

Quantifying the impact of quarantine duration on COVID-19 transmission *

Peter Ashcroft*, Sonja Lehtinen, and Sebastian Bonhoeffer

Institute of Integrative Biology, ETH Zurich, Switzerland

Abstract

The numbers of confirmed cases of SARS-CoV-2 infection are increasing in many places. Consequently, the number of individuals placed into quarantine is increasing too. The large number of individuals in quarantine has high societal and economical costs, as well as infringing on the freedom of the individual. This has led to a vigorous debate about the duration of quarantine, particularly in light of the potentially low specificity of quarantine (i.e. low probability of quarantined individuals indeed being infected). We present a mathematical model that leverages empirically determined distributions of incubation period, infectivity, and generation time to quantify how the duration of quarantine affects transmission. With this model we address the impact of shortening the quarantine for returning travellers and traced contacts of confirmed cases, both in terms of prevented transmission and the ratio of prevented transmission to days spent in quarantine. We also consider the impact of i) test-and-release strategies; ii) additional hygiene measures imposed upon release after a negative test; iii) the development of symptoms during quarantine; iv) the relationship between quarantine duration and adherence; and v) the specificity of quarantine. When considering the benefit versus cost utility of quarantine, we find that the diminishing impact of longer quarantine on transmission prevention may support a quarantine duration below 10 days, particularly for returning travellers. A greater gain of utility can be achieved through a test-and-release strategy, and this can be even further strengthened by imposed hygiene measures post-release. We also find that unless a test-and-release strategy is considered, the specificity of quarantine does not affect the optimal duration of quarantine. Therefore, the argument that we should shorten quarantine because of lack of specificity is misguided.

1 Introduction

Quarantining individuals with high risk of recent infection is one of the pillars of the non-pharmaceutical interventions to control the ongoing SARS-CoV-2 pandemic. Due to the large fraction of pre-symptomatic or asymptomatic transmission (Ashcroft et al., 2020; He et al., 2020; Ferretti et al., 2020a; Buitrago-Garcia et al., 2020), quarantine can prevent a significant fraction of onward transmission that would not be detectable and is difficult to prevent. Indeed, thermal screening at airports allowed more than 50% of infected travellers to enter the general population (Quilty et al., 2020; Gostic et al., 2020), which could have been prevented by mandatory quarantine. With the high or

*Code is publicly available at <http://github.com/ashcroftp>. Current version: 24 September, 2020; Corresponding author: peter.ashcroft@env.ethz.ch

increasing case numbers that are observed in many places around the globe, however, more and more people are being placed into quarantine. In theory, quarantine periods could be avoided altogether through testing of the high risk individuals, but the low specificity of current testing technology, particularly in early infection (Kucirka et al., 2020), as well as limited testing capacity, precludes this approach. The high economic and societal costs (Nicola et al., 2020; Brooks et al., 2020), the restrictions of individual freedom (Parment & Sinha, 2020) and the often low number of individuals in quarantine that turn out to be infected, have fuelled an active public debate on the appropriate duration of quarantine.

Individuals are generally placed into quarantine for one of two reasons: either they have been identified as a recent close contact of a confirmed case by contact tracing, or they have returned from recent travel to a high-risk area with community transmission (WHO, 2020). These groups of quarantined individuals differ in two important aspects: compared to traced contacts, travel returners may have lower probability of being infected and have less precise information about the likely time of exposure. This raises the question whether the duration of quarantine should be the same for these two groups of individuals.

To our knowledge there are no clinical trials published that directly assess impact of duration of quarantine on transmission. Therefore we here present a mathematical model that allows quantifying the effects of changing quarantine duration. To this end we use the distributions of incubation time (time from infection to onset of symptoms), infectivity (infectiousness as a function of days since symptom onset), and generation time (difference of time points of infection between infector and infectee). These distributions have recently been estimated (Ferretti et al., 2020a) combining multiple transmission pair studies (Ferretti et al., 2020b; Xia et al., 2020; Cheng et al., 2020; He et al., 2020).

Using this model, we explore multiple factors that affect the duration of quarantine. Specifically we address how test-and-release strategies affect the fraction of transmission prevented by quarantine, taking into account data on the false-negativity rate as a function of days since exposure (Kucirka et al., 2020) as well as the time delay between test and result. These considerations are particularly important given that multiple testing has been shown to be of little benefit (Clifford et al., 2020). We also address the role of presymptomatic patients turning symptomatic and therefore being isolated independent of quarantine. Furthermore, as one of the arguments for shortening the duration of quarantine is to increase the number of people complying with the recommendation, we investigate by how much adherence needs to increase to offset the effects of earlier release from quarantine. Finally, we assess the role of a mask wearing policy for individuals released early from quarantine.

Making policy decisions about the duration of quarantine fundamentally requires

specifying how the benefits of quarantine relate to its costs. Benefits can be measured in terms of the overall reduction of transmission, while both economical, societal and individual costs are likely a function the days spent in quarantine. We therefore present results from two perspectives: one purely epidemiological, considering only reduction in transmission, and the other considering the ratio of transmission prevented to the average number of days spent in quarantine.

2 Methods

2.1 Quantifying the benefit of quarantine

Our primary goal is to quantify how much transmission is prevented by quarantining individuals who have been potentially exposed to SARS-CoV-2. To achieve this we need to know the time at which the individual was exposed (t_E), as well as when they enter (t_Q) and are released from (t_R) quarantine (Fig. 1). The timing of onward transmission is determined by empirical distributions based on multiple studies of transmission pairs (Ferretti et al., 2020a). These distributions are: the generation time distribution describing the time interval between the infection of an infector and infectee (Fig. 2A); the infectivity profile describing the time interval between the onset of symptoms in the infector and infection of the infectee (Fig. 2B); and the incubation period distribution describing the time between the infection of an individual and the onset of their symptoms (Fig. 2C). A detailed discussion about the relationships between these distributions can be found in Lehtinen et al. (2020).

