outcomes include: the probability of cases being undetected and the infectiousness of any undetected cases after being released from MIQ. We propose a metric that can be used to estimate the level of transmission occurring internally within MIQ facilities. We evaluate possible policy decisions and their potential outcomes, e.g. introducing special exemptions, cohort demarcation, and shortening the mandatory quarantine period. We only model the risk that international arrivals themselves pose, and do not consider the risks associated with immigration officers and MIQ workers coming into contact with recent international arrivals.

Methods

Infected arrivals have a probability of being subclinical $p_{sub} = 42.5\%$ (Lavezzo et al, 2020). All individuals are tested on specified days and interviews are conducted daily in which symptomatic individuals have a $p_{DetectSymptoms} = 33\%$ chance of meeting the case definition, with the results being returned and actioned on the following day. Detected cases are moved to a stricter MIQ facility, which is assumed to have no risk of discharging an infected case. Individuals that do not test positive or meet the case definition are released $LOS = 14$ days after arrival. The case definition is the required level of symptoms to be considered a suspect case, and thus be moved to a stricter facility. The model is run in discrete time steps of one day.

When enabled, individuals interact with each other within MIQ and each interaction has a probability of transmitting the virus. The assumption of Poisson distributed contacts ignores the possibility of superspreaders or superspreading events, which are very unlikely within the strictly controlled MIQ environment (though see Discussion). Individuals travelling together are not explicitly modelled. Transmission between family members or other travelling companions staying in the same hotel room is

expected to occur, although we expect that such contacts will be detected so they pose very little risk. This needs to be considered when comparing model results with observed data.

Key assumptions:

- The secondary attack rate is proportional to the distribution of generation times (Feretti et al, 2020), scaled and peaks at 0.7%, the average found in Cheng et al. (2020). This assumes individuals in close contact in isolation facilities are likely to be more careful than the general public and to have limited opportunity for high-risk contacts, such as gathering in large groups or socialising in crowded spaces (Leclerc et al., 2020). Small variations in this parameter have little influence on the relative effects of different policies.
- All individuals are assigned randomly distributed incubation periods (i.e. time from infection to symptom onset) with distribution $\sim\Gamma(\mu = 5.5\,days, \sigma = 2.3)$ (Lauer et al., 2020). For subclinical cases this is interpreted as the date of peak infectiousness.
- Infected arrivals are randomly assigned infection dates between 0 and 9 days prior to arrival $\sim U\{0,9\}$. This means that on average symptom onset occurs 1 day after arrival, consistent with NZ data. Infected individuals displaying symptoms before departure have a $p_{DetectSymptoms}$ chance of not travelling. This parameter is also used as the probability that a symptomatic individual within MIQ is detected on any given day.
- Test sensitivity is a function of time since exposure, a linear interpolation of the false negative rates reported in Kucirka et al. (2020), scaled to give a peak sensitivity of 94.3% (Wikramaratna et al., 2020) three days after symptom onset (Kucirka et al., 2020). This assumes testing is more sensitive than suggested in Kucirka et al. (2020), as the tests are administered by trained nurses rather than volunteers.
- Subclinical individuals are assumed to be less infectious than clinical individuals by a factor of $relInf = 50\%$ (Davies et al, 2020) and have a lower test sensitivity, $relSens = 80\%$.
- Each infected individual has a Poisson number of contacts: $C \sim Poisson(meanContacts)$, resulting in a binomial number of secondary infections: $\sim Binomial(C, SAR)$, where SAR is the relevant secondary attack rate. These secondary infections are chosen randomly from all individuals in the simulated MIQ.
- The effective reproduction number R_{eff}, i.e. the expected number of secondary cases caused by a single infected arrival if they were in MIQ for the full duration of their infectious period:

$$R_{eff} = meanContacts\,[(1 - p_{sub}) + relInf \times p_{sub}] \sum_{i=1}^{t_{max}} SAR(t_i)$$

  For the default parameter values, $R_{eff} = 0.143$. Testing, symptom monitoring and removal of confirmed and probable cases from the quarantine facility will reduce the effective reproduction number below this value.

