Royal Society DELVE Report on Test, Trace, Isolate and Support

Summary

Implemented at scale, Test, Trace, Isolate (TTI) can contribute to controlling the UK COVID-19 epidemic when effectively implemented at scale, but only as part of a wider package of public health interventions, including physical and social distancing, control of infection procedures, outbreak investigation and control. TTI is most effective in breaking chains of transmission, and reducing the effective reproductive number, when there is maximum: (i) **speed**, i.e., quick turn-around of both index case testing and contact tracing (and testing); (ii) **compliance**, i.e., a high proportion of people in each chain are willing and able to follow guidance; and (iii) **coverage**, i.e., identification of most chains through integration of consistent case data and real-time, high-precision population surveillance. Each of these three aspects of TTI needs careful attention, as do the trade-offs implicit in choices of how precisely to implement TTI in terms of who to test, trace and isolate, and when to do so.

Based on our modelling work, we find that adding TTI to a broader package of interventions can generate a reduction of 5-15% in the number of new infections. The upper end of this range represents scenarios where the overall test and trace period for contacts has been reduced from five days to three days. Furthermore, the level of compliance with TTI guidance strongly affects its usefulness, as there are many steps in the TTI system at which cases and contacts can be lost. Phone-based apps may be able to increase TTI speed and compliance but is likely to be an adjunct to a manual TTI system. Surveillance and TTI are mutually beneficial, since TTI can capture important data on index cases and contacts, while surveillance can provide indications of who/where to target for testing, even when they are not part of an identified transmission chain. Incentives to participate in TTI and comply with isolation measures are also likely to be needed. Finally, TTI will require substantial coordination across a wide range of organizations, including central and local government departments, PHE, the NHS and business groups. In particular, local integration of systems is likely to maximize ability to conduct the agile, locally differentiated outbreak management that may be needed as the epidemic progresses.

Key points

1. **The role of TTI in COVID-19 response**. At time of writing, it seems likely that the UK's focus in the short- to medium-term will be on containing the COVID-19 epidemic and driving down case numbers, while balancing policies to reduce transmission alongside policies to manage the wider health and economic impacts of the epidemic. Test, Trace, Isolate (TTI), defined as the chained process of testing index individuals with symptoms or known contact with past cases, monitoring contacts of these index cases and potentially limiting their interactions (through isolation and quarantine) can play an important role in controlling COVID-19. In combination with other measures, TTI has been comprehensively implemented early in epidemics in several countries who have controlled their epidemics, and maintained when case numbers increased.

2. **Factors that influence optimal performance of a TTI system**. COVID-19, like any infectious disease epidemic, is a collection of transmission chains. Modelling by several teams, including new analysis presented here, in addition to experiences with previous epidemics, highlights that TTI for COVID-19 can be effective at breaking chains of transmission when: (i) there is quick turn-around between testing index cases and tracing (and testing) contacts; (ii) a high proportion of people in each chain are identified and willing and able to comply with TTI guidance; and (iii) a high proportion of transmission chains are identified through real-time, high-precision surveillance (i.e., regular, quasi-random nationwide diagnostic testing). It is notable that countries with successful COVID-19 control strategies integrated TTI within a wider framework of measures, and were effective in all three of these areas. Each of these three aspects of TTI therefore needs careful attention.

3. **Increasing speed of testing and tracing**. The short serial interval (average time between index case and infected contact becoming infectious, estimated at 5-6 days) and high level of likely pre-symptomatic transmission of COVID-19 means that speed is of the essence in using TTI to break infection chains. When there are delays in getting tests for index cases and tracing contacts of proven cases, secondary cases are often not found until they themselves have been infectious for some time. Shortening the time taken to test and to trace individuals is vital to TTI being effective. Our modelling found that reducing this time to three days lead to a 60% greater reduction in R_e than does a five-day gap; however, this faster turnaround amounted to only a 10-15% drop in absolute transmission rates. There are several ways in which testing and tracing could be sped up using existing infrastructure and experiences from optimizing care for other health conditions (e.g., Tuberculosis, sexually transmitted infections). Policy choices on overall TTI capacity are critical, and affect decisions on how to be utilise TTI. As capacity is approached, TTI speed will be strongly affected, and bringing more people into the system (e.g., tracing contacts before index test results are known, testing non-symptomatic contacts) can create trade-offs in terms of resource requirements and epidemic growth. In particular, due to the poor sensitivity and specificity of COVID-19 symptoms, and high incidence of non-COVID-19 COVID symptoms, tracing contacts of all those reporting these symptoms before test results are available will likely prove inefficient, placing a large demand on the system and potentially undermining its speed and effectiveness.

4. **Maximizing population participation and compliance with TTI guidance**. Keeping all those individuals found to be in contact chains engaged within the TTI system is also crucial to its success. Cases can leak from the TTI system at the point of initial symptom reporting (due to not having symptoms or choosing not to report them), and at every stage thereafter, including timely testing, contact finding and compliance with requests/requirements to test, quarantine or isolate. As a result, the impact of adding TTI on transmission is sensitive to the ability of the system to reach affected individuals and such individuals' ability to comply with guidance. Some of these leakages can be addressed through improved TTI systems, including potentially the use of phone-based apps. However, incentives to participate and comply are also likely to be needed. Insights from other health and non-health work suggest several options for creating such incentives, including incentives for app use (e.g., more rapid testing, improved access to health advice and support during quarantine and isolation) and working with employers and communities to incentivize groups through benefits for all (e.g., access to relaxed NPI regimes).

5. **Increasing epidemic coverage of TTI**. Bringing more contact chains within the ambit of TTI is central to its effectiveness. Increasing TTI coverage requires strong data collection and management systems, and the integration of case-based data with broader surveillance efforts, particularly for capturing new chains as they flare up. In this respect, surveillance and TTI are mutually beneficial, since TTI can capture important data on index cases and contacts, while surveillance can provide indications of who/where to target for testing, even when they are not part of an existing identified chain. This paper proposes ways in which the UK might design an efficient surveillance process and analyse the data collected to maximize the effectiveness of TTI. Existing data collection efforts - including those from TTI, from other ad-hoc systems (e.g., self-reported symptoms or calls to health actors) and from systematic population-based testing work such as the ONS COVID-19 Infection survey – need to be coordinated to ensure standardized data collection that will allow triangulation of information and localization of responses. This requires increased granularity of data in terms of person, time and place for new transmission chains, outbreaks and each individual case and contact.

6. **Managing TTI capacity constraints**. As the TTI system becomes faster and more comprehensive, tracing and testing capacity may be reached, which will in turn slow testing and tracing down, reducing the benefits of the system. While in the long-term TTI capacity may be expandable, in the shorter-term if capacity limits are reached, important decisions will need to be made about how to prioritize within tracing testing and isolating. These choices can be made on at least two key axes: prioritizing index case and contacts on the basis of risk; and acting based either on index case symptoms or test results. In particular, in our model assuming moderate NPIs, tracing and quarantining contacts based on index case symptoms as opposed to a positive test led to a five-fold increase in the number of tracing events required (to as many as 1 million per day), and a 52-86% increase in the number of quarantine days required. All the successful TTI programmes worldwide that we reviewed based contact tracing on laboratory confirmed index cases. To manage all these choices, a clear dynamic strategy will be needed for managing TTI capacity as the epidemic changes size and location. Strong integration of information from within TTI with wider surveillance and electronic health records will help

improve the decision process (e.g., by predicting likely positive infections in index cases and contacts).

7. **Effective TTI within a broader epidemic response**. TTI is most effective when it is comprehensive and efficient, rapidly reaching and ending most infection chains. However, even in the best of circumstances, TTI will not capture all transmissions, especially for COVID-19 due to asymptomatic and mild cases. Our review of existing literature and our own modelling exercise strongly suggest that TTI can offer some assistance to the COVID-19 epidemic response, provided that it is well-integrated with other complementary, population-based NPIs and intensive outbreak investigations in settings where the force of infection is high and widespread (e.g., care homes, hospitals, hostels). Effective TTI will require substantial coordination across a wide range of organizations, including central and local government departments, Public Health England, the NHS and business groups. Deciding when to adjust NPIs will be informed by surveillance as well as the capacity of the local TTI system itself. Integration of TTI and surveillance at local levels would create important sources of data to support decision making for, and potentially provide synergies for implementation of, locally differentiated outbreak management. As the national epidemic declines, TTI will be play an increasingly important role in ending chains of transmission arising from distinct outbreak events and preventing re-emergence of generalized community transmission.

