Quarantine and testing strategies in contact tracing for SARS-CoV-2

Billy J Quilty* & Samuel Clifford*^, Stefan Flasche, Adam J Kucharski, CMMID COVID-19 Working Group, W John Edmunds

* These authors contributed equally
^ sam.clifford@lshtm.ac.uk

All authors are affiliated with the Centre for Mathematical Modelling of Infectious Diseases, London School of Hygiene and Tropical Medicine, London WC1E 7HT, United Kingdom

The following authors were part of the Centre for Mathematical Modelling of Infectious Disease COVID-19 Working Group. Each contributed in processing, cleaning and interpretation of data, interpreted findings, contributed to the manuscript, and approved the work for publication: Akira Endo, David Simons, Kaja Abbas, Desmond Yung-Wai Chan, Sophie R Meakin, Sam Abbott, James W Rudge, Kathleen O'Reilly, James D Munday, Graham Medley, Rosalind M Eggo, Nikos I Bosse, Emily S Nightingale, Charlie Diamond, Joel Hellewell, Yang Liu, Jon C Emery, Alicia Rosello, Thibaut Jombart, Petra Klepac, Megan Auzenbergs, Quentin J Leclerc, Rosanna C Barnard, Hamish P Gibbs, Amy Gimma, Stéphane Hué, Katherine E. Atkins, Georgia R Gore-Langton, C Julian Villabona-Arenas, Rein M G J Houben, Nicholas G. Davies, Kevin van Zandvoort, Arrinder K Deol, Damien C Tully, Yung-Wai Desmond Chan, Simon R Procter, Katharine Sherratt, Gwenan M Knight, Rachel Lowe, Carl A B Pearson, Mark Jit, Christopher I Jarvis, Matthew Quaife, Timothy W Russell, Fiona Yueqian Sun, Sebastian Funk, Kiesha Prem, Oliver Brady, Sam Abbott, Anna M Foss.

Summary

Previous work has indicated that contact tracing and isolation of index case and quarantine of potential secondary cases can, in concert with physical distancing measures, be an effective strategy for reducing transmission of SARS-CoV-2 (1). Currently, contacts traced manually through the NHS Test and Trace scheme in the UK are asked to self-isolate for 14 days from the day they were exposed to the index case, which represents the upper bound for the incubation period (2). However, following previous work on screening strategies for air travellers (3,4) it may be possible that this quarantine period could be reduced if combined with PCR testing. Adapting the simulation model for contact tracing, we find that quarantine periods of at least 10 days combined with a PCR test on day 9 may largely emulate the results from a 14-day quarantine period in terms of the averted transmission potential from secondary cases (72% (95%UI: 3%, 100%) vs 75% (4%, 100%), respectively). These results assume the delays from testing index cases' and tracing their contacts are minimised (no longer than 4.5 days on average). If secondary cases are traced and quarantined 1 day earlier on average, shorter quarantine periods of 8 days with a test on day 7 (76% (7%, 100%)) approach parity with the 14 day quarantine period with a 1 day longer delay to the index cases' test. However, the risk of false-negative PCR tests early in a traced case's infectious period likely prevents the use of testing to reduce quarantine periods further than this, and testing immediately upon tracing, with release if negative, will avert just 17% of transmission potential on average. In conclusion, the use of PCR testing is an effective strategy for reducing quarantine periods for secondary cases, while still reducing transmission of SARS-CoV-2, especially if delays in the test and trace system can be reduced, and may improve quarantine compliance rates.

NOTE: This preprint reports new research that has not been certified by peer review and should not be used to guide clinical practice.
Method

Following the notation of Kretzschmar et al. (2020) (5), we consider the following events to be relevant to the tracing of the contacts of an index case - an individual assumed to be newly-symptomatic with COVID-19 and seeking a test (Figure 1). Each of the following variables are specific to an individual, but we omit a subscript, $i$, for brevity. An individual is exposed and becomes infected at time $T_0$. We assume the index case has onset of symptoms at time $T_2$, lasting until time $T_2'$. For asymptomatic cases, no symptoms are ever displayed and hence both $T_2$ and $T_2'$ are undefined. For sensitivity, we assume testing of the index case occurs at time $T_3$, 1, 2 or 3 days after symptom onset, with the results of the test available at time $T_3'$; those testing positive will go on to isolate for 10 days from their symptom onset (6). We assume that positive cases are immediately referred to contact tracers, with the index case's contacts’ information sourced at $T_4'$, and these contacts are then traced and quarantined at time $T_4'$. For comparison, we consider the baseline for index case testing delay to be 2 days.