Model Outputs

Three key metrics are considered: (1) the number of undetected cases as a proportion of the number of infected arrivals; (2) the number of significantly infectious cases released into the community as a proportion of the number of infected arrivals; and (3) the ratio of cases detected in the second week after arrival to cases detected in the first week after arrival. We define "significantly infectious" as being within the first three days since symptom onset (or equivalent time for asymptomatic cases). This is when individuals are assumed to have passed 93% of their total infectiousness. When enabled, transmission within MIQ may theoretically increase the values of (1) and (2) above 100% if there is sufficient transmission within MIQ so that more infected individuals are released than arrive. The ratio of cases detected in the second week to cases detected

in the first week was chosen as a measurable indicator of transmission within MIQ. Parameter values are shown in Table 1.

Name	Description	Default Value	Source
pSub	Proportion that are asymptomatic	42.5%	Lavezzo et al. (2020)
relInf	Relative infectiousness of subclinical individuals	50%	Davies et al. (2020)
relSens	Relative sensitivity of test of subclinical individuals	80%	Assumption
pDetectSymptoms	Probability a symptomatic individual's symptoms are detected	33%	NZ Estimate
LOS	Length of stay	14 days	NZ Policy
testDays	When tests administered, days since arrival	{3, 12}	NZ Policy
peakSAR	Peak secondary attack rate	0.7%	Cheng et al. (2020)
Generation time distribution	Distribution of generation times, used to calculate SAR(t), the function of secondary attack rates.	$Weibull(5.67, 2.83)$ days	Feretti et al. (2020)
meanContacts	Mean number of contacts each individual has	0 (no transmission), 5 (moderate transmission)	NZ Estimate
Onset distribution	Distribution of time from exposure to symptom onset	$\Gamma(5.8, 0.95)$ days	Lauer et al. (2020)

Table 1. Parameter descriptions and default values.

Results

Observed Data

From 9th June 2020, arrivals in New Zealand MIQ facilities have been tested twice, once around day 3 and once around day 12 (Ministry of Health, 2020). We consider the two-week period between 23rd June and 6th July, during which all individuals have been subject to these requirements for their entire stay. During this time, 21 cases of COVID-19 were reported in MIQ facilities. Table 2 gives a breakdown of these arrivals.

For comparison, 1,000 trials of the model were run for the same period. The number of daily arrivals was taken from NZ international arrival count data from StatsNZ. The probability of an arrival being infected was assumed to be 0.5%. This value was chosen so that the model (under the assumption of no transmission within MIQ) detected a similar number of cases as were reported. The model was also run with a moderate level of transmission in MIQ. Results are shown in Table 2.

In the model with no internal transmission, there were an average of 0.086 (0.046, 0.13) cases detected in the second week for every case detected in the first week. When a moderate amount of internal transmission was introduced, this increased to 0.12 (0.059, 0.18). Ignoring the two cases that were known close contacts of other cases, we observed a ratio of 0.12 in the data (2/17), within the range of plausible values for both no transmission and moderate transmission.

Two of the total observed cases, both detected in the second week, were each confirmed to be travelling and isolating with another case. We are not explicitly modelling these so they are ignored when comparing results.

	Observed	Model (no transmission within MIQ)	Model (moderate transmission within MIQ)
Total Detected	21	20.2 (17, 23)	21.0 (18, 24)
Detected in first week	17	18.6 (16, 21)	18.6 (16, 22)
Detected in second week	4	1.6 (1, 2)	2.3 (1, 3)
Detected by Day 3 Test	14	12.2 (10, 15)	12.2 (10, 15)
Detected by Day 12 Test	1	0.99 (0, 2)	1.4 (1, 2)
Detected by Symptoms/Other	6	8.1 (6, 10)	8.6 (6, 10)
Clinical Cases Detected	8	13.2 (11, 15)	13.8 (11, 16)
Subclinical Cases Detected	13	7.0 (5, 9)	7.1 (5, 9)
Cased Infected Pre-Arrival	Approx 20	20.2 (17, 23)	20.2 (17, 23)
Internally Acquired Cases	Approx 1	0	0.77 (0, 1)
Undetected Cases	Unknown	2.2 (1, 3)	2.8 (2, 4)

Table 2. Observed and modelled quarantine case detection for the period 23rd June to 4th July 2020. The model allows for a single case to be detected in multiple ways (e.g. if they declare their symptoms on the same day as a test), so totals may not match. 1st and 3rd quartile simulated values are given in parenthesis. Undetected cases may not be infectious when they leave.