Index

Summary	1
Key points	1
Test, trace, isolate and support	6
1. The role of TTI in COVID-19 response	6
2. Factors that influence optimal performance of a TTI system	8
3. Increasing speed of testing and tracing	10
4. Maximizing population participation and compliance with TTI guidance	12
5. Increasing epidemic coverage of TTI	14
6. Managing TTI capacity constraints	16
7. Effective TTI within a broader epidemic response	19
8. Next steps	20
Technical Documents	
TD1. The Potential Role of Firms in TTI	21
TD2. Surveillance for TTI	24
TD3. Modelling TTI Scenarios	32
TD4. A Review of International Approaches to TTI	33

Test, trace, isolate and support

1. The role of TTI in COVID-19 response

In early May 2020, the UK was estimated to be experiencing 10-20,000 incident cases of COVID-19 per day. The UK's focus in the short- to medium-term appears likely to be on containing the COVID-19 epidemic and driving down case numbers, while balancing policies to reduce transmission alongside policies to manage the wider health and economic impacts of the epidemic. Achieving this balance will require the dynamic balancing of non-pharmaceutical interventions (NPI) as the epidemic size fluctuates. Testing, tracing and isolation (TTI) is a tool that helps to identify and diagnose cases, reduce onward infections, and provide vital information that can support decision making on policy balance. TTI's overall effectiveness and ability to contribute to epidemic control is a function of policy choices regarding the TTI system's capacity, optimisation and support for compliance, alongside wider choices about surveillance and other NPI measures.

All aspects of a coordinated TTI system must be firmly guided by the core public health purpose of reducing transmissions and contributing to maintaining an effective reproduction number R_e below 1. Alongside its public health benefits, the system enables identification of cases for clinical care and provides intelligence on the course of the epidemic (surveillance), which in turn enables TTI to be targeted to optimise its primary purpose.

This report combines data and ideas relating to TTI from several sources, including an empirical review of the implementation and impact of TTI in the context of COVID-19, reviews of the potential role of the business sector and of systematic surveillance in supporting TTI, and a single-generation mathematical model to capture how variation in TTI implementation might affect the effective reproductive number (R_e). The report's overall goal is to present evidence on how TTI might be implemented and what its impact might be as part of a COVID-19 epidemic response.

COVID-19, like any infectious disease epidemic, is a collection of transmission chains. A core principle of epidemic control for infectious disease lies in preventing onward transmission by breaking these chains through reducing interactions between infectious index cases and susceptible contacts. This requires interventions to identify infected individuals and quarantine their contacts before they themselves become infectious.

TTI is the chained process of testing individuals with symptoms or known contact with past cases (index individuals), and then tracing and monitoring contacts of these index cases and potentially limiting their interactions (through supported isolation or quarantine[1]). TTI reduces the speed at which the epidemic grows by identifying those at greatest risk of having been infected and separating them from the general population. Contact tracing can allow infected

[1] Isolation refers to the separation of infected individuals from uninfected individuals, while quarantine refers to the separation of individuals exposed to infection in order to determine whether they have contracted a disease.

contacts to be identified while they are still incubating the infection (and thus not able to transmit) and while asymptomatically infectious (curtailing any onward transmissions). A combination of testing, tracing and isolation can therefore be potentially powerful in controlling COVID-19. In this report, we consider TTI as reactive, starting when index cases self-reports symptoms, as opposed to proactive population testing (potentially based on risk factors), although we do discuss how the two might be integrated and support one another.

TTI is typically applied in the context of other actions that can reduce the number of potential infectious interactions in the population. These actions fall roughly into two categories: those reducing the chance of infection per contact, and those reducing the number of contacts. Measures that reduce the chances that an interaction leads to transmission include infection control in institutional settings where social distancing may not be possible (e.g., hospitals, care homes, prisons), increased hand washing, respiratory hygiene and use of masks and other personal protective equipment. Measures that reduce the number of contacts between all individuals in the population include social distancing (e.g., working from home, avoiding meetings with friends and family), bans on mass gatherings and closure of schools, shops and restaurants. Importantly, the latter greatly reduce inter-household and community transmission, but do not much affect intra-household transmission, a major source of secondary infections. Contact tracing in particular can therefore be seen as complementary to social distancing and infection control in the context of COVID-19, insofar as it is able to either drive within-household infection prevention efforts (i.e., self-isolation), or provide a gateway to extra-household isolation if required.

Countries that have managed to, at least temporarily, control their COVID-19 epidemics have almost all enacted and maintained substantial testing and contact tracing efforts from early in their epidemics. These countries include China, Iceland, New Zealand, Singapore, South Korea and Taiwan (see summary in Technical Document 4). There are several commonalities in these countries' TTI approaches:

1. Comprehensive TTI was started early in the epidemic, when the number of contacts needing tracing, and thus of follow-on tests, were small;
2. Testing provision was widespread, decentralised and accessible in both traditional and novel locations, including primary healthcare settings;
3. Turnaround times from symptom reporting to test result provision were short. For example, it takes around 5 hours from swab collection to test result provision in Vietnam[2] as a result of the government ramping up laboratory analysis capacity. Similarly, in Taiwan[3], tests results can be provided in 4 hours and in South Korea[4], tests results are provided through automated text messages within 24-48 hours of swab collection.

[2] Quang Thai P., (2020). Addressing COVID-19 in Vietnam: Progress to date and future priorities. Usher Institute Webinars.May 13 2020, https://www.youtube.com/watch?v=w_bA34w8Xyo&feature=youtu.be

[3] Lin, C., Braund, W., Auerbach, J., Chou, JH., Teng, JH., Tu, P. and Mullen, J. (2020), Policy Decisions and Use of Information Technology to Fight 2019 Novel Coronavirus Disease, Taiwan. Emerging Infectious Diseases, Vol. 26. (doi: 10.3201/eid2607.200574)

[4] The Government of Republic of Korea (2020). How Korea responded to a pandemic using ICT Flattening the curve on COVID-19. Published online April 15. Available at:

4. Contact tracing was conducted rapidly, ensuring contacts were reached before they became infectious. South Korea, for instance, uses an information communications technology (ICT) system that integrates GPS data, credit card information and CCTV footage to create a moving history (i.e. transmission route) of the confirmed case in 10 minutes, which is matched with the patient interview, and contacts are then identified and informed via text messages on the same day. The whole process of testing, contact tracing and isolation advice for contacts takes approximately 2-3 days in South Korea.
5. Compliance with isolation was high due either to tailoring to homes (where physical separation was feasible) or through physical separation in institutions (e.g., hotels) or enforcement through fines on violation (South Korea and Taiwan)[5][6];
6. Traditional manual tracing strategies were supplemented with app-based approaches for efficiently notifying contacts of cases and conducting follow-up symptom checks.

However, it is not yet possible to quantify the independent effect TTI has on COVID-19 epidemic control, since these countries generally also had strong early social distancing and infection control procedures.

2. Factors that influence optimal performance of a TTI system

COVID-19 presents a particularly challenging disease for control via TTI because of its:

1. Short serial interval (time between an index case and infected contacted becoming infectious);
2. High level of pre-symptomatic transmissions[7] (those occurring prior to symptom presentation);
3. Non-specific and often mild symptoms; and
4. Sometimes subclinical presentation (leading to asymptomatic transmissions).

These challenges mean that three aspects of a TTI system will prove crucial to its effectiveness:

1. The **speed** at which testing and tracing contacts can be conducted at scale;
2. The level of **compliance** with guidance and participation in TTI; and
3. The **coverage** of new chains of transmission TTI, based on a wider surveillance system.