![Figure 1 - Example schematic of the contact tracing process and associated timings where an index case causes two secondary cases, one of which is symptomatic and one of which is asymptomatic. Darker shaded regions of each cases’ timeline indicate periods of increased infectivity. Arrows indicate transmission events, with red crosses indicating transmission prevented through quarantine of traced contacts. As the asymptomatic secondary case is quarantined (dashed red line) before they become infectious, they never spend any time infectious in the community.]

Rather than assuming a specific time at which infectivity begins ($T_1$ in Kretzschmar's notation) we consider the infectivity profile, i.e, a distribution of times at which transmission is likely to occur. This distribution is derived by considering the incubation period (time from exposure to onset of symptoms), $T_2 - T_0$, and delay from infectiousness to onset of symptoms $T_2' - T_1'$, and using the corrections by Ashcroft et al. (2020) (7) to the method of He et al. (2020) (8) with incubation periods sampled from the distribution in (9).
For the index case we parameterise the delays associated with the contact tracing system (having a test to receiving the results \(T_3 - T'_3\), sourcing contact information \(T_4 - T_3\), and tracing \(T_4' - T_4\)) according to the latest NHS Test and Trace data from the week 16 July 2020 to 22 July 2020 (Table 1) (10). These times are reported as 24 hour intervals \(\{0 \leq t < 1, 1 \leq t < 2, 2 \leq t < 3, t \geq 3\}\) days), which we used to derive a Gamma distribution considering the delay in each index case's awaiting a test result, sourcing of contacts and tracing of contacts as doubly-censored observations on the specified time intervals using the fitdistcens function from the fitdistrplus package in R (11).

We consider the same quarantine stringency settings as in our previous work (3), namely: low, moderate, high and maximum stringencies, based on the expected reduction of onwards transmission potential (Table S1). Any secondary case displaying symptoms during their quarantine period will continue to isolate until 10 days have passed since onset of symptoms (6). Low stringency quarantine consists of a test at time of tracing and release from quarantine a day later if negative. Moderate stringency consists of mandatory quarantine periods of 3, 5 or 7 days, releasing on that day if no testing is considered or, if testing is considered, \(T_3' - T_3\) days later if the test is negative. The high stringency scenarios consider double testing in order to minimise the amount of time spent in quarantine; a 14 day maximum quarantine period is in effect, but individuals returning two negative tests in this time are granted early release. We consider delays until first test of \(\{0, 1, 2, 3\}\) days from initial time of quarantine and then delays from first to second test of \(\{2, 4, 6\}\) days, which results in the potential for early release after \(\{3, 4, \ldots, 10\}\) days of quarantine, accounting for a 1-day turnaround for test results. The maximum stringency setting, 14 days of quarantine, represents the time by which it is expected that 95% of ever-symptomatic cases will display symptoms and continue to self-isolate. As in the moderate stringency setting, release is at the end of the mandatory quarantine period if no test is considered, or after \(T_3' - T_3\) when the test is negative.

Further details on the testing scenarios, infection history generation, and test sensitivity are provided in Tables S1 and S2 in the Supplementary Appendix, adapted from Tables 2 and 3 in Clifford and Quilty et al. (3).

For each secondary case we calculate the mass of the infectivity profile distribution from exposure to post-tracing isolation as a measure of transmission potential prior to quarantine. Similarly, the mass of the infectivity after release is a measure of transmission potential after quarantine. We assume that infectivity is zero 14 days after the incubation period, effectively truncating the infectivity distribution to the right, parameterised in terms of number of days from onset (7). We also truncate on the left for each secondary case's exposure time on the left (here, \(t = - T_2\)) and rescale the mass of the distribution to account for these truncations. We therefore calculate the transmission potential prior to tracing, after release, and the amount of transmission potential which is averted by quarantine. We report the median and 95% uncertainty interval of these simulated values based on 1000 simulated index cases each with 1000 secondary cases generated.

Model code is available at https://github.com/cmmid/pcr_track_trace
Results

Delay distributions

The summary statistics of the fitted distributions of return of index cases’ test results, and subsequent sourcing and tracing of contacts, are given in Table 1 and Figure S1. A majority of all activities relevant to contact tracing are completed within 24 hours of their beginning. The average modelled contact tracing takes approximately 2.5 days from time of initial test to completion of tracing. Here we have assumed that the duration of each of these activities are independent.