The model consistently over-predicts the number of clinical cases and under-predicts the number of subclinical cases. There are at least three factors that might contribute to this: (1) international arrivals are typically younger so are more likely to be asymptomatic than the general population, and (2) clinical cases that have not developed symptoms on the day of testing may be listed as asymptomatic, with their status not updated when symptoms develop; (3) prevention or disinclination of symptomatic cases from travelling may be stronger than assumed in the model.

Scenarios

We consider seven scenarios. These are run both without transmission in MIQ and with a moderate level of transmission in MIQ, equivalent to each individual having 5 contacts per day on average.

Scenario 1 – Test on Arrival Only

- Each individual is tested once on arrival and held until the results are ready
- As in the full model, symptomatic individuals have a 33% chance of meeting the clinical definition and being detected.
- No exemptions permitted.

Scenario 2 – Test on Departure and Arrival

- Each individual is tested once before departure and once on arrival. They are held until the results are ready. The test before departure is assumed to be of the same quality as a domestic test.
- As in the full model, symptomatic individuals have a 33% chance of meeting the clinical definition and being detected.
- No exemptions permitted.

Scenario 3 – Five Day Quarantine

- Individuals are required to stay in a government managed quarantine facility for five days.
- Individuals are tested twice: once on arrival, and once on day four.
- No exemptions permitted.

Scenario 4 – 10 Day Quarantine

- Individuals are required to stay in a government managed quarantine facility for 10 days.

- Individuals are tested twice: once on day three, and once on day 8.
- No exemptions permitted

Scenario 5 – 14 Day Quarantine (Current)

- Individuals are required to stay in a government managed quarantine facility for 14 days.
- Individuals are tested twice: once on day three, and once on day 12.
- No exemptions permitted

Scenario 6 – Exemptions Allowed

- Individuals are required to stay in a government managed quarantine facility for 14 days.
- Individuals are tested twice: once on day three, and once on day 12.
- Exemptions are permitted at any time. Each individual has a 5% chance of being granted an exemption and is tested the day before their release.

Scenario 7 – Late Exemptions Allowed

- Individuals are required to stay in a government managed quarantine facility for 14 days.
- Individuals are tested twice: once on day three, and once on day 12.
- Exemptions are permitted in the second week only. Each individual has a 5% chance of being granted an exemption and is tested the day before their release.