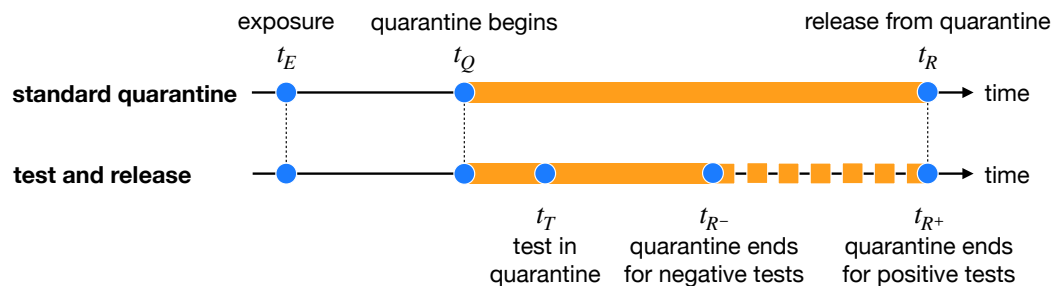


Fig. 1 The timeline of quarantine. Individuals are exposed to an infector at time t_E , and then quarantined at time t_Q . Under the standard quarantine protocol, this individual is quarantined until time t_R , and no onward transmission is assumed to occur during this time. Under the test-and-release protocol, quarantined individuals are tested at time t_T and released at time t_R- if they receive a negative test result. Otherwise the individual remains in quarantine until t_R+ .

Ultimately, the fraction of transmission prevented by the quarantine of an infected individual is the area under the generation time distribution $q(t)$ [Fig. 2C] (or alternatively under the infectivity profile, Fig. 2B) between the times at which the individual

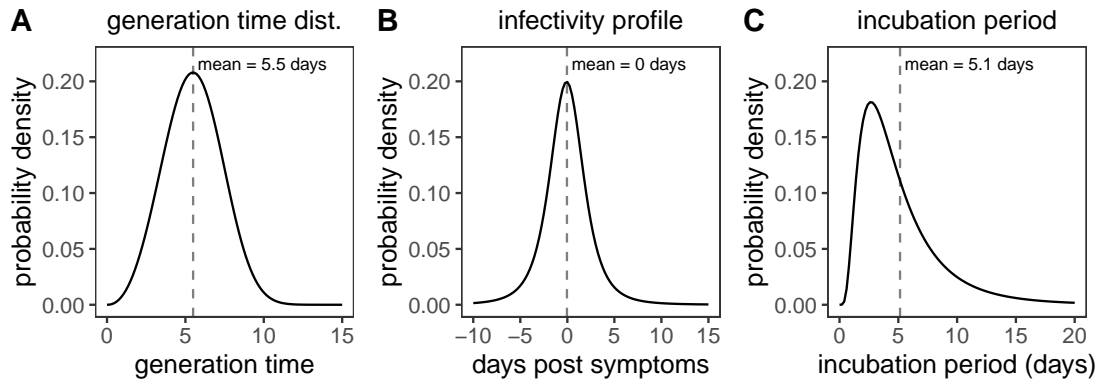


Fig. 2 A) The generation time distribution $[q(t)]$ follows a Weibull distribution (Ferretti et al., 2020a). B) The infectivity profile follows a shifted Student's t distribution (Ferretti et al., 2020a). C) The distribution of incubation times follows a log-normal distribution (Li et al., 2020).

enters and leaves quarantine (Grantz et al., 2020). Here we use the generation time distribution, such that the fraction of transmission prevented is

$$F = \int_{t_Q}^{t_R} dt' q(t' - t_E). \quad (1)$$

2.2 Specificity of quarantine

If only a fraction s of the individuals placed in quarantine are infected, then the average reduction in transmission across all individuals in quarantine is sF . We refer to s as the specificity of quarantine.

2.3 Test-and-release

A further quarantine strategy is to prematurely release individuals who produce a negative test result during the quarantine. As illustrated in Fig. 1, a test is issued at time $t_T > t_Q$. If the test is negative, the individual is released when the test result arrives at time t_{R-} . Otherwise, the individual remains in quarantine until time t_{R+} . One problem with this strategy is the high probability of a false-negative test result (i.e. an infected individual is prematurely released into the population). As reported in Kucirka et al. (2020), the false-negative rate is 100% on days 0 and 1 post infection, falling to 67% (day 4), 38% (day 5), 25% (day 6), 21% (day 7), 20% (day 8), and 21% (day 9), before rising to 66% on day 21. We label this function $f(x)$, the false-negative probability on day x after infection. The fraction of transmission prevented by quarantine under the test and release strategy is:

$$F_{\text{test}} = \int_{t_Q}^{t_{R-}} dt' q(t' - t_E) + [1 - f(t_T - t_E)] \int_{t_{R-}}^{t_{R+}} dt' q(t' - t_E), \quad (2)$$

where the first term captures that all individuals are quarantined until at least the test result day t_{R-} , and the second term accounts for transmission prevented by remaining in quarantine until t_{R+} following a positive test. Again expression (2) is conditional on the quarantined individual being infected, and the average effect across all quarantined individuals is sF_{test} for specificity s .

2.4 Reduced quarantine

We further consider the possibility of a reduced quarantine, where individuals released after a negative test are asked to maintain strict hygiene, mask wearing, and social distancing protocols until t_{R+} . We assume transmission is reduced by a fraction r due to these protocols, and hence the onward transmission prevented by quarantining an infected individual is

$$F_{\text{reduced}} = F_{\text{test}} + rf(t_T - t_E) \int_{t_{R-}}^{t_{R+}} dt' q(t' - t_E), \quad (3)$$

where the extra term is the transmission prevented by the reduced quarantine when an infected individual is prematurely released from quarantine.