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http://www.moj.go.kr/moj_eng/1765/subview.do;jsessionid=OxKrsTASgh8vttNtuzZN_O7ALY7MJKl8vWSrtLao.wizard-10-25vxg?enc=Zm5jdDF8QEB8JTJGYmJzJTJGbW9qX2VuZyUyRjUxJTJGNTIyODIyJTJGYXJ0Y2xWaWV3LmRvJTNG

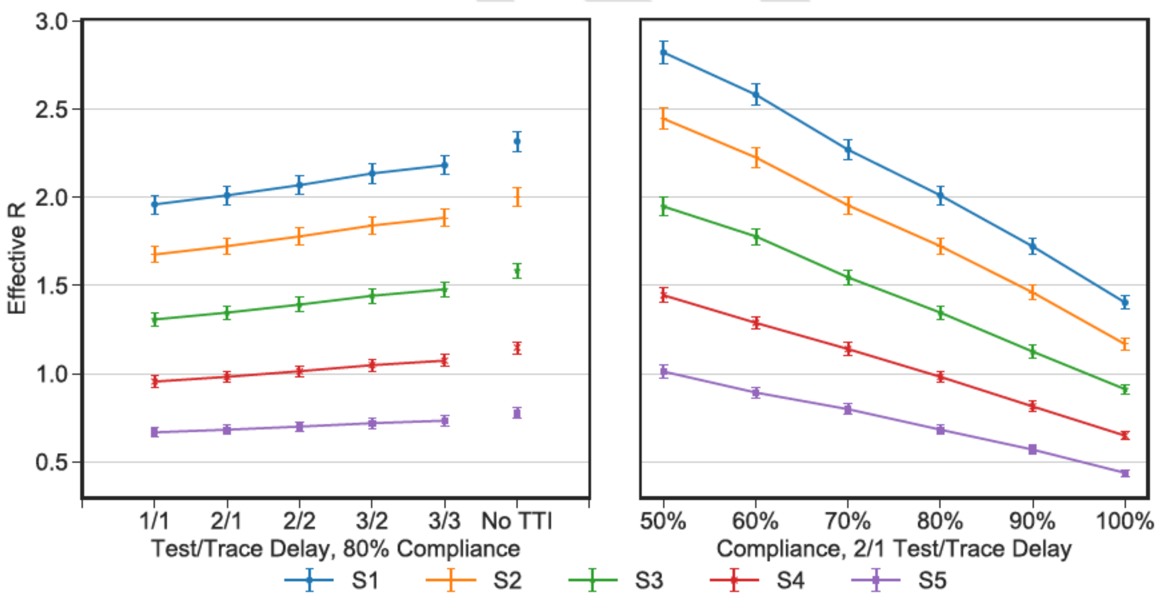
[5] Normile, D. (2020) Coronavirus cases have dropped sharply in South Korea. What's the secret to its success? 17 March 2020. Science. Available at: https://www.sciencemag.org/news/2020/03/coronavirus-cases-have-dropped-sharply-south-korea-whats-secret-its-success#

[6] Sheng-lun, H. et al. (2020) New Taipei City man fined, taken to quarantine center. Taipei Times. 1 April 2020 https://www.taipeitimes.com/News/taiwan/archives/2020/04/01/2003733788

[7] Cheng H, Jian S, Liu D, et al. (2020) Contact Tracing Assessment of COVID-19 Transmission Dynamics in Taiwan and Risk at Different Exposure Periods Before and After Symptom Onset. *JAMA Intern Med.* Published online May 01, (doi:10.1001/jamainternmed.2020.2020)

Several recent models have shown that while TTI help with epidemic control, a TTI system will need to be very efficient (little or no leakage,[8] fast testing and tracing,[9] comprehensive use of digital app-based contact tracing[10]) if used in isolation to have a substantive impact on a COVID-19 epidemic. This has led several teams have concluded that TTI will need to be part of a combined COVID-19 control strategy.[11] [12] [13]

Technical Document 3 presents a single-generation individual-based model, based on that of Kucharski et al., which explores the impact of pipeline speed and population compliance on the effectiveness and resource requirements of TTI over the coming summer in the UK. It considers three TTI strategies which trade off resource requirements and TTI pipeline speed: (i) initiating contact tracing on symptom presentation; (ii) initiating contact tracing only upon the index case testing positive; and (iii) each of these with additional testing of contacts. These strategies are evaluated in the context of a range of other government measures with varying stringencies, including app-based digital contact tracing.



S1 to S5 are increasingly stringent NPI scenarios. S1 involves no restrictions on social interaction, only requiring households of symptomatic individuals to quarantine; S5 reflects the situation before May 9th. Re

[8] Hellewell, J., Abbott, S., Gimma, A., Bosse, N., Jarvis, C., Russell, T., Munday, J., Kucharski, A., Edmunds, WJ., Sun, F., Flasche, S., Quilty, B., Davies, N., Liu, Y., Clifford, S., Klepac, P., Jit, M., Diamond, C., Gibbs, H., van Zandvoort, K., Funk, S. and Eggo, R. (2020) Feasibility of controlling COVID-19 outbreaks by isolation of cases and contacts, The Lancet Global Health, Issue 4, 488-496 (doi:10.1016/S2214-109X(20)30074-7)

[9] Kretzschmar ME, Rozhnova G, Bootsma M, van Boven ME van de Wijgert J, Bonten M. Time is of the essence: impact of delays on effectiveness of contact tracing for COVID-19. MedRxiv. https://www.medrxiv.org/content/10.1101/2020.05.09.20096289v1

[10] Ferretti, L., Wymant, C., Kendall, M., Zhao, L., Nurtay, A., Abeler-Dörner, L., Parker, M., Bonsall, D. and Fraser, C. (2020) Quantifying SARS-CoV-2 transmission suggests epidemic control with digital contact tracing, Science (doi:10.1126/science.abb6936)

[11] Kretzschmar, M., Rozhnova, G., and van Boven, M. (2020) Isolation and Contact Tracing Can Tip the Scale To Containment of COVID-19 In Populations with Social Distancing. PrePrint: The Lancet (doi: 10.2139/ssrn.3562458)

[12] Kucharski, A., Klepac, P., Conlan, A., Kissler, S., Tang, M., Fry, H., Gog, J., Edmunds, J. and CMMID COVID-19 Working Group (2020) Effectiveness of isolation, testing, contact tracing and physical distancing on reducing transmission of SARS-CoV-2 in different settings, medRxiv 2020.04.23.20077024 (doi: 10.1101/2020.04.23.20077024)

[13] Goscé, L., Phillips, A., Spinola, P., Gupta, R.K., and Abubakar, I. (2020) Modelling SARS-COV2 Spread in London: Approaches to Lift the Lockdown. Preprints 2020, 2020050055

reflects transmissions from secondary contacts of index cases to their contacts. Delays are in days. See Technical Document 3 for details.

Our understanding that the present intention in the UK is to include within the TTI system an app that combines symptom reporting with anonymized contact tracing and facilitates access to testing, but that most contact tracing will be done manually through PHE, with an as-yet unfinalized interface mechanism. Our model assumes a system that combines manual and app-based contact tracing and varies the level of app uptake. As a result, in our model an app can rapidly identify and inform contacts otherwise unknown to index cases, and speed quarantining of secondary contacts.

The findings of our model highlight the importance of speed and compliance to the effectiveness of TTI. The figure above summarizes the results for test-based TTI across five scenarios ranging from most (S5) to least (S1) severe NPI measures. Overall, this simulation indicates that TTI can generate a reduction in R_e of 5-15%, depending on the stringency of other government measures and under reasonable assumptions about testing/tracing speed and public compliance.

3. Increasing speed of testing and tracing

The speed at which TTI can move along transmission chains is determined by two quantities: the time between an index case reporting symptoms and their test results being available, and the time required to trace their contacts. COVID-19 combines a short serial interval (5-6 days on average) and substantial pre-symptomatic transmission (up to 2 days prior to symptom presentation).[14] This provides a short window within which infected contacts need to be reached by a TTI system to avoid onward transmission. Between January and March in the UK, the time taken to obtain a test result averaged 3 days, and the time to find a contact 2 days.[15] This amounts to the entire pre-symptomatic period of the average secondary case, meaning that by the time contacts were found, half of their onward transmissions to tertiary cases had already occurred. Our simulation model finds that reducing the overall turnaround time from five days to three leads to 60% improvement in effectiveness of the test-based TTI system (in terms of reduction in Re), due to the quarantining of infected contacts just as they are expected to be most infectious.