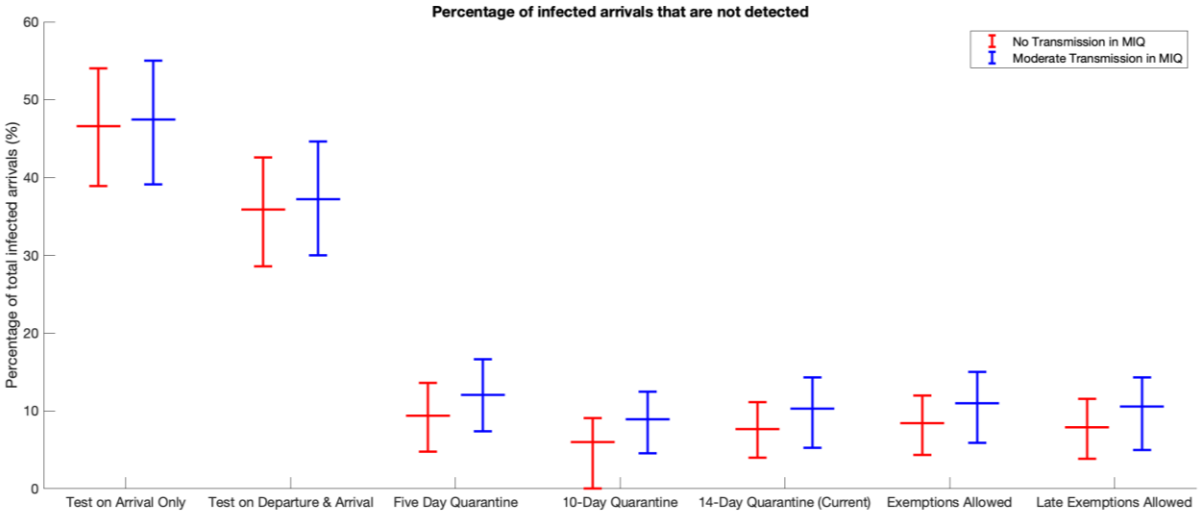

Figure 1. Relying on repeated testing and having no MIQ would significantly increase the risk of missed cases. Number of undetected cases as a percentage of infected arrivals. Vertical bars give the interquartile range for fortnightly values using the observed June NZ arrival and prevalence rates, and the wider horizontal line gives the expected value. Red bars are the results with no transmission in MIQ, and blue bars are the results with moderate transmission in MIQ.

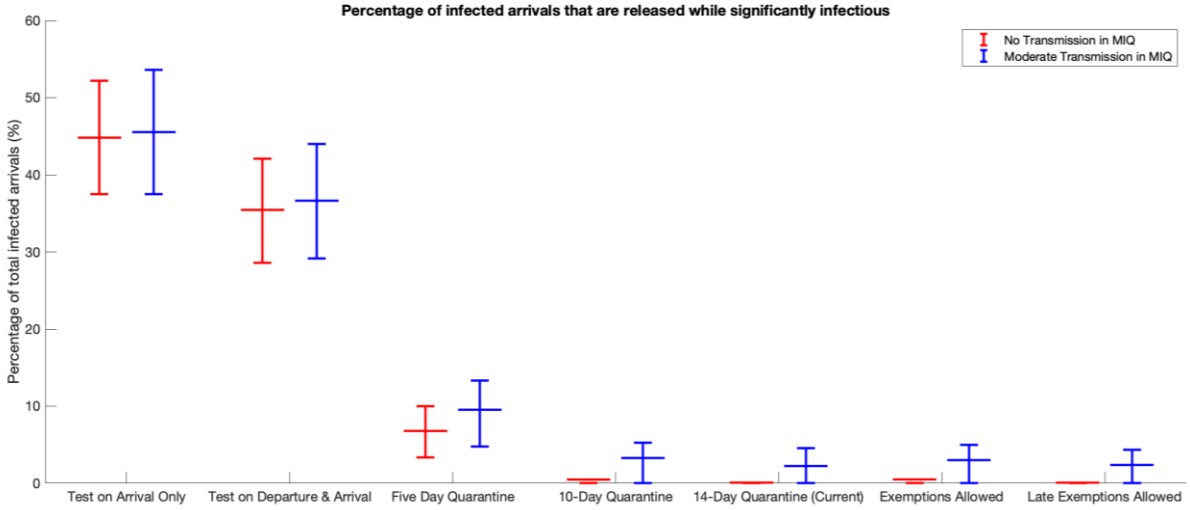

Figure 2. A shorter quarantine period would significantly increase the chance of a highly infectious individual entering the community. Number of significantly infectious cases released into the community as a percentage of the number of infected arrivals. The vertical bars give the interquartile range for fortnightly values (same duration as observed data), and the wider horizontal line gives the expected value. Red bars are the results with no transmission in MIQ, and blue bars are the results with moderate transmission in MIQ.