2.5 Traced contacts versus travellers

We consider the scenarios of a traced contact and a returning traveller differently, because the values of t_E , t_Q , and t_R are implemented differently in each case.

2.6 Cost-benefit analysis

An important metric that we consider is the utility of a strategy, which compares the usefulness of quarantine (overall transmission prevented) to the number of person days spent in quarantine. For an efficacy F , specificity s , and average time spent in quarantine T , we define the utility as

$$U = \frac{sF}{T}. \quad (4)$$

Note that this is only one possible definition of utility and defining the appropriate function is ultimately a policy question.

3 Results

3.1 Quarantining traced contacts

Following a positive test result, a confirmed index case has their recent close contacts traced. From contact tracing interviews, we know when these traced contacts were last exposed to the index case (t_E) relative to the symptom onset of the index case ($t = 0$). The contacts are then placed into quarantine at time $t_Q = \Delta_Q$, where Δ_Q is the sum of the delay to the index case receiving a positive test result after developing symptoms and the further delay to tracing the contacts. Under the standard quarantine procedure, the traced contacts are quarantined until day $t_R = t_E + n$, i.e. they are quarantined until n days after their last exposure. Note that the time spent in quarantine is $t_E + n - \Delta_Q$, which is shorter than n .

The expected onward transmission (from an infected contact) that is prevented by quarantine [Eq. (1) and Fig. 3A] shows the diminishing return of increasing the quarantine duration. Furthermore, as the time delay to quarantine (Δ_Q) increases, the maximum efficacy of quarantine is reduced (because infected contacts have already transmitted more before being quarantined). If the duration of quarantine is already long (say, 10 days), then little can be gained in terms of prevention by quarantining for longer, but reducing the delay to starting quarantine does lead to increased efficacy. A final – though obvious – point to note, is that any shortening of a traced contact's quarantine duration reduces the efficacy of quarantining that individual.

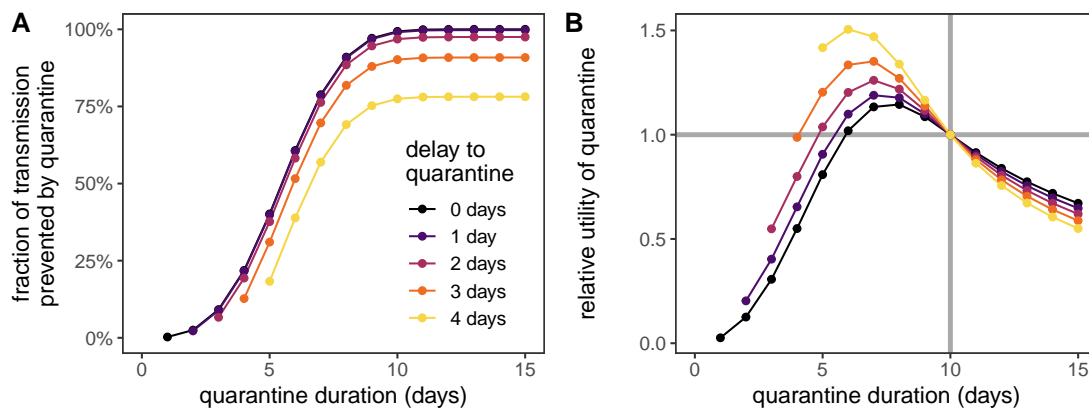


Fig. 3 A) The fraction of total onward transmission per quarantined infected contact that is prevented by quarantine [Eq. (1)]. B) The relative utility of different quarantine durations (x-axis) compared to $n = 10$ days, i.e. $U(n')/U(10)$ [utility as defined Eq. (5)]. Colours represent the delay to starting quarantine, Δ_Q . We use $t_E = 0$, which from the infectivity profile is the mean infection time of contacts if the index case develops symptoms at $t = 0$.

Note that we have assumed that the contact was infected at the last time of exposure. If there have been multiple contacts between them and the index case, then

transmission may have occurred earlier and we would overestimate the efficacy of quarantine.

The efficacy shown in Fig. 3A describes only the epidemiological benefit of quarantining infected individuals. However, quarantine also comes at a cost in terms of days spent in confinement. The utility of this quarantine strategy, as defined in Eq. (4), is

$$U(n) = \frac{sF(n)}{t_E + n - \Delta_Q}, \quad (5)$$

which depends on the specificity s . However, comparing two different strategies n and n' through their relative utility, i.e. $U(n')/U(n)$, eliminates this dependence on s . Therefore, the argument that we should shorten quarantine because of lack of specificity is misguided. By calculating the relative utility we observe that there exists an optimal strategy which maximises the benefit/cost ratio (Fig. 3B). This would be a duration of six to eight days, depending on the delay to starting quarantine Δ_Q .

Testing and releasing

We consider a test-and-release strategy where quarantined individuals are tested x days after exposure and released if the test result is negative. As above, quarantine begins at time $t_Q = \Delta_Q$. The test is conducted at $t_T = t_E + x$, and the result is received after a delay Δ_T at time $t_{R-} = t_T + \Delta_T$. Individuals with a negative test result are released, otherwise they remain in quarantine until time $t_{R+} = t_E + n$.

The fraction of infections prevented by quarantining an infected traced contact under the test-and-release strategy [F_{test} ; Eq. (2)] is always less than the fraction of transmission prevented by standard quarantine of the same duration (Fig. 4A). This is due to the considerable chance of prematurely releasing an infectious individual because of a false-negative test result. The deficiency of the test-and-release strategy decreases if we test later in quarantine, because we not only increase the duration of quarantine but also reduce the false-negative probability.