A key element of TTI effectiveness is system speed at breaking transmission chains. While the testing and tracing process can be sped up by asking secondary contacts to quarantine at the point where either their index case tests positive or even shows COVID-19 symptoms, these approaches have very large economic consequences in terms of days lost to quarantine (see section 6). Speeding up testing and tracing processes is thus vital. App-based contact tracing can reduce the time needed for manual tracing. However, the effectiveness of app-based tracing is determined by overall smartphone usage and willingness to install and use the app -

[14] He, X., Lau, E., Wu, P., Deng, X., Wang, J., Hao, X., Lau Y et al. (2020) Temporal dynamics in viral shedding and transmiss bility of COVID-19. *Nature Medicine*: 26, 672-675 (doi: 10.1038/s41591-020-0869-5)

[15] PHE, personal communications

smartphones and app use is lower among children, the elderly and lower socioeconomic status populations, and there are ongoing concerns around privacy and centralised vs decentralised tracing systems.

Some ways in which each delay in the system might be addressed are suggested below. Achieving substantial increases in speed is likely to require a system-wide approach utilising existing public health infrastructure and capacity, with greater linkage with primary and community care. This decentralised approach is likely to enable faster test turnaround and improve on tracing delays.

1. Time from symptoms onset to patient self-reporting. This can be helped by a well-designed, clear public information campaign on how and where to report symptoms which provide access appropriate to all – for example via the NHS COVID 19 App, NHS 111 or GP. The use of apps more generally to speed up reporting for at least a subsection of the population is likely to help too.
2. Time from symptom reporting to test taking place. This requires multiple access points and channels to testing, but any appointment systems must have minimal delays (at home or at a test centre). These systems could integrate the use of apps, as used recently for a chlamydia testing and risk assessment system.[16] Self-swabs may increase speed but delivery would need to be rapid - one potential approach would be pick-up from central community points (e.g., pharmacies).
3. Time from testing to lab. Courier services are likely to be central here, but pharmacies as collation points for pick up within communities could also help, as might local NHS specimen collection.
4. Time to get test results in the lab. Optimisation is needed for specimen processing and RT-PCR speed, using agreed standard operating procedures (SOPs). Expansion of testing to any certified laboratory could also improve throughput.
5. Time to lab confirmation of results. Automation of results with verification codes is a possibility but timing and accuracy is of importance. Careful SOP use and automation may also improve quality assurance and minimize loss of tests and identifiers.
6. Time to return results to testee. Automation of results reporting by phone, app or text message have the potential to help here, if done with care include a secure method of verifying receipt, and to include simple and clear guidance on: (i) self-isolation household quarantine; (ii) preventing intra-household transmission; and (iii) the contact tracing process.
7. Time from positive result to contact tracing. Patient details need to be concurrently passed to PHE as they are communicated to the testee. Once an app is live, some contacts will be automatically informed once index informed, and whether the information has been verified to be received by the recipient, but those without the app will still need to be managed manually. This manual PHE system will need to be linked with the app to know who has/has not been informed, especially if multiple testing

[16] Estcourt CS, Gibbs J, Sutcliffe LJ, et al. (2017) The eSexual Health Clinic system for management, prevention, and control of sexually transmitted infections: exploratory studies in people testing for Chlamydia trachomatis. Lancet Public Health, 2(4): e182-e190. (doi:10.1016/S2468-2667(17)30034-8)

channels are in place; this interface will be central. The creation of contact lists prior to testing generates logistical burdens and collects a lot of personal information that will ultimately not be used (since most people will test negative), which may reduce overall compliance.

4. Maximizing population participation and compliance with TTI guidance

While the mechanisms of the TTI system can be designed carefully to maximize speed and efficiency, its effectiveness relies centrally on the willingness of society to engage with it. There are multiple points in the TTI system where non-participation can occur:

1. Those with asymptomatic infections will not have symptoms to report,
2. Symptomatic cases may not self-report, due either to not noticing (subclinical infections) or concern regarding loss of earnings if required to self-isolate and social stigma if their contacts are required to quarantine;
3. Individuals may not complete a test if requested to complete one;
4. Tracing of at-risk contacts is likely to be incomplete, missing some important contacts and being unable to find others due to anonymity (e.g., on public transport) given the respiratory and fomite-related nature of transmission, or due to non-cooperation of index cases;
5. Finally, identified contacts may not comply with requests to self-isolate on their own volition in their own homes, or not be willing or able to maintain infection control within their home (e.g., isolation in a separate bedroom, bathroom and cutlery, mask use).

As a result, the potential for transmissions and infectious individuals to escape the TTI process is substantial.

In our simulation study, we used a single compliance parameter to represent general compliance with government guidelines, specifically it refers to the proportion of the population who will: (i) report symptoms when they get them; (ii) quarantine their households; and (iii) self-isolate when instructed to when contact-traced from an index case. We found that the level of compliance significantly affects our results. For example, for test-based TTI in the context of moderate NPIs, R_e falls from 1.9 at 50% compliance to 1.4 at 80% compliance. We considered the added benefit of app-based tracing, but found it to have a relatively minor impact on effectiveness in our base-case scenario. This reflected our assumptions that all contacts of each index case will still be (more slowly) manually traced in addition to any app-based tracing (assuming we will not be able to tell which of a person's contacts have been traced via the app), and an optimistic one-day turnaround time to carry out manual tracing. Since app-based tracing is effectively instantaneous, the longer manual tracing takes, the greater the benefits of the app.

Maximizing population participation and compliance will necessarily draw on psychological and economic, as well as technological, factors. Approaches will need to consider two key factors:

Avoid Perception of Negative Consequences from Engaging in TTI

People are less likely to engage in the TTI process if they believe that this will lead to a substantial burden in terms of testing, quarantine or isolation for themselves or others. An important consideration when considering whether to quarantine contacts based on index case symptoms (rather than a positive test) is how the resulting unpopularity with family and work colleagues - particularly if they ultimately test negative for SARS-COV-2 - will affect the willingness of index cases to report those symptoms. The speed benefits of quarantining contacts at the point that index cases report symptoms may be outweighed by decreased TTI engagement.

Another important consideration in the context of integrating a tracking app into the TTI process is the level of public confidence engendered by a centralized app system. Independent of the actual risks of data integrity, perceptions of the possibility of data being lost or misused will affect willingness to use the app or become involved in the TTI process more broadly. These uptake costs will need to be considered in light of the technological benefits of a centralized system, and careful public messaging will be required to reassure the public that the risks are reasonable given the benefits.

Incentivize Participation in TTI

As well as minimizing avoidable losses in the TTI process, there are steps that can be taken to actively increase involvement. Moreover, effective deployment of TTI requires consideration of incentives to participate and comply at all stages of the process. This means harnessing both personal and social motives that can be enhanced by messaging and giving those involved a clear understanding of the purpose of the system. Evidence from RCTs in developing countries have shown that even small incentives can enhance compliance with testing for HIV partly because they increase the salience of the benefits of such tests.[17] Messaging to the public can emphasize that involvement in TTI will provide population-level benefits, by reducing epidemic spread, and potentially allowing greater freedoms. It is important to disseminate this through local networks where trust is highest such as GP surgeries, clubs, community groups, unions and professional associations.

Making messaging effective involves much more than providing credible information, it relies on creating a consistent and appealing narrative for TTI. One area where this will be crucial is for any tracking app - since its usefulness scales quadratically with uptake (both index and contact need to have the app for it work). Involvement in TTI can also provide individual-level benefits since infected participants will have earlier information about their illness than non-participants. Again, this can be concretized in the example of the tracking app, if it provides regular symptom checks and health advice and faster access to testing and results. Another area where clear messaging is needed is in providing practical advice about how to comply with TTI guidance,

[17] Kranzer K, Simms V, Bandason T, Dauya E, McHugh G, Munyati S, Chonzi P, Dakshina S, Mujuru H, Weiss HA, Ferrand RA. (2018) Economic incentives for HIV testing by adolescents in Zimbabwe: a randomised controlled trial. Lancet HIV, 5, 2, e79-e86. (doi: 10.1016/S2352-3018(17)30176-5)

including reporting procedures, testing processes and how to effectively self-isolate and practice infection control within the household.