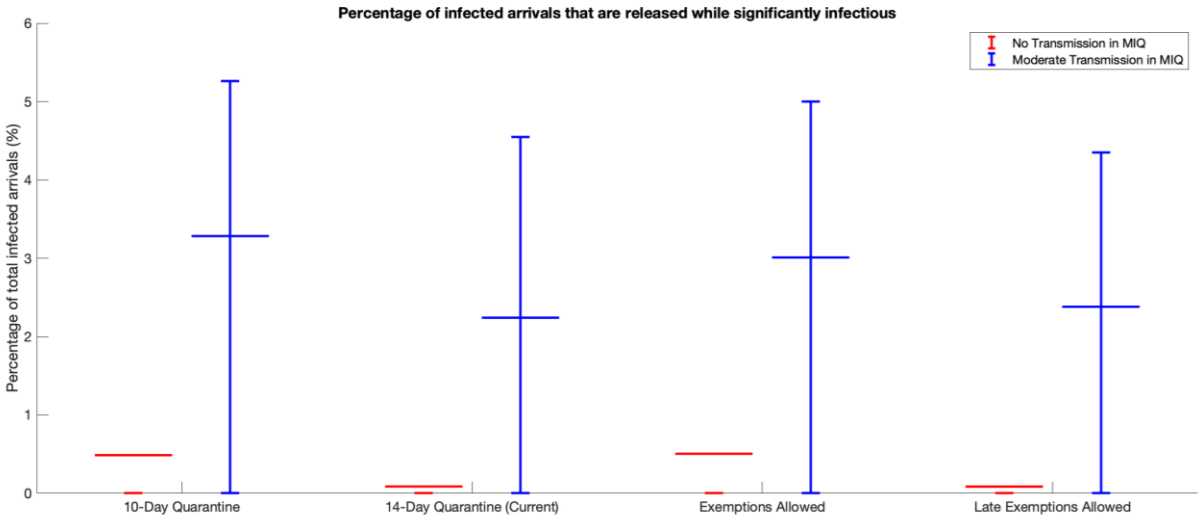

Figure 3. Number of significantly infectious cases released into the community as a percentage of the number of infected arrivals. This is cropped to highlight the differences resulting from exemptions. The vertical bars give the interquartile range for possible values over one week, and the wider horizontal lines give the expected value. In these scenarios, the 1st and 3rd quartile values are sometimes zero, while the mean is >0, so there may be no vertical lines. Red bars are the results with no transmission in MIQ, and blue bars are the results with moderate transmission in MIQ.

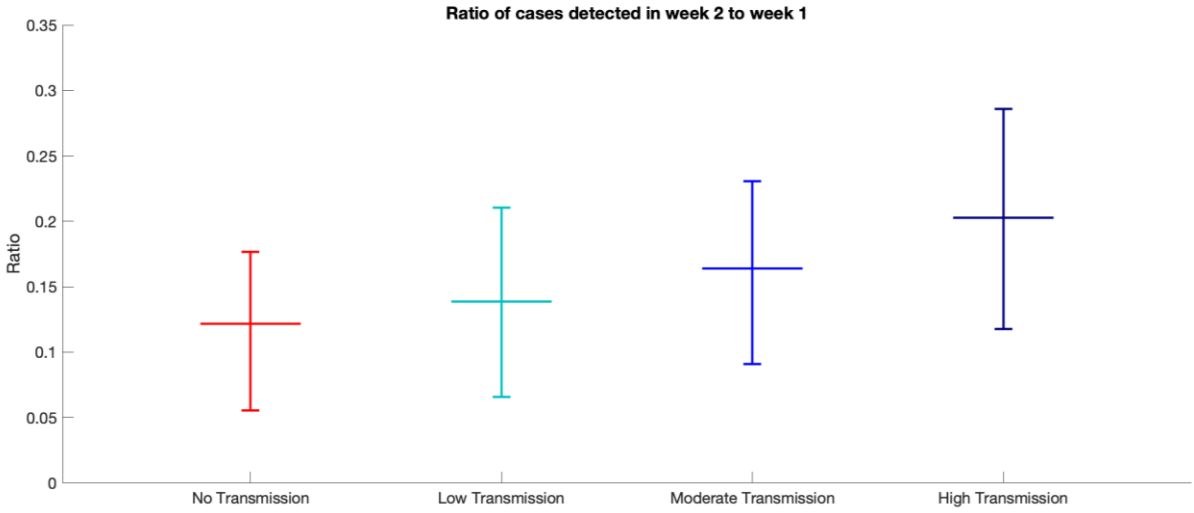

Figure 4. Ratio of cases detected in week 2 to week 1 under the current scenario (14-day quarantine). Four levels of transmission in MIQ are modelled: none, low (2 contacts on average), moderate (5 contacts on average) and high (10 contacts on average). These correspond to effective reproduction numbers of 0, 0.018, 0.052 and 0.104 respectively. The vertical bars give the interquartile range for possible values over a fortnight, and the wider horizontal line gives the expected value. The red bar is the results with no transmission in MIQ, and the blue bars are the results with moderate transmission in MIQ.