Again the function F_{test} shown in Fig. 4A describes only the epidemiological benefit of quarantine. The average time spent in quarantine will be $t_2 + x + \Delta_T - \Delta_Q + s[1 - f(x - t_E)](n - x - \Delta_T)$, where only positive cases s have the ability to return a positive test and remain in quarantine (i.e. we assume there are no false-positive test results). Hence the utility of the test-and-release strategy, using the definition in Eq. (4), is

$$U_{\text{test}}(n, x) = \frac{sF_{\text{test}}}{t_2 + x + \Delta_T - \Delta_Q + s[1 - f(x - t_E)](n - x - \Delta_T)}. \quad (6)$$

We can now compare the test-and-release strategy of duration n' and test day x with standard quarantine of duration n using the relative utility $U_{\text{test}}(n', x)/U(n)$, which now depends on the specificity s . Based on this metric of utility, we see that early

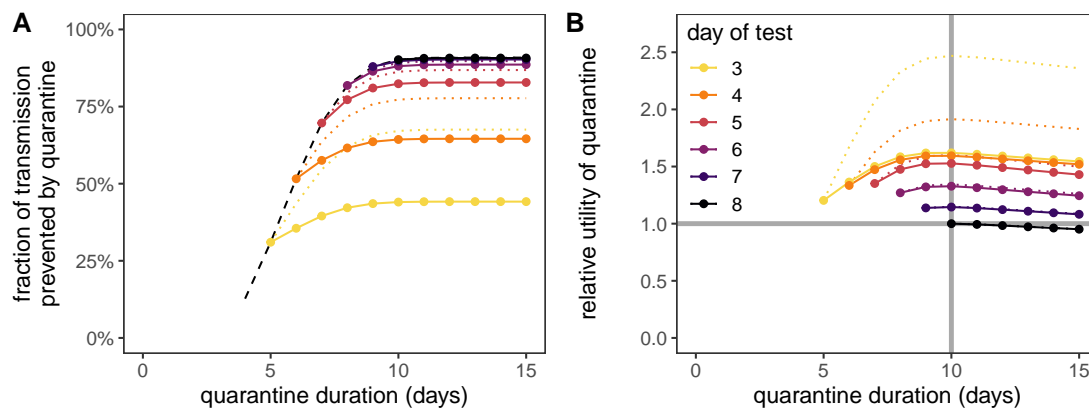


Fig. 4 A) The impact of the test-and-release quarantine strategy, in terms of what fraction of total onward transmission per infected traced contact is prevented by quarantine [F_{test} ; Eq. (2)]. The dashed line shows the result of standard quarantine without testing [F ; Eq. (1)]. B) The relative utility of different test-and-release quarantine durations compared to standard quarantine with duration $n = 10$ days, i.e. $U_{\text{test}}(n', x)/U(10)$ [Eq. (6)]. We use $t_E = 0$, which from the infectivity profile is the mean infection time of contacts if the index case develops symptoms at $t = 0$, and $\Delta_Q = 3$ as the delay until quarantine begins. Individuals are tested on day x after exposure (colour) and released on day $x + 2$ if negative (we assume it takes $\Delta_T = 2$ days to receive a test result). We assume a specificity of $s = 0.1$ and that there are no false-positive test results. Dotted lines in both panels assume the released individuals have a 50% reduced transmission ($r = 0.5$) due to extra hygiene and social distancing measures imposed by reduced quarantine [Eq. (3)].

testing is the optimal strategy (Fig. 4B). Testing on day five and releasing on day seven (we consider a fixed delay $\Delta_T = 2$ days) with a quarantine duration of $n = 10$ days has a relative utility of 1.5 compared to a standard 10 day quarantine, but with transmission only reducing from 90% to 82%.

Finally, we consider the reduced quarantine strategy, where individuals who receive a negative test result are released from quarantine but must adhere to strict hygiene and social distancing protocols until the end of the full quarantine. Considering a 50% reduction of post-quarantine transmission, we see very large increases in both efficacy and utility for early testing strategies, but with diminishing returns as the time at which tests are conducted is increased (dotted lines in Fig. 4). Note that we assume no contribution to the cost in the utility function due to mask wearing and social distancing in the post-release phase.

Further considerations: adherence and symptoms

Another factor that can affect the efficacy of quarantine is the level of adherence to a given strategy. For a quarantine duration of n days, a fraction $\alpha(n)$ of identified contacts will adhere to the strategy, while a fraction $1 - \alpha(n)$ will ignore the guideline. Hence the fraction of transmission prevented due to quarantine is $s\alpha(n)F(n)$, where again s is the specificity of quarantined individuals which we assume is independent of n . We expect $\alpha(n)$ to be a decreasing function of n , i.e. longer quarantines have a lower adherence. For two quarantine strategies with durations n and n' to have the same overall efficacy, the adherences must satisfy

$$\frac{\alpha(n')}{\alpha(n)} = \frac{F(n)}{F(n')}. \quad (7)$$

In other words, the change in the fraction of transmission prevented by quarantine must be compensated by an inverse change in the adherence. Shortening the duration of quarantine from 10 days to 5 days would require more than twice as many individuals to adhere to the quarantine guidelines in order to maintain the same overall efficacy (Fig. 5A). If quarantine is shortened further, then the required increase in adherence grows rapidly and soon becomes infeasible (the maximum possible adherence is $\alpha = 1$, so depending on the baseline level of adherence it may be impossible to increase this by the required factor). Hence the argument of shortening quarantine to increase adherence is of limited use.