Table 1: Time periods for return of index cases’ test result, sourcing of contacts, and tracing of contacts. Gamma distribution mean, standard deviation, median and 95% prediction interval for time to source contacts from case and time to trace said contacts. *The total is derived from the sum of 100,000 sampled values and no closed form distribution exists.

| Delay distribution                  | Mean, $\mu$ | Std. Dev., $\sigma$ | 2.5%  | 50%  | 97.5% |
|-------------------------------------|-------------|---------------------|-------|------|-------|
| Return of index cases’ test result  | 1.11 days   | 0.67 days           | 0.21 days | 0.98 days | 2.74 days |
| Sourcing of contacts                | 0.76 days   | 0.66 days           | 0.02 days | 0.54 days | 2.77 days |
| Tracing of contacts                 | 0.58 days   | 0.75 days           | 0.01 days | 0.38 days | 2.27 days |
| Total*                              | 2.46 days   | 1.18 days           | 0.75 days | 2.26 days | 5.28 days |

Reduction in transmission potential

The longer the delay to the index case’s seeking a test, the more potential for transmission from as yet untraced secondary cases there is. This is independent of the stringency scenarios as transmission occurs prior to tracing. If the delay from symptom onset of the index case to having a test is 2 days, 25% (95% UI: 0%, 95%) of the secondary cases’ maximum transmission potential occurs prior to tracing. If this is reduced to a 1 day delay, the pre-quarantine transmission potential is 15% (0%, 91%); for an increase to 3 days’ delay, the transmission potential increases to 38% (0%, 98%).

Longer quarantine periods decrease the proportion of the transmission potential spent in the community after release (Figure 2). If the delay from symptom onset of the index case to having a test is 2 days, and no testing or quarantine is conducted, 75% (4%, 100%) of transmission potential occurs after tracing. For a 14 day quarantine with no testing, the transmission potential after release is reduced to less than 0.02% (0%, 17%). However at 8 days quarantine with a single test on day 7, the median transmission potential after release decreases to 1%, albeit with a long tail (upper 97.5% quantile: 82%).
Effect of PCR testing

We find that the transmission potential averted, i.e., the proportion of transmission potential spent in quarantine and isolation instead of in the community, increases as the quarantine period increases. The transmission potential averted can be increased further if PCR testing is conducted on the final day of
quarantine. We see that, assuming a delay to index case test of 2 days, the introduction in the low stringency setting of a test with a single day's turnaround (effectively a one day quarantine) is to avert 17% (0%, 100%) of infectivity (Figure 2, low). However as the quarantine period increases, the relative contribution of a test is lessened. In the maximum stringency scenarios, with 14 days of mandatory quarantine, 75% of transmission potential is averted (95% UI: (4%, 100%)) both with and without a test (Figure 2, max).

Table 2: Averted transmission potential stratified by number of days and testing in quarantine and delay to index cases' test and isolation.

| Days in quarantine (and test) | Delay to index cases' test and isolation (days) | Median transmission potential averted | 50% UI (IQR) | 95% UI |
|-------------------------------|-----------------------------------------------|--------------------------------------|-------------|-------|
| 14 (no test)                  | 1                                             | 84%                                  | (55%, 97%)  | (8%, 97%) |
| 10 (day 9)                    |                                               | 81%                                  | (52%, 93%)  | (7%, 93%) |
| 10 (days 3 & 9)               |                                               | 82%                                  | (54%, 94%)  | (7%, 100%) |
| 14 (no test)                  | 2                                             | 75%                                  | (41%, 95%)  | (4%, 100%) |
| 10 (day 9)                    |                                               | 72%                                  | (40%, 91%)  | (4%, 100%) |
| 10 (days 3 & 9)               |                                               | 73%                                  | (40%, 93%)  | (4%, 100%) |
| 14 (no test)                  | 3                                             | 62%                                  | (28%, 90%)  | (2%, 100%) |
| 10 (day 9)                    |                                               | 60%                                  | (27%, 87%)  | (2%, 100%) |
| 10 (days 3 & 9)               |                                               | 61%                                  | (28%, 88%)  | (2%, 100%) |

PCR testing can be used to achieve a modest reduction in quarantine duration. For all index case test delays considered, the 14 day quarantine averted transmission potential can be achieved by testing on day 9 and releasing on day 10 if negative (2 day index test delay, 72% (3%, 100%), Figure 3, mod.). The additional benefit of a second test - 0, 1, 2, or 3 days into quarantine - is negligible for longer quarantine periods (Figure 3, high, Table 2). Varying the day of the first test in double testing scenarios also had little effect.
Reducing index cases’ test delays