Scenario	Transmission in MIQ	% of All Cases	Median Value	First Quartile Value	Third Quartile Value
Test on Arrival Only	None	47%	47%	39%	54%
	Moderate	47%	48%	39%	55%
Test Departure & Arrival	None	36%	36%	29%	43%
	Moderate	37%	37%	30%	45%
Five Day Quarantine	None	9.4%	8.7%	4.8%	14%
	Moderate	12%	11%	7.4%	17%
10-Day Quarantine	None	6.0%	5.3%	0.0%	9.1%
	Moderate	8.9%	8.3%	4.5%	13%
14-Day Quarantine	None	7.7%	6.9%	4.0%	11%
	Moderate	10%	10%	5.3%	14%
Exemptions Allowed	None	8.4%	7.7%	4.3%	12%
	Moderate	11%	11%	5.9%	15%
Late Exemptions Allowed	None	7.9%	7.1%	3.8%	12%
	Moderate	11%	10%	5.0%	14%

Table 3. Number of undetected cases as a percentage of infected arrivals. The numerator includes undetected cases that acquired their infection during their stay. Median and quartiles are estimated from fortnightly windows.

Scenario	Transmission in MIQ	% of All Cases	Median Value	First Quartile Value	Third Quartile Value
Test on Arrival Only	None	45%	45%	38%	52%
	Moderate	46%	45%	38%	54%
Test Departure & Arrival	None	35%	35%	29%	42%
	Moderate	37%	36%	29%	44%
Five Day Quarantine	None	6.8%	5.9%	3.3%	10%
	Moderate	10%	9.1%	4.8%	13%
10-Day Quarantine	None	0.5%	0.0%	0.0%	0.0%
	Moderate	3.3%	3.3%	0.0%	5.3%
14-Day Quarantine	None	0.1%	0.0%	0.0%	0.0%
	Moderate	2.2%	0.0%	0.0%	4.5%
Exemptions Allowed	None	0.5%	0.0%	0.0%	0.0%
	Moderate	3.0%	0.0%	0.0%	5.0%
Late Exemptions Allowed	None	0.1%	0.0%	0.0%	0.0%
	Moderate	2.4%	0.0%	0.0%	4.3%

Table 4. Number of significantly infectious cases released into the community as a percentage of the number of infected arrivals. The numerator includes undetected cases that acquired their infection during their stay. Median and quartiles are estimated from fortnightly windows.

Scenario	Transmission in MIQ	*Effective Reproduction Number*	Overall Ratio	Median Value	First Quartile Value	Third Quartile Value
14 Day Quarantine	None	*0*	0.122	0.111	0.056	0.176
	Low	*0.018*	0.139	0.132	0.066	0.211
	Moderate	*0.052*	0.164	0.154	0.091	0.231
	High	*0.104*	0.203	0.190	0.118	0.286

Table 5. Effective reproduction number and ratio of cases detected in the second week to cases detected in the first week under various levels of transmission in MIQ. Low transmission is equivalent to 2 contacts per day, moderate transmission is equivalent to 5 contacts per day, and high transmission is equivalent to 10 contacts per day. Median and quartiles are estimated from fortnightly windows.

Testing on arrival, or testing on departure and arrival, only detect around 53% and 64% of arriving infected cases respectively. This could be improved if more accurate tests are developed but would always be the least recommended strategy.

A 5-day quarantine period detects as many cases as the full 14-day period but is not as effective in preventing highly infectious cases reaching the community. Under a 5-day quarantine period, around 6.8% of infected arrivals are released while highly infectious. With recent arrival rates (assuming no transmission in MIQ) this equates to an infectious case being released into the community every 9 days on average. The 10-day period reduces this to an infectious case being released every 100 days on average, and the 14-day period (the current scenario) reduces this even further to approximately 600 days.

Under the current 14 day quarantine scenario, a moderate level of transmission in MIQ (where each individual has contact with an assumed 5 others daily), increases the risk of a highly infectious case reaching the community rises from one every 600 days (no transmission) to one every 27 days. With a higher level of transmission in MIQ (equivalent to an average of 10 contacts per day) this risk increases even further. This highlights the importance of minimising contacts within MIQ facilities.