There is plenty of evidence across a range of public programs that we cannot rely exclusively on appealing to an individual's pro-social motivation especially when they are asked to take actions which are personally costly. Even if the aim is to bring about changes in social norms, there is a role for inducements and sanctions. Harnessing pre-existing social networks in messaging can enhance trust in the system. Reaching beyond the individuals directly involved in TTI, there is also potential to incentivize employers and communities, as outlined in Technical Document 1. This will have benefits beyond TTI, for example when rolling out a vaccination program if that happens. Workplaces or geographies with high participation in testing, tracing, isolation or app use might be offered faster access to relaxed NPI regimes or workplace reopening; the extension of the furlough scheme and sickness payments could also incentivise staff compliance with testing and isolating as appropriate, among those who cannot work from home.

Whatever incentive structures are put in place, it will be important to consider their potential equity impacts, both for intrinsic reasons and since impact unequal effects are likely to suppress willingness to participate overall. Notably, some groups at greatest risk of COVID-19 acquisition and poor outcomes (e.g., the elderly, black, Asian, and minority ethnic communities,[18] frontline service-sector workers[19]) may be less likely to have smartphone access.

5. Increasing epidemic coverage of TTI

The existence of pre-symptomatic, and particularly asymptomatic or symptom non-specific, transmission for COVID-19 may generate a substantial number of transmission chains that will not be picked up even by a highly efficient TTI system. Beyond the mechanics of the TTI process, there are a number of ways in which the use of TTI can be targeted to further increase efficiency. These revolve around maximizing the ability to identify those most likely to be infected. Strategies to achieve this include continuously improving predictive models as knowledge of more specific symptoms of COVID-19, such as loss of smell, comes to light, and prioritising individuals likely to have greatest potential transmission to others (e.g., through their occupation or geographical localisation). Provided testing protocols are consistent, TTI test results can be used to augment survey data and so refine local estimates of incidence.

Finding people infected with COVID-19 when community transmission is common will require a detailed understanding of how incidence, prevalence and risk factors for COVID-19 vary across geography, demography and economic sectors. Such understanding will in turn, as outlined in Technical Document 2, require well-designed country-wide stratified quasi-random sampling and diagnostic testing, which can be triangulated with self-reported symptom data (e.g., through apps such as the Zoe COVID Symptom Study app) and case reporting data.

[18] Aldridge, R.W., Lewer, D., Katikireddi, S.V., Mathur, R., Pathak, N., Burns, R., Fragaszy, E.B., Johnson, A.M., Devakumar, D., Abubakar I, Hayward, A., 2020. Black, Asian and Minority Ethnic groups in England are at increased risk of death from COVID-19: indirect standardisation of NHS mortality data. Wellcome Open Research, 5: 88 (doi: 10.12688/wellcomeopenres.15922.1)

[19] Lan FY, Wei CF, Hsu YT., Christiani DC, Kales SN, (2020) Work-related Covid-19 transmission. *medRxiv*. Available at: https://www.medrxiv.org/content/10.1101/2020.04.08.20058297v2

This triangulated data will provide real-time, stratum-specific incidence predictions to inform selection of individuals for TTI follow-up, as well as sample adaptation for subsequent surveillance. Such surveillance data can help target initial testing procedures at those likely to become infected (e.g., young people) and those likely to be infectious (e.g., service staff in busy establishments, especially health and social care settings). They can also help target tracing and secondary testing efforts (e.g., focusing on household contacts, those still working). A fuller understanding of the geographic spread of COVID-19 could also allow focused use of scarce contact tracing resources to key areas of the country, especially as the epidemic grows smaller.

Technical Document 2 provides details on how the UK might design an efficient surveillance process and analyse the data collected to maximize the effectiveness of TTI, building on existing serological surveys such as that led by the Office for National Statistics.[20] In addition to surveillance activities, business sectors could be profiled in a risk assessment exercise to determine the frequency with which testing would be required to reopen, with employers potentially responsible for compliance (see Technical Document 1). Expanding regular pro-active testing (and subsequent TTI as needed) to key economic sectors might also help to increase the overall proportion of transmission chains brought within the TTI system. Decisions to open sectors would need to be linked to how each business type might affect epidemic spread and its economic value.

Surveillance and TTI are mutually beneficial, since TTI can capture important data on index cases and contacts, while surveillance can provide indications of who/where to target for testing even when they are not part of an existing chain. For these synergies to be realised, however, data collection efforts need to be coordinated and asynchronous. Coordination is required through standardized data collection to allow triangulation across TTI, other health surveillance systems (e.g., calls to health actors or app-based symptom tracking) and systematic population-based testing. Maximum benefit will be gained when that surveillance systems provide information complementary to that arising from TTI, and additional to standardly available information sources. This combination of characteristics will allow surveillance to add benefit to TTI, helping to localize responses (e.g., by sector, by geography).

Standardized data collection processes will have to balance the need for key information with the data quality losses, and lack of participation, that may arise from asking for too much data. Core population-level data will need to include the number of newly infected individuals (including pre-symptomatic, asymptomatic and untested), stratified by geography, demography and sector. Prevalence of current (PCR) and past (antibody) infection can be estimated and tracked over time by stratified random population studies and case, hospital and mortality data. Added precision may be obtainable by supplementing “hard outcome” data of this kind with information from symptom tracker apps. At the individual level, key sociodemographic information will also need to be collected, including minimally age, sex, ethnicity, geographic

[20] Office for National Statistics. Coronavirus (COVID-19) Infection Survey pilot: England, 10 May 2020. https://www.ons.gov.uk/peoplepopulationandcommunity/healthandsocialcare/conditionsanddiseases/bulletins/coronaviruscovid19infectionsurvey/england10may2020

location, household composition and occupation. An understanding of how index cases are connected to known transmission chains will hopefully be captured in the TTI process. All of these data allow for targeting of limited resources, including testing algorithms, and planning for future resource needs and scenario feasibility.

6. Managing TTI capacity constraints

Building a faster, more comprehensive TTI system is central to it playing an effective role in combating the epidemic. Importantly, however, as tracing and testing capacity is reached, the speed of both is likely to reduce, which in turn reduces the benefits of the TTI system. While in the long-term TTI capacity may be expandable, in the shorter-term if capacity limits are reached, important decisions will need to be made about which activities will be prioritized.

Which contacts should be traced?

In an epidemic with highly sensitive and specific symptoms, it is more feasible to trace contacts of anyone presenting with symptoms. Since COVID-19 lacks specific symptoms (many are similar to a range of other common respiratory infections) and asymptomatic and pre-symptomatic cases are common, symptom-based tracing can become extremely resource intensive when epidemics are large or when other health conditions generate many false positives (e.g., seasonal influenza and colds). Furthermore, requiring many contacts of false-positive index cases to quarantine (if this is policy) will have substantial consequences for the economy, and could have limited public acceptability of TTI when contacts realise they have been needlessly isolated.