While the inclusion of a test or the lengthening of quarantine can reduce the transmission potential, efforts to reduce the delay in the index case’s seeking of a test (and subsequently isolating) can lead to a reduction in quarantine period while averting the same amount of transmission potential. If the current delay to index case testing is 3 days, the same averted transmission potential for a 14 day quarantine (62%, (2%, 99%)) is
achieved at a 2 day delay with a quarantine lasting 6 days with a test on day 5 (62%, (4%, 100%)). Similarly, if the current delay is 2 days, reducing the delay to 1 day could replace a 14 day quarantine (transmission potential averted 74% (5%, 100%)) with one lasting 8 days with a test on day 7 (76% (7%, 100%)). In effect, decreasing index cases’ delay to a test by 1 day and adopting PCR testing at the end of the quarantine period may reduce length of quarantine by 1 week.

The impact of asymptomatic infections

Much of the uncertainty in transmission potential for a given index case testing delay and quarantine scenario is due to the variation in onset of symptoms in secondary cases relative to the time of exposure of the index case. The overall transmission potential is a combination of that of the symptomatic and asymptomatic cases. In the low stringency scenarios, we see that asymptomatic cases are unlikely to be detected by a test at day 0 and that the ability to reduce transmission potential in the ever-symptomatic cases is dependent on the index case’s delay to testing and isolation (Figure 4, Table 3). For both the high (double testing) and maximum (14 day quarantine) scenarios, the averted transmission potential for the ever-symptomatic cases is approximately the same within each index case testing delay (Figure 4, Table 3) as conducting multiple tests during the quarantine period gives a greater chance of detecting the infection. For a delay of 1 day, 86% (8%, 100%) of the transmission is averted, decreasing to 76% (4%, 100%) and 63% (2%, 100%) for 2 and 3 days respectively. For the asymptomatic cases in the high testing scenario, earlier testing returns false negative tests and some asymptomatics are released too early and may go on to cause additional cases. In both the moderate and high scenarios, the averted transmission potential for symptomatic and asymptomatic cases converge the longer the quarantine lasts.

Table 3: Averted transmission potential stratified by number of days and testing in quarantine, delay to index cases’ test and isolation, and type of infection (asymptomatic = never symptomatic, pre-symptomatic = ever symptomatic and released from quarantine prior to the detected onset of symptoms).

| Days in quarantine (and test) | Delay to index cases’ test and isolation (days) | Infection type | Median transmission potential averted | 50% UI (IQR) | 95% UI |
|-------------------------------|-----------------------------------------------|----------------|----------------------------------------|--------------|--------|
| 14 (no test)                  | 1 Symptomatic                                  | 86% (57%, 98%) | (8%, 100%)                             |              |        |
|                               | Asymptomatic                                  | 84% (54%, 96%) | (8%, 99%)                              |              |        |
| 10 (day 9)                    | 1 Symptomatic                                  | 85% (55%, 98%) | (8%, 100%)                             |              |        |
|                               | Asymptomatic                                  | 79% (51%, 92%) | (6%, 100%)                             |              |        |
| Day   | Symptomatic | 76% (40%, 96%) | 4%, 100% | Asymptomatic | 71% (39%, 90%) | 4%, 100% |
|-------|-------------|----------------|----------|--------------|----------------|----------|
| 2     | Symptomatic | 62% (28%, 91%) | 2%, 100% | Asymptomatic | 59% (27%, 86%) | 2%, 100% |
| 3     | Symptomatic | 69% (14%, 96%) | 0%, 100% | Asymptomatic | 15% (7%, 78%)  | 0%, 99%  |
| 1 (day 0) | Symptomatic | 58% (13%, 91%) | 0%, 100% | Asymptomatic | 14% (8%, 66%)  | 0%, 99%  |
|       | Symptomatic | 42% (11%, 82%) | 0%, 100% | Asymptomatic | 14% (7%, 50%)  | 0%, 99%  |
Figure 4: Averted transmission potential stratified by type of infection (asymptomatic = never symptomatic, pre-symptomatic = ever symptomatic and released from quarantine prior to the detected onset of symptoms). Row facets indicate delay from symptom onset to having a PCR test for the index case. Scenarios with no testing are denoted by orange bars; single tests with purple bars, and two tests with blue bars. Labels in the High stringency scenario indicate the different combinations of days of first and second test relative to entering quarantine. We assume that test results are delayed by 1 day and hence persons leave quarantine 1 day after their final test. Central bar = median; light bar = 95% uncertainty interval; dark bar = 50% uncertainty interval.