Despite the additional test, exemptions do pose a small amount of additional risk. This can be mostly mitigated by restricting exemptions to the second week only.

The ratio of the number of cases detected in the second week to cases detected in the first week increases as internal transmission increases. This is an observable quantity that can be easily calculated. Although, it is noisy tracking this value over time should give some insight into the level of transmission in MIQ. If this ratio increases substantially, then internal procedures should be evaluated.

Other Scenarios

Cohort demarcation, as suggested by the review into MIQ (NZ Government, 2020b), is another policy option being considered. This is where recent arrivals are kept separate from those nearing the end of their stay. While somewhat useful in reducing risk when there was transmission in MIQ, especially when exemptions were allowed, it was not as effective as simply reducing transmission in MIQ. Furthermore, although it wasn't explicitly modelled, the act of moving people during their stay likely increases their contacts. This would increase risk, possibly by more than the reduction obtained by the separation. We also modelled a small number of testing refusals, although provided these individuals were kept for an additional 14 days and well isolated from other guests, there was no significant change in risk.

Although not well documented, it is possible that some infected individuals may be super-shedders, meaning they are significantly more infectious than average. To test the effect of individual heterogeneity in infectiousness, we assigned each case an individual value for the peak secondary attack rate, drawn from a gamma distributed with mean 0.007 (which is the default assumption) and shape parameter 3. Any effects of this were not discernible even with a high number of contacts.

Sensitivity Analysis

Sensitivity analysis of the main model outputs was performed to key model parameters for the scenario of 14-day quarantine with two tests. We tested sensitivity to a time offset (Table 6) or a scaling (Table 7) of either the secondary attack rate function or the test sensitivity function. We also tested sensitivity to the probability of detecting symptoms, the proportion of infections that are subclinical, and the distribution of pre-arrival exposure dates (Table 8).

The ratio of cases detected in the 2nd week to cases detected in the 1st week was sensitive to all assumptions. The proportion of cases missed, and the proportion released while significantly infectious, was somewhat sensitive to a shifting of test sensitive and moderately sensitive to scaling of the same assumption. They were both also sensitive to the distribution of pre-arrival exposure dates, although only the former was sensitive to the proportion of cases that were subclinical.

		Percentage Missed		**Percentage Released While Significantly Infectious**		**Ratio of Cases Detected in 2nd Week to 1st Week**	
Function	Shift	No Transmission	Moderate Transmission	No Transmission	Moderate Transmission	No Transmission	Moderate Transmission
Secondary Attack Rate	1-day earlier	7.8%	11%	0.08%	2.4%	0.121	0.164
	Current value	8.1%	10%	0.05%	2.3%	0.122	0.162
	1-day later	7.7%	10%	0.09%	2.1%	0.123	0.157
Test sensitivity	1-day earlier	8.0%	11%	0.06%	2.0%	0.099	0.128
	Current value	8.0%	11%	0.04%	2.5%	0.124	0.160
	1-day later	8.1%	11%	0.1%	2.6%	0.174	0.208

Table 6. Sensitivity to shifts in the secondary attack rate as a function of time from symptom onset and test sensitivity as a function of time since exposure. There is a moderate level of sensitivity to these shifts, however, the relative effects of various policies remain very similar.

		Percentage Missed		Percentage Released While Significantly Infectious		Ratio of Cases Detected in 2nd Week to 1st Week	
Function	Scale	No Transmission	Moderate Transmission	No Transmission	Moderate Transmission	No Transmission	Moderate Transmission
Secondary Attack Rate	50% greater	8.3%	12%	0.07%	3.5%	0.116	0.187
	Current value	7.9%	10%	0.06%	2.1%	0.123	0.167
	50% lower	8.2%	9.4%	0.06%	1.1%	0.121	0.140
Test sensitivity	10% greater	6.0%	8.0%	0.06%	2.0%	0.102	0.134
	Current value	8.1%	10%	0.04%	2.2%	0.122	0.154
	10% lower	11%	14%	0.10%	2.6%	0.147	0.186

Table 7. Sensitivity to scaling in the secondary attack rate and test sensitivity.