As a final consideration, we note that our quantification of the fraction of transmission prevented by quarantine is more relevant to asymptomatic cases than to those who develop symptoms during the quarantine phase. If a traced contact develops symptoms and ultimately tests positive while in quarantine, we can remove them from the population indefinitely as they would have to isolate themselves. Import-

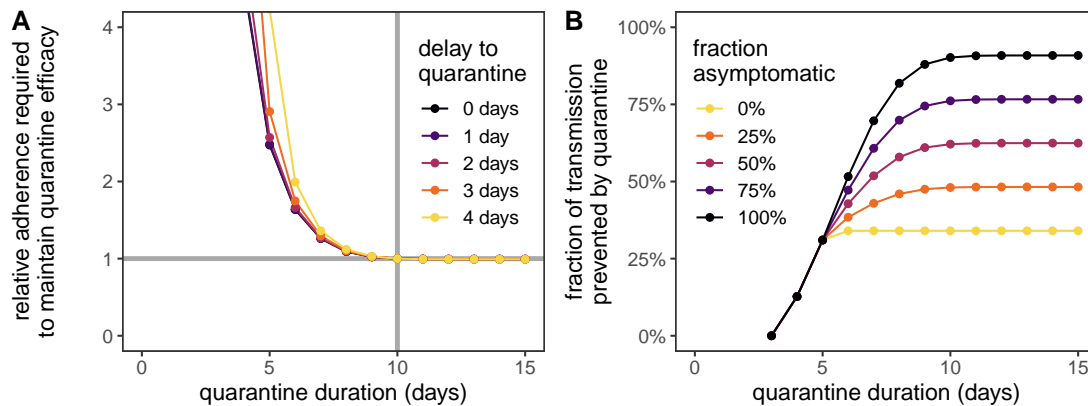


Fig. 5 A) The change in adherence needed to maintain quarantine efficacy of the $n = 10$ day strategy if we change the quarantine duration to n' days (x-axis), i.e. $\alpha(n')/\alpha(10)$ [Eq. (7)]. B) The impact of symptomatic cases on the fraction of total onward transmission per infected traced contact that is prevented by quarantine [Eq. (8)]. We fix $\Delta_Q = 3$ as the delay until quarantine, and $t_S = 5$, which is the mean incubation time. The curve for $a = 1$ corresponds to Fig. 3A. In both panels we use $t_E = 0$, which is the mean infection time of secondary cases based on the infectivity profile.

tantly, this individual would be removed from the population regardless of quarantine, so the reduction of cases due to their isolation should not be counted towards the efficacy of quarantine.

Let a be the fraction of asymptomatic cases, who will be quarantined using the standard strategy from time $t_Q = \Delta_Q$ until $t_R = t_E + n$. We assume that the symptomatic cases would anyway be isolated once they develop symptoms (at time t_S as described by the incubation period distribution, Fig. 2C), so these individuals are effectively quarantined until $t_R = \min(t_E + n, t_S)$. Therefore, for each traced contact who is put into quarantine, the fraction of infections that would be prevented by quarantine is

$$F(n, a) = a \int_{\Delta_Q}^{t_E+n} dt' q(t' - t_E) + (1 - a) \int_{\Delta_Q}^{\min(t_E+n, t_S)} dt' q(t' - t_E). \quad (8)$$

The fraction of transmission prevented by quarantine is an increasing function of the fraction of asymptomatic cases (Fig. 5B). This means that we likely overestimate the efficacy of quarantine as we are also counting transmission that is prevented by isolation following a positive test result.

3.2 Quarantining returning travellers

Unlike our traced contacts, we do not know when travellers were (potentially) exposed. This means that quarantine starts from the date that they return ($t_Q = 0$) and lasts for n days until time $t_R = n$. For simplicity, we assume a traveller was infected

at some time over a multi-day travel period $-y \leq t_E \leq 0$, where y is the duration of travel. For each exposure time t_E , we compute the fraction of total transmission that would be prevented by quarantine $[F(n); \text{Eq. (1)}]$, and then compute the average over the travel duration. Quarantine is most beneficial after shorter travel durations, as the majority of transmission would occur once the traveller has returned, which quarantine would prevent (Fig. 6A). We note that this is the absolute fraction of transmission prevented by quarantine, as opposed to how much transmission is blocked relative to the total transmission possible after arrival [which would be $F(n)/F(\infty)$].

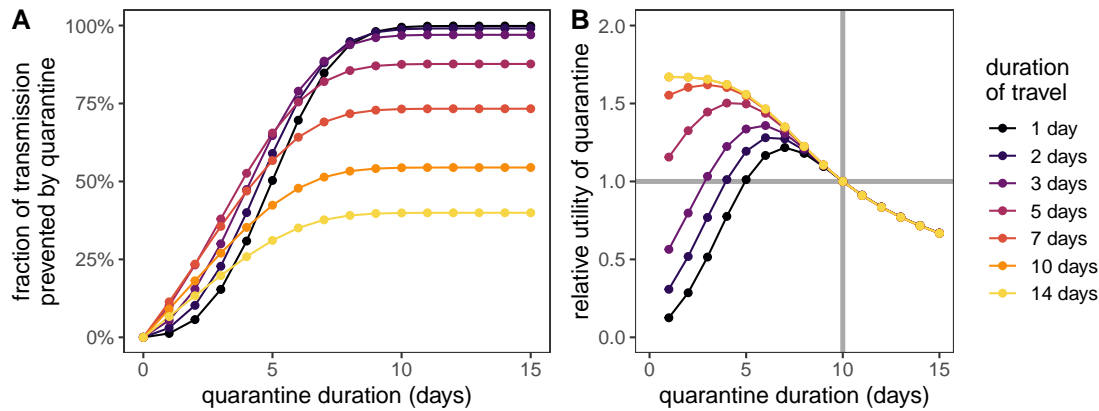


Fig. 6 A) The fraction of total onward transmission per quarantined traveller that is prevented by quarantine $[F; \text{Eq. (1)}]$. B) The relative utility of different quarantine strategies (x-axis) compared to $n = 10$ days, i.e. $U(n')/U(10)$ [Eq. (9)]. Colours represent the duration of travel y and we assume infection can occur on any day $-y \leq t_E \leq 0$ with uniform probability.