Discussion

The number of days secondary cases spend infectious prior to testing of the index case and tracing of contacts is dependent on the delays from the onset of symptoms of the index case to tracing of the secondary case, some of which can be reduced by more effective sensitisation of the public to COVID-19 symptoms, and more effective tracing systems.

We find that, provided the time from the index case’s symptom onset to tracing of secondary contacts are moderately short (≤ 4.5 days on average, comprising 2 days for onset to a test and 2.5 days on average for all subsequent tracing), a quarantine period of at least 10 days may largely emulate the 14 day quarantine period in the reduction of traced infectious individuals entering the community. If this can be reduced to 3.5 days, the quarantine period could be shortened further to 9 days, as currently-infectious individuals are in quarantine or isolation for longer overall. In our analysis we assumed that delays in test result return, sourcing of contacts and contacting them to encourage quarantine are all independent. The delays may be positively correlated, however, with common structural causes, which could lead to a total delay distribution with a smaller median and larger variance. This would have the effect of getting more people into quarantine quicker, but those who are delayed in being quarantined are delayed longer. Longer delays to quarantining reduce the relative effectiveness of shorter quarantine periods in comparison to a 14 day quarantine period, as individuals spend less of their infectious period in quarantine after initial tracing and may exit prior to onset of symptoms. Longer delays also result in a predictable increase in the number of days individuals
spend infectious prior to being traced. Notably, even a 14-day quarantine period does not eliminate the risk of individuals spending time infectious after release. However, this represents individuals who are late in their infectious period and largely asymptomatic, where their true transmission potential is likely minimal, according to the infectivity profile as detailed in Ashcroft et al. 2020 (7).

Inclusion of a PCR test provides some benefit with shorter quarantine periods. This additional benefit diminishes with longer quarantine duration, as infectious persons have a higher probability of developing symptoms (if ever-symptomatic) and self-isolating. The high probability of a false-negative test result early on in a person's infection prevents their use from fully replacing long quarantine periods. Having two tests has a negligible effect on reducing the transmission potential above that of a single test, and the additional benefit is again lessened with longer quarantine periods.

We find considerable uncertainty in our estimates of secondary cases' transmission potential primarily due to variation in the simulated incubation period of index cases, which infectivity is dependent on, leading to a wide spread in the time of exposure of secondary cases. This is then compounded by the variation in infectivity of secondary cases, as well as variation in testing and tracing delays.

Due to a lack of currently available data, we have assumed that index cases effectively self-isolate (and hence cease generating secondary cases) once their symptoms develop to the point that they seek out and take a PCR test, with a central assumption of 2 days. However, if this period can be reduced through sensitisation of the public to COVID-19 symptoms and the importance of early action, shorter quarantine periods with testing at the end of the period becomes more viable. If digital contact tracing were introduced, it is estimated that great advances could be made in improving the effectiveness of contact tracing through a reduction in the delays associated with sourcing and quarantining contacts (2,3), a process which we estimate currently takes an average of 2.5 days.

In this analysis we consider only the performance of quarantine and testing strategies with respect to infection history timings and tracing delays, and as such we do not consider other aspects of the test and trace system which may result in poor outcomes, such as the fraction of index cases that do not engage with the service (12), variation in the number of cases generated by each index case (13), the proportion of secondary cases missed by tracers (14), or the non-adherence or evasion of quarantine by secondary cases. A survey by Smith et al. found, in UK households with a person exhibiting COVID-19 symptoms, 75.1% of households had a member leave the premises within the past 24 hours, indicating a worrying lack of compliance with quarantine rules (15). It is likely that longer quarantine periods result in a decrease in both the proportion of individuals adhering to quarantine requirements and the degree to which they comply, and throughout this work we have assumed perfect compliance that does not wane. It may be possible to derive a waning function through a meta-analysis of previous studies of quarantine compliance, yet these are likely to show large heterogeneity due to the factors identified by Webster et al. (16). If shorter quarantine periods with PCR testing can maintain the averted transmission potential from the current 14 day quarantine policy and do indeed increase the degree of compliance, as well as reduce evasion, then the risk of transmission from secondary cases will be lower than under the current quarantine policy. As such, while we have shown that PCR testing combined with 10 days of quarantine can reduce the transmission potential from secondary cases to similar levels produced by a 14 day quarantine, addressing other structural issues in contact tracing such as testing delays and non-adherence would provide a synergistic effect, further reducing risk.
Acknowledgements