All the established TTI systems we reviewed (Technical Document 4) trace only the contacts of index cases who have tested positive for COVID-19, as opposed to all those reporting symptoms. While test-based tracing introduces a delay into the system that will generate some secondary cases, if capacity is limiting this may be balanced by a faster contact tracing process once begun, due to the reduced number of tracing events required, and reduced resource requirements. For example, daily incident COVID infections in mid-May were estimated to be 10,000 (we used an upper confidence bound of 20,000 in our simulations),[21] while daily pre-COVID fever or cough presentations over the summer averaged 100,000,[22] [23] and the average number of close contacts that would have to be quarantined is on the order of 10-12 per index

[21] Flaxman, S., Mishra, S., Gandy, A., Unwin, H., Coupland, H., Mellan, T., Zhu, H., Berah, T., Eaton, J., Perez Guzman, P. and Schmit, N. et al. (2020) Report 13: Estimating the number of infections and the impact of non-pharmaceutical interventions on COVID-19 in 11 European countries. (doi: 10.25561/77731)

[22] Smith, C.M., Conolly, A., Fuller, C., et al. (2019). Symptom reporting, healthcare-seeking behaviour and antibiotic use for common infections: protocol for Bug Watch, a prospective community cohort study. BMJ Open, 9, 5 (doi: 10.1136/bmjopen-2018-028676)

[23] Cowling, B. et al (2020) Impact assessment of non-pharmaceutical interventions against coronavirus disease 2019 and influenza in Hong Kong: an observational study. *The Lancet Public Health* (doi: 10.1016/S2468-2667(20)30090-6)

case.[24] [25] [26] Our simulations found that a symptom-based tracing system generated 52-86% more person-days of quarantine and over five times as many manual traces than a test-based one – on the order of 1 million contacts needing manual tracing each day, over 80% of whom will later prove unnecessary when the index case tests negative. While absolute numbers here are driven by seasonality and epidemic stage, the relative resource requirement of symptom-based testing remains substantially higher across a reasonable range of scenarios.

An intermediate position between a fully-symptom and fully-test-positive approach could be to augment symptoms with other information about index cases (e.g., risk factors for transmission such as occupation) to decide whether or not to immediately start contact tracing. As TTI system capacity improves, or the epidemic wanes, contact tracing could be expanded to an ever-wider set of symptom-positive index cases. If a surveillance system is in place, it can be used to increase specificity of symptom-based contact tracing to target (e.g., local outbreaks) and lowering risks to vulnerable populations (e.g., in care homes and primary care).

Beyond selectively choosing to trace index cases' contacts as a whole, there is the potential within TTI to choose which contacts to trace. It is well established that household and other repeated, close or prolonged contacts (e.g., work colleagues) are at greater risk of acquisition[27] [28] [29] [30] [31] [32] and might therefore usefully be prioritized. Similarly, the tracing effort required to find one-off, relatively brief contacts unknown to the index case is likely to be greater, suggesting that when capacity is constrained a focus on well-known contacts may be an efficient choice. Again, this provides an opportunity to use data gathered from other sources, including household contact studies, alongside the wealth of TTI information on secondary infection yield by contact type to target contact tracing if necessary. Real-time analysis integrating data from pre-existing sources, case/TTI systems and designed incidence studies to produce stratum-specific predictive probability maps of incidence can inform selection of individuals for TTI follow-up, potentially through risk assessments on app or triage systems that are dynamically adjusted by epidemic and NPI levels. These predictive maps can also be used to adapt future

[24] PHE, personal communications.

[25] Klepac, P., Kissler, S. and Gog J. (2018) Contagion! The BBC Four Pandemic - The model behind the documentary., *Epidemics Volume 24*, 49 - 59 (doi: 10.1016/j.epidem.2018.03.003)

[26] Mossong, J., Hens, N., Jit, M., Beutels, P., Auranen, K., Mikolajczyk, R., Massari, M. et al. (2008) Social contacts and mixing patterns relevant to the spread of infectious diseases. *PLoS medicine* 5, 3. (doi: 10.1371/journal.pmed.0050074)

[27] Bi Q, Wu Y, Mei S, Ye C, Zou X, Zhang Z, et al. (2020) Epidemiology and Transmission of COVID-19 in Shenzhen China: Analysis of 391 cases and 1,286 of their close contacts: a retrospective cohort study. Lancet Infectious Diseases. 2020 (doi:10.1016/S1473-3099(20)30287-5)

[28] Burke RM, Midgley CM, Dratch A, Fenstersheib M, Haupt T, Holshue M, et al. (2020) Active Monitoring of Persons Exposed to Patients with Confirmed COVID-19 — United States, January–February 2020. MMWR Morb Mortal Wkly Rep. 6 March 2020, 69, 9, 245–6 (doi: 10.15585/mmwr.mm6909e1)

[29] Luo L, Liu D, Liao X, Wu X, Jing Q, Zheng J, et al. (2020) Modes of contact and risk of transmission in COVID-19 among close contacts, MedRxiv, (doi: 10.1101/2020.03.24.20042606)

[30] Cheng H-Y, Jian S-W, Liu D-P, Ng T-C, Huang W-T. (2020) Taiwan COVID-19 outbreak investigation team, et al. High transmissibility of COVID-19 near symptom onset. MedRxiv http://medrxiv.org/lookup/ (doi: 10.1101/2020.03.18.20034561)

[31] Chen Y, Wang A, Yi B, Ding K, Wang H, Wang J, et al. (2020) The epidemiological characteristics of infection in close contacts of COVID-19 in Ningbo city. Chin J Epidemiol. 41

[32] Jing Q-L, Liu M-J, Yuan J, Zhang Z-B, Zhang A-R, Dean NE, et al. (2020) Household Secondary Attack Rate of COVID-19 and Associated Determinants. MedRxiv. (doi: 10.1101/2020.04.11.20056010)

sampling strategies where pro-active TTI is being conducted, to maximise efficiency and coverage.

Which contacts should be tested, and when?

A key question in the context of TTI is whether to test contacts, and if so when. In our modelling we showed that, depending on the severity of the other NPIs in place, testing all contacts of index cases who test positive would require 50-171% more tests than using symptoms to guide such tests, but without a substantial impact on R_e (since given testing and tracing delays, the only people they differentially capture are those who are asymptomatic). In situations where all contacts of positive index cases are advised to quarantine for 14 days, even though policies typically require testing only occur after symptom onset, most onward transmission will be strongly limited by the quarantine process. However, as noted above, this has a substantial social and economic impact on quarantined individuals and requires ongoing monitoring effort from the TTI system. When capacity is limited, selective testing of contacts may allow them to be released from quarantine (and thus from active symptom surveillance) earlier - as well as allowing the contacts of infected secondary contacts to be rapidly followed up. Prioritization decisions might again rely on the likelihood of having acquired infection, but might also want to take account of the opportunity cost of being quarantined (e.g., focus on working-age adults). It is, however, vital not to test too early in the infection process (since RT-PCR tests are insensitive during much of the incubation period,[33] or to consider repeated testing after a period equivalent to the presumed incubation period, before releasing people from quarantine. Optimization of testing strategies will therefore require a clear understanding of likely transmission timing.

Which contacts should be asked to isolate, and when?

The 'isolate' part of the TTI system also raises the potential for trade-offs. The most comprehensive approach would be to quarantine contacts based on symptoms in the index case, as soon as they are found. If capacity is limiting, the very large number of people under TTI monitoring may overwhelm capacity, at least in the short term. Once more, these numbers can be reduced either by changing the criteria based on the index case (so isolating contacts based on the index case testing positive instead of based on symptoms), or by selecting those contacts at greatest risk of being infected or generating onward transmissions. This balance can again be calibrated depending on capacity constraints and epidemic stage.

[33] Kucirka LM, Lauer SA, Laeyedecker O, Doon D, Lessler J Variation in False-Negative Rate of Reverse Transcriptase Polymerase Chain Reaction–Based SARS-CoV-2 Tests by Time Since Exposure. Annals of Internal Medicine. 2020. https://doi.org/10.7326/M20-1495

7. Effective TTI within a broader epidemic response

The effectiveness of contact tracing is highest when the information picture of contact chains (through surveillance and reporting) is robust, when TTI capacity can contain almost all known contact chains, and speed, efficiency and compliance is high. With a growing epidemic, as the capacity to infection ratio declines, so do the benefits of TTI. In the midst of a large outbreak with substantial community spread, TTI is likely to be resource-intensive, while providing a relatively small benefit due to slow turnaround times. Nevertheless, under the expectation that the UK is likely in the short- to medium-term to focus on containing the COVID-19 epidemic and driving down case numbers, TTI can play an important role. The exact nature of this role will depend on the resources available to it, and the policy decisions made regarding how it fits within the wider epidemic response. We have outlined some of the possible TTI activity choices and explored their likely impacts.