The human cost of quarantine here is n days, and hence the utility is simply $U(n) = sF(n)/n$. Comparing two different strategies n and n' , we have the relative utility

$$U(n')/U(n) = \frac{n' \langle F(n) \rangle_y}{n \langle F(n') \rangle_y}, \quad (9)$$

where $\langle \cdot \rangle_y$ represents the average over the travel duration y . An individual who has been infected during a long-duration travel will have, on average, been infected earlier and therefore will have, on average, less remaining infectivity potential upon return compared to an individual who travelled for a short duration. Hence if an individual traveller is to be quarantined, then the optimum duration of quarantine, based on this metric of utility, would depend on the duration of their travel, with shorter journeys requiring longer quarantine (Fig. 6B). This might be counter-intuitive because individuals who have been on longer journeys to high risk countries have a higher probability of being infected. However, here, we are not considering the question of whether to quarantine or not, but we are assuming that the individual is quarantined and are trying to optimise the duration of quarantine in response to the expected in-

fection dynamics. As the relative utility [Eq. (9)] is independent of the specificity s , the prevalence of disease in the travel destination (which should correlate the fraction of travellers becoming infected at that destination) does not influence the optimal quarantine duration.

Testing and releasing

If a returning traveller is tested at time $t_T = x$ during quarantine then they are released on day $t_{R-} = x + \Delta_T$ if the test is negative, or else kept in quarantine until day $t_{R+} = n$. The fraction of transmission prevented by quarantining an infected traveller [F_{test} ; Eq. (2)] accounts for false-negative test results. We show that there is little increase in transmission if quarantine is shortened for returning travellers who are tested on day x (Fig. 7A). However, the timing of the test has a significant impact on prevented transmission. Standard quarantine for ten days prevents 73% of transmission, testing on day five and releasing on day seven prevents 72% of transmission, but testing upon return at day zero only prevents 31% of transmission.

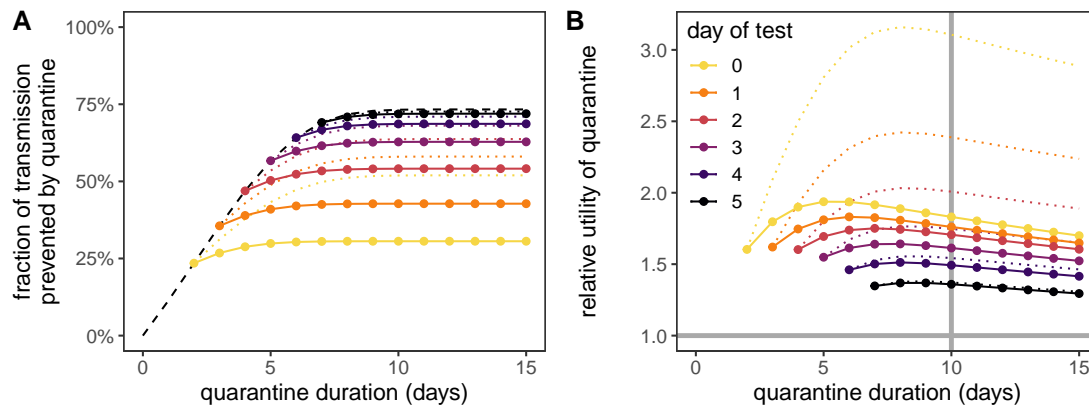


Fig. 7 A) The impact of test-and-release for quarantined travellers, in terms of what fraction of total onward transmission per quarantined infected traveller is prevented by quarantine [F_{test} ; Eq. (2)]. The dashed line shows the result of standard quarantine without testing [F ; Eq. (1)] B) The relative utility of different test-and-release quarantine durations compared to standard quarantine with duration $n = 10$ days, i.e. $U_{\text{test}}(n', x)/U(10)$. We consider a travel duration of $y = 7$ days and we assume infection can occur on any day $-y \leq t_E \leq 0$ with uniform probability. Individuals are tested on day x (colour) after returning on day 0 and released on day $x + 2$ if negative (we assume it takes $\Delta_T = 2$ days to receive a test result). We assume a specificity of $s = 0.1$ and that there are no false-positive test results. Dotted lines in both panels assume the released travellers have a 50% reduced transmission ($r = 0.5$) due to extra hygiene and social distancing measures imposed by reduced quarantine [Eq. (3)].

Again the function F_{test} shown in Fig. 7A describes only the epidemiological benefit of quarantining individuals. The average duration of quarantine will be $\langle x + \Delta_T +$

$s[1 - f(x - t_E)](n - x - \Delta_T)\rangle_y$, and hence the utility is

$$U_{\text{test}}(n, x) = \frac{s\langle F_{\text{test}} \rangle_y}{\langle x + \Delta_T + s[1 - f(x - t_E)](n - x - \Delta_T) \rangle_y}. \quad (10)$$

Comparing the test-and-release strategy of duration n' and test day x with standard quarantine using the relative utility, i.e. $U_{\text{test}}(n', x)/U(n)$, we see that shortening the duration of quarantine from 10 days (with x fixed) has small positive impact on the utility, but early testing greatly reduces the average duration of quarantine and hence leads to increased utility (Fig. 7B). Enforcing additional hygiene and social distancing guidelines following a negative test and release, we see large increases in both efficacy and utility for early testing strategies, but with diminishing returns as the time at which tests are conducted is increased (dotted lines in Fig. 7). We note that the relative utility of the test-and-release strategy depends on the specificity of quarantine s , and this specificity may change depending on disease prevalence at the travel destination and the duration of travel. E.g., the infected fraction of travellers returning from a long stay in a high-risk country is likely to be higher than the infected fraction of travellers returning from a short stay to a low risk country. In Fig. 7B we keep s fixed.

Further considerations: adherence and symptoms

For a quarantine of duration n days, a fraction $\alpha(n)$ of returning travellers will adhere to the strategy and remain quarantined, while a fraction $1 - \alpha(n)$ will ignore the guideline. We compute the relative change in adherence that is required to compensate a change in quarantine efficacy following a change in the duration of quarantine [Eq. (7); Fig. 8A]. We see that shortened travel durations require a greater increase in adherence when compared to longer travel durations.