This research was partly funded by the National Institute for Health Research (NIHR) (Billy Quilty is funded by 16/137/109 & 16/136/46) using UK aid from the UK Government to support global health research. The views expressed in this publication are those of the author(s) and not necessarily those of the NIHR or the UK Department of Health and Social Care. This research has been funded by UK Research and Innovation - MC_PC_19065 - Covid 19: Understanding the dynamics and drivers of the COVID-19 epidemic using real-time outbreak analytics (Samuel Clifford, W John Edmunds). This research was partly funded by the Wellcome Trust (Sir Henry Dale Fellowship: 208812/Z/17/Z, Stefan Flasche and Samuel Clifford; 206250/Z/17/Z, Adam J Kucharski). This project has received funding from the European Union's Horizon 2020 research and innovation programme - project EpiPose (W John Edmunds).

The authors declare no conflicts of interest.

The following funding sources are acknowledged as providing funding for the working group authors. Alan Turing Institute (AE). BBSRC LIDP (BB/M009513/1: DS). This research was partly funded by the Bill & Melinda Gates Foundation (INV-001754: MQ; INV-003174: KP, MJ, YL; NTD Modelling Consortium OPP1184344: CABP, GFM; OPP1180644: SRP; OPP1183986: ESN; OPP1191821: KO’R, MA). BMGF (OPP1157270: KA). DfID/Wellcome Trust (Epidemic Preparedness Coronavirus research programme 221303/Z/20/Z: CABP, KvZ). DTRA (HDTRA1-18-1-0051: JWR). Elrha R2HC/UK DfID/Wellcome Trust/This research was partly funded by the National Institute for Health Research (NIHR) using UK aid from the UK Government to support global health research. The views expressed in this publication are those of the author(s) and not necessarily those of the NIHR or the UK Department of Health and Social Care (KvZ). ERC Starting Grant (#757699: JCE, MQ, RMGJH). This project has received funding from the European Union's Horizon 2020 research and innovation programme - project EpiPose (101003688: KP, MJ, PK, RCB, YL). This research was partly funded by the Global Challenges Research Fund (GCRF) project 'RECAP' managed through RCUK and ESRC (ES/P010873/1: AG, CJJ, TJ). HDR UK (MR/S003975/1: RME). Nakajima Foundation (AE). NIHR (16/137/109: CD, FYS, MJ, YL; Health Protection Research Unit for Immunisation NIHR200929: NGD; Health Protection Research Unit for Modelling Methodology HPRU-2012-10096: TJ; NIHR200929: MJ; PR-OD-1017-20002: AR). Royal Society (Dorothy Hodgkin Fellowship: RL; RP\EA\180004: PK). UK DHSC/UK Aid/NIHR (ITCRZ 03010: HPG). UK MRC (LID DTP MR/N013638/1: GRGL, QJL; MC_PC_19065 - Covid 19: Understanding the dynamics and drivers of the COVID-19 epidemic using real-time outbreak analytics: AG, NGD, RME, TJ, YL; MR/P014658/1: GMK). Authors of this research receive funding from UK Public Health Rapid Support Team funded by the United Kingdom Department of Health and Social Care (TJ). Wellcome Trust (206250/Z/17/Z: TWR; 206471/Z/17/Z: OJB; 210758/Z/18/Z: JDM, JH, KS, NIB, SA, SFunk, SRM). No funding (AKD, AMF, CJVA, DCT, KEA, SH, YWDC).

References

1. Kucharski AJ, Klepac P, Conlan AJK, Kissler SM, Tang ML, Fry H, et al. Effectiveness of isolation, testing, contact tracing, and physical distancing on reducing transmission of SARS-CoV-2 in different settings: a mathematical modelling study. Lancet Infect Dis. 2020 Jun;S1473309920304576.
2. UK Government. NHS Test and Trace: if you've been in contact with a person who has coronavirus [Internet]. National Health Service; 2020 Aug. (Coronavirus (COVID-19)). Available from: https://www.nhs.uk/conditions/coronavirus-covid-19/testing-and-tracing/nhs-test-and-trace-if-you've-been-in-contact-with-a-person-who-has-coronavirus/

3. Clifford S, Quilty BJ, Russell TW, Liu Y, Chan Y-WD, Pearson CAB, et al. Strategies to reduce the risk of SARS-CoV-2 re-introduction from international travellers [Internet]. Epidemiology; 2020 Jul [cited 2020 Aug 3]. Available from: http://medrxiv.org/lookup/doi/10.1101/2020.07.24.20161281

4. Quilty BJ, Clifford S, Flasche S, Eggo RM, CMMID nCoV working group. Effectiveness of airport screening at detecting travellers infected with novel coronavirus (2019-nCoV). Euro Surveill Bull Eur Sur Mal Transm Eur Commun Dis Bull. 2020;25(5).