Several of these decisions relate to a careful balance of the health and economic impacts of the epidemic. Central to such a balancing act are careful decisions about when to adjust NPIs. TTI provides a policy tool that may allow somewhat greater relaxation of NPIs than would otherwise be possible, thus the resources required to conduct TTI may provide benefits in terms of reduced NPI stringency and thus greater economic productivity. However, TTI's benefits will depend on how it is implemented. As highlighted above, TTI is most effective when it is able to be comprehensive and efficient, rapidly reaching and ending most infection chains. It is likely to be particularly important when considering relaxing NPIs, e.g., when the number of new cases (in a given area/sector) is declining. Deciding when to adjust NPIs will be best informed by surveillance as well as the capacity of TTI itself.

Importantly, contact tracing approaches alone are unlikely to be efficient in settings with very high force of infection (e.g., care homes, hospitals) since tracing is most useful when some people are at substantially greater acquisition risk than the general population - although TTI for families and other close contacts of healthcare staff will still be important. In high-risk settings, outbreak investigation and infection control approaches are needed, to identify both who has been infected (likely widely dispersed across the institution) and where infection control has failed allowing the initial and secondary infections to arise.

Based on all of the above, we believe that TTI will require a joined-up epidemic response, both to maximize its internal efficiency and its effectiveness in support of other work. Effective TTI will benefit social distancing and other contact-reducing interventions by reducing the number of potentially infectious contacts through increasing infected individuals' status awareness and their willingness to isolate. Effective TTI can also bolster the effectiveness of antiviral treatments (once available), by getting infected individuals onto treatment early in their infection, rapidly controlling their viral load.

Nevertheless, effective TTI will require substantial coordination across a wide range of organizations. This will include public health bodies such as Public Health England, healthcare bodies such as the NHS and private healthcare (as well as NHSx), central government departments covering healthcare, finance and business, and local authorities who can potentially play a vital role coordinating activities as the response become localized in response to epidemic heterogeneity. For example, strong coordination between app-based tracing (managed by NHSx) and manual tracing (managed by PHE) will be needed to avoid duplication of work and to reduce the pressure on manual tracing. Finally, integration of TTI and surveillance at local levels would, in particular, create important sources of data to support decision making for, and potentially provide synergies for implementation of, locally differentiated outbreak management.

8. Next steps

This report, and its technical addenda, are necessarily limited by the time-sensitive nature of the topic. There are several important ways in which this work could be extended. These could include: the addition of cost-effectiveness analysis to weigh up the lost productivity of quarantine versus health and healthcare costs; a consideration of the trade-offs inherent in tight or loose criteria for contact tracing; the addition of more robust data for parameter estimation; an explicit consideration of how surveillance and TTI might interact in a modelling framework; and the extension of the current single-generation model to a dynamic longer-term model. Many of these points highlight the need to include ongoing evaluation of the TTI system as it is rolled out and the epidemic progresses.

Technical documents

The following are materials prepared by individual members of DELVE as inputs into this report.

9. TD1. The Potential Role of Firms in TTI

An effective system of TTI has to align with the incentives of firms, individuals and households. Such a system must look carefully at incentives and tie the logistics of the TTI system to economic incentives. For example, a system that demands isolation from work and family without recognizing the economic costs and trying to compensate those who lose will make many individuals reluctant to submit to testing, let alone isolation.[34] That is why it is essential to have a system which is integrated into the system of measures which are already in place for supporting firms and workers. This is particularly important as the furlough system is rolled back. Even as it ceases to be a core means of income support, it can play a crucial role in creating incentives for an effective TTI system. Social incentives, responses to messaging and a sense of pro-sociality matter too. But should be based on robust evidence that compliance can be achieved.

Effective delivery of TTI has to combine household delivery and firm-level delivery. As the economy opens up, this will mean extending the system beyond the health and social care centres encompassing workers in all parts of the economy. The structure of the UK economy gives a clue to the scale of the challenge. There are around 28 million employed workers in the UK scattered across around 5.9 million firms with about 40% of all employment in the 7700 businesses that have more than 250 employees. About 5.8 million firms have fewer than 50 employees and around 4.9 million have no employees.[35] On top of this, there are just under 5 million registered self-employed.

Since many businesses are keen to open, it is not unreasonable to enlist their assistance in delivering public health measures. And establishing this for TTI will be useful if a vaccine is discovered and needs to be rolled out. Giving firms a role in administering key public programs is not unprecedented and has been key to the government's furlough program. Firms already administer sickness pay schemes and maternity pay schemes which require delegated compliance. And the whole of the tax system (at least VAT, national insurance and income

[34] Attitudinal data from a study in Israel is consistent with the idea that compensation is important. The authors of the study asked respondents about their hypothetical willingness to comply with self-isolation with and without compensation for lost wages. If compensation was offered, then 94% said that they would comply but this dropped to 57% without compensation; see Bodas, M. and Peleg, K. (2020) Self-Isolation Compliance In The COVID-19 Era Influenced By Compensation: Findings From A Recent Survey In Israel, Health Affairs (doi: 10.1377/hlthaff.2020.00382). The wider literature surveyed in Webster et al. (2020) is more equivocal identifying a range of factors in shaping compliance including knowledge about the disease, the procedures used, social norms, perceived risk of the disease and financial considerations due to loss of earnings. See: Webster, R., Brooks, S., Smith, L., Woodland, L., Wessely, S., and Rubin, G. (2020) How to improve adherence with quarantine: rapid review of the evidence, 182, 163-169 (doi: 10.1016/j.puhe.2020.03.007). A small scale study of the SARS epidemic in Toronto also mentions financial compensation as a factor but cannot isolate its importance given the approach taken. DiGiovanni, C., Conley, J., Chiu, D. and Zaborski, J. (2004) Factors influencing compliance with quarantine in Toronto during the 2003 SARS Outbreak, Biosecurity and Bioterrorism: Biodefense Strategy, Practice and Science, 2, 4, 265-72 (doi: 10.1089/bsp.2004.2.265).

[35] UK Government (2019) Business population estimates for the UK and the regions 2019, available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/852919/Business_Population_Estimates_for_the_UK_and_regions_-_2019_Statistical_Release.pdf

taxes) require firms to be the main agent acting on behalf of the government. This would be a new way of regulating the economy but possibly the only way to get a balance between economic cost and public health.

To make a TTI system work, the first step would be to provide a risk assessment of each type of business based on the way that it deals with customers and employees. This must include an assessment based in part on transportation usage. Some of this could be done on a self-reported basis with a monitoring and auditing system to ensure compliance. It could begin with large employers and then be rolled out to smaller businesses. Based on this, the system could assess a frequency for testing for employees and apply for this through an official testing scheme with employers being responsible for compliance by workers. Positive test results could be tied to employer-administered furlough grants for a period of isolation but only an employee could not be assigned to home work (this would be an extension of current sickness pay arrangements which would, in any case, be operative for employees showing symptoms). Employers could also be incentivized to ensure that their employees using tracing apps where appropriate. A scheme such as this would have a useful bi-product of creating usable data on the spread of infection by location and age group. Over time, the scheme could be rolled out to smaller firms, particularly those where risks are particularly high by location or nature of business. Self-employed workers could also be given access to testing facilities in due course.

Targeting is essential to make best use of scarce testing capacity. This means categorizing businesses according to risk and offering testing on this basis. The criterion should not be the transmission rate associated with the business, but the marginal benefit associated with testing a business which would depend on how bringing it into the testing system reduces the spread of the infection and creates economic value. Lines of business where the transmission rate cannot be controlled by TTI and are high will have to remain closed. But if the transmission rate is low, for example, due to the location of the business or the effectiveness of other measures to reduce transmission, there is also need to cover it with TTI. How much TTI can increase economic value by getting people back to work should also be a factor in deciding where to target resources. Developing systematic criteria will make the system more effective. This process can, and should be, evidence-based. It can be enhanced by using standard economic data which is available in existing surveys and particularly in HMRC given that it is administering the furlough program.