Finally, we note that the above calculations are more suitable for describing asymptomatic cases, because cases who develop symptoms would be isolated anyway following a positive test. The fraction of transmission prevented by a quarantine of n days while accounting for the self-isolation of travellers who show symptoms during the quarantine period can be calculated analogously to Eq. (8). The fraction of transmission prevented by quarantine is an increasing function of the fraction of asymptomatic cases, such that we are likely overestimating the efficacy of quarantine as we are also counting transmission that is prevented by isolation (Fig. 8B).

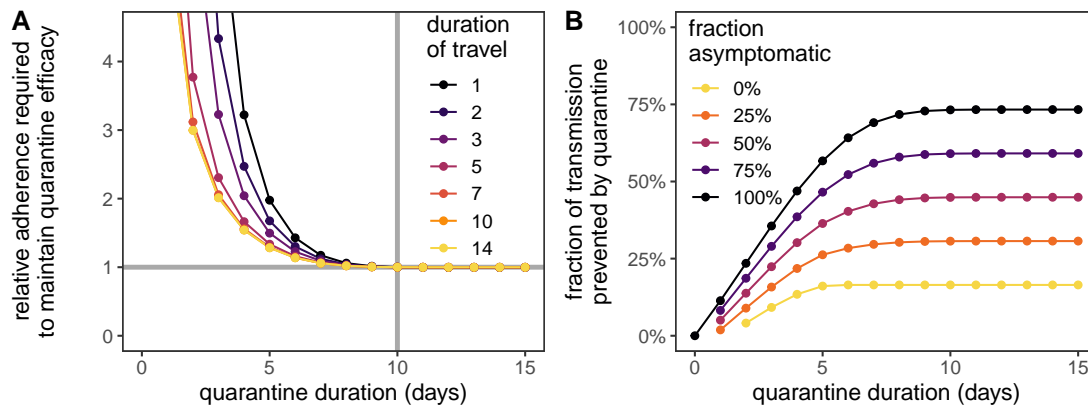


Fig. 8 A) The change in adherence needed to maintain quarantine efficacy of the $n = 10$ day strategy if we change the quarantine duration to n' days (x-axis), i.e. $\alpha(n')/\alpha(10)$. B) The impact of symptomatic cases on the fraction of total onward transmission per quarantined traveller that is prevented by quarantine. We fix the travel duration to $y = 7$ days and assume t_E is uniformly distributed between $-y$ and 0. The curve $a = 1$ corresponds to Fig. 6. We use the mean incubation time of five days, such that $t_S = t_E + 5$.

4 Discussion

Due to the large fraction of presymptomatic and asymptomatic transmission of COVID-19, quarantine is one of the most important measures in controlling the ongoing SARS-CoV-2 epidemic. We have shown that quarantining an infected traced contact for 10 days can prevent 75-99% of their onward transmission. For infected returning travellers, the efficacy is more uncertain due to unknown date of infection: if infection occurred significantly prior to return, travellers would not be expected to remain infectious for long after returning. However, in the worst case scenario of a contact being infected on the return flight, a 10 day quarantine will prevent 99% of onward transmission.

Any decrease in the duration of quarantine of an infected individual will result in increased onward transmission, and this fact cannot be ignored. However, there are diminishing returns for each day that we add to quarantine: shortening from 10 days to 9 days has little effect in terms of additional transmission. One therefore has to assess how much human cost, measured in terms of days spent in quarantine, are we willing to spend to prevent disease transmission. By comparing the ratio of prevented transmission to quarantine duration, we have shown that maximal utility strategies can exist. Importantly, under this metric the specificity of quarantine does not affect the optimal duration of quarantine. Therefore, the argument that we should shorten quarantine because of lack of specificity is misguided.

To further improve the utility of quarantine, the quarantined individuals can be tested and released given a negative result. This test-and-release strategy will lead to

an increase in the specificity of quarantine, and a lower average quarantine duration across infected and non-infected individuals. However, due to the considerable false-negative probability of the PCR test (Kucirka et al., 2020), this strategy also leads to increased transmission as infectious individuals are prematurely released. Nevertheless, a strategy of testing on day five and releasing negative cases on day seven carries a 1.5-fold increase in utility compared to a standard 10 day quarantine for traced contacts.

An argument for shortening the duration of quarantine is that it could lead to higher adherence. We quantify the increase in adherence that is required to maintain quarantine efficacy if the duration of quarantine is modified. Halving the duration from 10 days to 5 days would require more than twice as many individuals to enter quarantine to maintain the same efficacy. If quarantine is shortened further then the required increase in adherence would be too much to achieve. Hence this argument is limited in its usefulness.

Throughout we have assumed that individuals would fulfil 100% of their transmission potential in the absence of quarantine. This may not be true if individuals develop symptoms and are isolated as a result of a positive test. Therefore our approach will overestimate the efficacy of quarantine, but it is representative of the total transmission prevented by quarantine and isolation.

For travellers, another consideration is that lengthy quarantine is seen as a deterrent to travel to high risk areas (IATA, 2020). Any shortening of quarantine may lead to an increase in travel volume, potentially leading to a compounded increase in disease transmission.

Here, we have considered the utility of quarantine in terms of prevented transmission, regardless of the effective reproduction number. Another perspective is that the utility of preventing transmission is crucially dependent on whether it brings the reproductive number under one. Ultimately, bringing the reproductive number below one through quarantine is only possible in the presence of efficient contact tracing to find the potentially exposed individuals in a short time, as well as surveillance of disease prevalence to identify high-risk travel. Further improving the speed and accuracy of testing will allow average quarantine durations to be shorter, which increases the benefit to cost ratio of quarantine.