		Percentage Missed		Percentage Released While Significantly Infectious		Ratio of Cases Detected in 2nd Week to 1st Week	
Parameter	Values	No Transmission	Moderate Transmission	No Transmission	Moderate Transmission	No Transmission	Moderate Transmission
Probably of detecting symptoms	25%	8.0%	11%	0.05%	2.2%	0.135	0.173
	33% (current)	8.0%	10%	0.08%	2.2%	0.124	0.157
	50%	7.5%	9.8%	0.05%	2.2%	0.111	0.149
Proportion Subclinical	30%	6.0%	8.4%	0.03%	2.4%	0.101	0.144
	42.5% (current)	8.1%	10%	0.1%	2.4%	0.124	0.161
	60%	11.3%	14%	0.08%	2.2%	0.154	0.191
Exposure Dates	[-14, 0]	10%	12%	0.04%	1.8%	0.114	0.144
	[-9, 0] (current)	7.6%	11%	0.08%	2.4%	0.123	0.159
	[-3, 0]	8.3%	11%	0.16%	2.8%	0.230	0.278

Table 8. Sensitivity to variation in probability of detecting symptoms, proportion that are subclinical, and exposure dates.

Discussion and recommendations

A 14-day period of managed isolation or quarantine (MIQ) reduces the risk of an infectious case being released into the community to a very low level. Combined with day 3 and day 12 testing, daily symptom checks, and complete isolation of confirmed cases, the risk of releasing an infectious case into the community is approximately 0.1% per arriving case. Significantly reducing the length of stay in MIQ would increase the risk of a highly infectious individual entering the community.

The greatest reduction in risk associated with quarantined international arrivals can be obtained by minimising mixing among guests in the facilities. This can be achieved by eliminating shared spaces such as smoking and exercise areas. Evidence suggests that speaking, especially while exercising, can substantially increase the chances of transmission (Buonanno et al, 2020). Removing the possibility of contacts between guests in MIQ facilities reduces the probability that someone acquires the disease during their stay and remains undetected. It also allows special exemptions to operate with significantly reduced risk, and results in lower overall infection in the facility, so the risk to MIQ workers is reduced.

The ratio of cases detected in the second week to cases detected in the first week, is an effective indicator of the level of transmission in MIQ. The absolute value of this ratio is difficult to estimate due to high sensitivity to key modelling assumptions. The ratio is also noisy, with limited cases being detected. Despite this, it is a useful metric to track over time, and trends in this data are likely to be informative.

In recent weeks the number of arrivals have increased, and the prevalence of COVID-19 overseas is also rising. Both of these factors lead to increased risk over time. This risk may be amplified if lower-quality MIQ facilities are used. The triaging of arrivals into "high-risk" and "low-risk" facilities is one possible solution to minimising risk and should be included in future modelling work.

There are other sources of risk associated with the border such as flight crew, immigration officers, and hotel workers. We have not explicitly modelled the risk of transmission from an infected hotel guest to a staff member because of a lack of data about the number of contacts between guests and staff and the associated secondary attack rate. It is possible this risk is comparable to or greater than the risk of releasing an imported case into the community. For example, recent community outbreaks in Melbourne are thought to have been seeded as a result of hotel staff being infected by people in quarantine facilities. Contacts between hotel guests and staff should be minimised and physical distancing and proper use of personal protective equipment by hotel staff at all times.

We did not model superspreaders or superspreading events as these are unlikely to occur within MIQ. It is possible that communal spaces and surfaces (such as buses, elevators, reception areas, door handles) could provide an avenue for environmental transmission. This would effectively correspond to an increase in the mean number of contacts parameter in the model, but is unlikely to cause superspreading events given the restrictions on individual movements. Nevertheless, communal spaces and surfaces should be regularly cleaned and good hand hygiene encouraged to minimise the possibility of environmental transmission. Supershedders (individual heterogeneity in infectiousness) can increase the risk of release an infectious case, but this effect is small providing existing procedures are followed. We did not explicitly model families or other groups travelling together. It is possible that these will increase the number of cases detected in the second week because of transmission between people staying in the same room, but for the purposes of measuring widespread transmission in MIQ should not be considered in the ratio calculation.

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