5. Kretzschmar ME, Rozhnova G, Bootsma MCJ, van Boven M, van de Wiijger JHHM, Bonten MJM. Impact of delays on effectiveness of contact tracing strategies for COVID-19: a modelling study. Lancet Public Health. 2020 Jul;S2468266720301572.

6. UK Government. How long to self-isolate [Internet]. National Health Service; 2020 Aug. (Coronavirus (COVID-19)). Available from: https://www.nhs.uk/conditions/coronavirus-covid-19/self-isolation-and-treatment/how-long-to-self-isolate/

7. Ashcroft P, Huisman JS, Lehtinen S, Bouman JA, Althaus CL, Regoes RR, et al. COVID-19 infectivity profile correction. ArXiv200706602 Q-Bio Stat [Internet]. 2020 Jul 13 [cited 2020 Aug 5]; Available from: http://arxiv.org/abs/2007.06602

8. He X, Lau EHY, Wu P, Deng X, Wang J, Hao X, et al. Temporal dynamics in viral shedding and transmissibility of COVID-19. Nat Med. 2020 May;26(5):672–5.

9. Li Q, Guan X, Wu P, Wang X, Zhou L, Tong Y, et al. Early Transmission Dynamics in Wuhan, China, of Novel Coronavirus-Infected Pneumonia. N Engl J Med. 2020 26;382(13):1199–207.

10. UK Government. Weekly NHS Test and Trace bulletin, England: 16 July to 22 July 2020 [Internet]. Department of Health & Social Care; 2020 Aug. (Transparency Data). Available from: https://www.gov.uk/government/publications/nhs-test-and-trace-statistics-england-16-july-to-22-july-2020

11. Delignette-Muller ML, Dutang C. fitdistrplus: An R Package for Fitting Distributions. J Stat Softw [Internet]. 2015 [cited 2020 Aug 5];64(4). Available from: http://www.jstatsoft.org/v64/i04/

12. O’Dowd A. Covid-19: UK test and trace system still missing 80% target for reaching contacts. BMJ. 2020 Jul 17;m2875.

13. Endo A, Centre for the Mathematical Modelling of Infectious Diseases COVID-19 Working Group, Abbott S, Kucharski AJ, Funk S. Estimating the overdispersion in COVID-19 transmission using outbreak sizes outside China. Wellcome Open Res. 2020 Apr 9;5:67.

14. Keeling MJ, Hollingsworth TD, Read JM. Efficacy of contact tracing for the containment of the 2019 novel coronavirus (COVID-19). J Epidemiol Community Health. 2020 Jun 23;jech-2020-214051.

15. Smith LE, Amlôt R, Lambert H, Oliver I, Robin C, Yardley L, et al. Factors associated with adherence to self-isolation and lockdown measures in the UK; a cross-sectional survey [Internet]. Public and Global Health; 2020 Jun [cited 2020 Aug 10]. Available from: http://medrxiv.org/lookup/doi/10.1101/2020.06.01.20119040

16. Webster RK, Brooks SK, Smith LE, Woodland L, Wessely S, Rubin GJ. How to improve adherence with quarantine: rapid review of the evidence. Public Health. 2020 May;182:163–9.

17. Lauer SA, Grantz KH, Bi Q, Jones FK, Zheng Q, Meredith HR, et al. The Incubation Period of Coronavirus Disease 2019 (COVID-19) From Publicly Reported Confirmed Cases: Estimation and Application. Ann Intern Med. 2020 May 5;172(9):577–82.

18. Li Q, Guan X, Wu P, Wang X, Zhou L, Tong Y, et al. Early Transmission Dynamics in Wuhan, China, of Novel Coronavirus-Infected Pneumonia. N Engl J Med. 2020 26;382(13):1199–207.
19. Kucirka LM, Lauer SA, Laeyendecker O, Boon D, Lessler J. Variation in False-Negative Rate of Reverse Transcriptase Polymerase Chain Reaction–Based SARS-CoV-2 Tests by Time Since Exposure. Ann Intern Med. 2020 May 13;M20-1495.