References

- Ashcroft, P., Huisman, J. S., Lehtinen, S., Bouman, J. A., Althaus, C. L., Regoes, R. R., & Bonhoeffer, S. (2020). COVID-19 Infectivity Profile Correction. *Swiss Medical Weekly*, 150(3132), <https://doi.org/10.4414/smww.2020.20336>.
- Brooks, S. K., Webster, R. K., Smith, L. E., Woodland, L., Wessely, S., Greenberg, N., & Rubin, G. J. (2020). The Psychological Impact of Quarantine and How to Reduce It:

Rapid Review of the Evidence. *The Lancet*, 395(10227), 912–920, [https://doi.org/10.1016/S0140-6736\(20\)30460-8](https://doi.org/10.1016/S0140-6736(20)30460-8).

Buitrago-Garcia, D., et al. (2020). Occurrence and Transmission Potential of Asymptomatic and Presymptomatic SARS-CoV-2 Infections: A Living Systematic Review and Meta-Analysis. *PLOS Medicine*, 17(9), e1003346, <https://doi.org/10.1371/journal.pmed.1003346>.

Cheng, H.-Y., Jian, S.-W., Liu, D.-P., Ng, T.-C., Huang, W.-T., Lin, H.-H., & for the Taiwan COVID-19 Outbreak Investigation Team (2020). Contact Tracing Assessment of COVID-19 Transmission Dynamics in Taiwan and Risk at Different Exposure Periods before and after Symptom Onset. *JAMA Internal Medicine*, 180(9), 1156–1163, <https://doi.org/10.1001/jamainternmed.2020.2020>.

Clifford, S., et al. (2020). Strategies to Reduce the Risk of SARS-CoV-2 Re-Introduction from International Travellers. *medRxiv*, (pp. 2020.07.24.20161281), <https://doi.org/10.1101/2020.07.24.20161281>.

Ferretti, L., et al. (2020a). The Timing of COVID-19 Transmission. *medRxiv*, (pp. 2020.09.04.20188516), <https://doi.org/10.1101/2020.09.04.20188516>.

Ferretti, L., et al. (2020b). Quantifying SARS-CoV-2 Transmission Suggests Epidemic Control with Digital Contact Tracing. *Science*, 368(6491), <https://doi.org/10.1126/science.abb6936>.

Gostic, K., Gomez, A. C., Mummah, R. O., Kucharski, A. J., & Lloyd-Smith, J. O. (2020). Estimated Effectiveness of Symptom and Risk Screening to Prevent the Spread of COVID-19. *eLife*, 9, e55570, <https://doi.org/10.7554/eLife.55570>.

Grantz, K. H., Lee, E. C., McGowan, L. D., Lee, K. H., Metcalf, C. J. E., Gurley, E. S., & Lessler, J. (2020). Maximizing and Evaluating the Impact of Test-Trace-Isolate Programs. *medRxiv*, (pp. 2020.09.02.20186916), <https://doi.org/10.1101/2020.09.02.20186916>.

He, X., et al. (2020). Temporal Dynamics in Viral Shedding and Transmissibility of COVID-19. *Nature Medicine*, 26(5), 672–675, <https://doi.org/10.1038/s41591-020-0869-5>.

IATA (2020). Traveler Survey Reveals COVID-19 Concerns. <https://www.iata.org/en/pressroom/pr/2020-07-07-01/>.

Kucirka, L. M., Lauer, S. A., Laeyendecker, O., Boon, D., & Lessler, J. (2020). Variation in False-Negative Rate of Reverse Transcriptase Polymerase Chain Reaction–Based SARS-CoV-2 Tests by Time since Exposure. *Annals of Internal Medicine*, <https://doi.org/10.7326/M20-1495>.

Lehtinen, S., Ashcroft, P., & Bonhoeffer, S. (2020). On the Relationship between Serial Interval, Infectiousness Profile and Generation Time. *medRxiv*, (pp. 2020.09.18.20197210), <https://doi.org/10.1101/2020.09.18.20197210>.

Li, Q., et al. (2020). Early Transmission Dynamics in Wuhan, China, of Novel Coronavirus–Infected Pneumonia. *New England Journal of Medicine*, 382, 1199–1207, <https://doi.org/10.1056/NEJMoa2001316>.

418 Nicola, M., et al. (2020). The Socio-Economic Implications of the Coronavirus Pan-
 419 demic (COVID-19): A Review. *International Journal of Surgery*, 78, 185–193, <https://doi.org/10.1016/j.ijssu.2020.04.018>.
 420

421 Parmet, W. E. & Sinha, M. S. (2020). Covid-19 — The Law and Limits of Quar-
 422 antine. *New England Journal of Medicine*, 382(15), e28, [https://doi.org/10.1056/](https://doi.org/10.1056/NEJMp2004211)
 423 [NEJMp2004211](https://doi.org/10.1056/NEJMp2004211).

424 Quilty, B. J., Clifford, S., CMMID nCoV working group, Flasche, S., & Eggo, R. M.
 425 (2020). Effectiveness of Airport Screening at Detecting Travellers Infected with
 426 Novel Coronavirus (2019-nCoV). *Eurosurveillance*, 25(5), 2000080, [https://doi.org/](https://doi.org/10.2807/1560-7917.ES.2020.25.5.2000080)
 427 [10.2807/1560-7917.ES.2020.25.5.2000080](https://doi.org/10.2807/1560-7917.ES.2020.25.5.2000080).

428 WHO (2020). Considerations for Quarantine of Contacts of COVID-19 Cases.
 429 *WHO/2019-nCoV/IHR_Quarantine/2020.3*.

430 Xia, W., et al. (2020). Transmission of Corona Virus Disease 2019 during the Incubation
 431 Period May Lead to a Quarantine Loophole. *medRxiv*, (pp. 2020.03.06.20031955).,
 432 <https://doi.org/10.1101/2020.03.06.20031955>.