20. Grassly N, Pons Salort M, Parker E, White P, Ainslie K, Baguelin M, et al. Report 16: Role of testing in COVID-19 control [Internet]. Imperial College London; 2020 Apr [cited 2020 Aug 10]. Available from: http://spiral.imperial.ac.uk/handle/10044/1/78439

21. Buitrago-Garcia DC, Egli-Gany D, Counotte MJ, Hossmann S, Imeri H, Ipekci AM, et al. Asymptomatic SARS-CoV-2 infections: a living systematic review and meta-analysis [Internet]. Epidemiology; 2020 Apr [cited 2020 Aug 5]. Available from: http://medrxiv.org/lookup/doi/10.1101/2020.04.25.20079103

22. Van Vinh Chau N, Lam VT, Dung NT, Yen LM, Minh NNQ, Hung LM, et al. The Natural History and Transmission Potential of Asymptomatic Severe Acute Respiratory Syndrome Coronavirus 2 Infection. Clin Infect Dis. 2020 Jun 4;ciaa711.

Supplementary appendix

Table S1 - Strategies for risk mitigation. Where one of the described lines contains “or”, we consider all combinations contained within.

| Stringency of screening policy | Description of screening policy |
|--------------------------------|--------------------------------|
| **Low**                        | 01. No mandatory quarantine upon tracing, and  
                                | 02. Either no testing, or a single PCR test upon tracing.  
                                | 03. Release immediately after tracing (no test) or on receipt of negative result (test).  
<br>We consider a no-quarantine, no-testing scenario as the primary baseline for comparison.  
| **Moderate**                   | 01. Mandatory 3, 5, 7 or 9 days quarantine upon tracing, and  
                                | 02. Either no testing or a single PCR test at end of mandatory quarantine  
                                | 03. Release at end of mandatory quarantine period (no test) or on receipt of negative test at end of mandatory quarantine period.  
| **High**                       | 01. Mandatory quarantine upon tracing, and  
                                | 02. A first PCR test 0, 1, 2 or 3 days after tracing, and  
                                | 03. A second PCR test either 2, 4 or 6 days after the first  
                                | 04. Release after two negative test results or 14 days after the earliest positive test.  
| **Maximum**                    | 01. Mandatory 14 days quarantine upon tracing, and  
                                | 02. Either no testing or a single PCR test at end of mandatory quarantine  
                                | 03. Release at end of mandatory quarantine period (no test) or on receipt of negative test at end of mandatory quarantine period.  

Table S2 - Values of parameters in simulation of cases’ infection histories and PCR testing. Gamma distributions are parameterised in terms of a mean and variance, \( \Gamma(\mu, \sigma^2) \), and these are converted to shape and rate parameters via moment matching. Where quantiles are given but no distribution described, the parameter is derived from other distributions in the table and has no closed-form. \(^*\)Parameters are location and scale for log-Normal distribution, not summary statistics of observed incubation period.
| Incubation period (days) | Time from exposure to onset of symptoms. | $\log N (\mu = 1.63, \sigma = 0.41)$ | Median: 5.1 days | IQR: (3.9, 6.7) days | 95%: (2.3, 11.5) days |
|-------------------------|----------------------------------------|-------------------------------|-----------------|-----------------|-----------------|
| Symptomatic period (symptomatic cases, days) | Time after onset of symptoms until no longer symptomatic | $\Gamma (\mu = 9.1, \sigma^2 = 14.7)$ | Median: 8.6 days | IQR: (6.3, 11.3) days | 95%: (3.2, 18.0) days |
| Secondary case exposure times | Exposure times for secondary cases, relative to onset of index case’s symptoms | $\Gamma (\mu = 26.1, \sigma = 7.0)$ shifted 25.6 | Median: 0.42 days | IQR: (-1.3, 2.2) days | 95%: (-4.4, 6.0) days |
| PCR sensitivity for symptomatic infections | Probability of testing PCR positive $t$ days after infection, if infection is symptomatic | $P(t)$ | | | |
| PCR specificity | Probability of a negative PCR test given no infection with SARS-CoV-2. | 1 | | | |
| Asymptomatic fraction of secondary cases, $\alpha$ | Proportion of infections which are asymptomatic. | $Beta (51, 115)$ | Median: 0.31 | IQR: (0.28, 0.33) | 95%: (0.24, 0.38) |
| PCR sensitivity for asymptomatic infections | Probability of testing PCR positive $t$ days after infection, if infection is asymptomatic | $0.62P(t)$ | | | |

Figure S1: Observed delays (green bars) and modelled probability distributions (dark green curves) for the delays in the test and trace system. The total time delay is a kernel-smoothed empirical density based on the sum of 10,000 independent samples from the
distributions fit to the observed delays. For each distribution, the median is represented as a white circle and the 95% interval as a segment on the \( x \) axis.