As with the furlough program, reaching the self-employed creates a particular challenge given the informality of much of the work that they do. They are a heterogenous group, not only in the type of work that they do, but also in terms of the extent to which they engage in high risk activities in terms of transmission. Many are in sectors which will remain closed for the foreseeable future. Some are sub-contractors to larger firms and hence could fall under any workplace schemes. But it would be necessary to assess what kind of special provision is needed for them. They are less well covered by the furlough scheme and are therefore particularly keen to return to work. Even if they can be reached by a testing program, isolation without compensation would create poor incentives to be tested so some kind of bespoke program would have to be built which recognizes this challenge. But it could also encompass very small businesses which have zero employees. As with larger employers, building TTI together with the follow-on arrangements under the furlough program is essential recognizing that economic incentives have to be compatible with any TTI scheme.

This employee based system would also leave out key groups for whom alternative testing arrangements would have to be found, most notably home carers, vulnerable groups (who are already self-isolating), those who are not active in labour markets (there are around 12 million retirees) and children (around 12 million are currently under age 16). Harnessing existing social networks can aid information diffusion and trust.[36] Even small individual incentives for testing can also be important.[37]

[36] There is an emerging body of evidence from RCTs in developing countries that this is important, for example. For example: Tarozzi, A., Maertens, R., Ahmend, K. and van Geen, A. (2017) Water Testing Delivery Strategies to Reduce Arsenic Exposure through Safe Well Selection in Bangladesh, see: https://www.povertyactionlab.org/evaluation/water-testing-delivery-strategies-reduce-arsenic-exposure-through-safe-well-selection

[37] Thornton, R., Godlonton, S., Angotti, N., Bula, A., Gaydosh, L., Yeatman, S., Kimchi, E. (2006) The Demand for and Impact of Learning HIV Status in Malawi. See: https://www.povertyactionlab.org/evaluation/demand-and-impact-learning-hiv-status-malawi

10. TD2. Surveillance for TTI

What sort of epidemic surveillance is needed, and how it can aid TTI strategies?

Abstract

Any TTI strategy that can only involve a fraction of the at-risk population must begin with a surveillance study to establish how incidence, and therefore potential disease transmission, varies between sub-populations and between individuals within sub-populations. This section describes how a surveillance study might be designed and analysed, taking account of patterns of heterogeneity of exposure and risk across the population, and potentially drawing information from multiple data-sources. Implementation of a surveillance system of this kind would require: 1) the design and regular (potentially weekly) implementation of a country-wide stratified quasi-random sampling scheme of antigenic diagnostic tests, to act as a "gold-standard"; 2) diagnostic testing of sampled individuals; 3) real-time analysis of the resulting data to produce stratum-specific predictive probability maps of incidence that can inform selection of individuals for TTI follow-up and adaptation of future sampling so as to maximise overall utility. Coordination with multiple sources of non-randomised self-reported symptom data on probable/possible case incidence would also be desirable, as this would enable gold-standard and self-reported sources of data to be analysed together to make best possible use of all relevant data-sources, thus creating an agile real-time surveillance system that can be exploited to increase the efficiency of the TTI process.

Introduction

In the absence of unlimited resources, the necessary first step in a TTI strategy for COVID-19 is a system of *real-time surveillance* to provide an understanding of the evolving pattern of population-wide variation in disease incidence. Such a system can then inform a prioritisation of particular individuals or groups for TTI follow-up, by helping to identify individuals or groups of individuals who are most likely to transmit infection.

This task is particularly challenging when, as appears to be the case for COVID-19, a substantial (but unknown) proportion of cases are asymptomatic or pre-symptomatic but may nevertheless be capable of infecting others.

The remainder of this technical document (TD2) sets out a set of principles that could guide the design of a COVID-19 surveillance system and the analysis of the data that it provides. It then lists a range of potential sources of data, and describes strategies for study-design and data-analysis, before discussing the subsequent progression from surveillance to TTI.

Principles of surveillance

In considering the design of a surveillance system, it will be important to take into account the following. These principles apply equally to surveillance systems aimed at monitoring the spatio-temporal evolution of cumulative prevalence determined, for example, by antibody tests, or of current incidence, determined by antigen tests.

1. *Set specific objective(s)* For example, the objective may be to predict the pattern of variation in the current incidence of infectives for a COVID-19 across the UK population (sometimes called now-casting - using sampled data to understand the current state of a process that cannot be completely observed.

2. *Agree a minimal dataset* In any resource-limited setting a balance needs to be struck between how much information is requested from each sampled individual and from how many compliant individuals data can be obtained. Individual-level information is useful for understanding individual risk-factors, but only information that is available country-wide is useful for predicting geographical variation in prevalence. For COVID-19, potentially useful covariates available from the most recent national census include LSOA-level deprivation scores and demographic summaries. *Use a consistent definition of outcome*. This requires either a single diagnostic to be used for case-ascertainment or (see below) a way of calibrating across different diagnostics.

3. *Identify major sources of heterogeneity in risk.* In some sub-populations, notably care homes and hospitals, the patterns of exposure and risk are so different from those of the population at large that they are better treated as separate populations, each with their own surveillance system. Similarly, health workers need separate consideration. For the remainder of the population, it will be advantageous, both operationally and for statistical efficiency, to stratify by known sources of heterogeneity, for example by population density, deprivation and geographical region. Known individual level sources of heterogeneity, for which adjustment should be made at the analysis stage, include age, sex and ethnicity. Any residual variation in incidence can be considered as a proxy for all unknown, spatially or temporally structured sources of heterogeneity, allowance for which should also be made at the analysis stage.

4. *Sample as-if-at-random.* Only a randomised sampling framework can guarantee unbiased predictions of incidence. A stratified random sample of the UK population, with strata defined by the major sub-population risk-groups and adjustment at analysis stage for individual-level risk-factors may, however, be an unattainable ideal. Whilst stratification does not eliminate the potential for bias in a non-randomised sampling scheme, it should reduce it. It may therefore be possible to construct a context-specific sampling instrument that can be regarded as “as-if-random’’ after stratification and adjustment.

5. *Choose spatial and temporal scales for analysis and for reporting.* In principle, incidence is likely to vary continuously in time and space. For reporting purposes, it may be helpful to aggregate results to a temporal (weekly?) and spatial (regional?) scale on which operational decisions can be made. To avoid aggregation bias, surveillance data should be recorded and analysed at the finest substantively relevant temporal and spatial resolutions. In the current context, the finest relevant temporal scale could be daily or weekly, depending on the diagnostic used; for example, self-reported symptoms may be susceptible to weekday/weekend artefacts. The finest relevant spatial scale is likely to be a Lower Layer Super Output Area (LSOA); note, in particular, that several of the known sources of heterogeneity (ethnicity, deprivation) can vary substantially between adjacent LSOA’s.

Resolution to full post-code is technically possible but arguably too fine as, even in lock-down, a substantial proportion of the population will regularly move beyond their home post-code.

6. *Measure and report degree of uncertainty in predictions.* A conventional measure of statistical precision is the standard error of an estimate. In disease surveillance, arguably, a more relevant measure is a predictive probability, i.e. the probability, given the observed data, that the underlying process is in a specified state; for example, that the incidence of COVID-19 amongst 70-year-old white males at a particular location is at least 10%.

7. *Take account of major public health interventions.* In any statistical model, unexplained variation in the outcome is ascribed to stochastic variation, and the bigger the stochastic variation the less precise are the associated model-based predictions. Interventions that are likely to have a major effect on incidence should be included in the statistical model as change-points.

None of the above principles are specific to COVID-19, nor the statistical methods needed to analyse to resulting data. *We suggest that the COVID-19 epidemic could be the stimulus for creation of a national, real-time spatial surveillance system for emerging infectious diseases that would be adaptable to any future public health concerns*

Data sources

We make a distinction, admittedly not always sharp, amongst three broad types of data.

(a) *Designed studies* will include measurement of a recommended diagnostic test of current COVID-19 infection with good sensitivity and specificity[38], such as an RT-PCR swab-based test for COVID-19 infection. Two examples of such studies are the Imperial College REACT study[39] and the Oxford-ONS surveillance study[40],

(b) *Routinely recorded health outcome data* potentially useful for surveillance can come from a variety of sources, including: the zoe app[41], calls to NHS Direct; indicators monitored by PHE as part of its network of surveillance systems, such as FluSurvey, GP In Hours (GPIH) syndromic surveillance system, GP Out of Hours (GPOH) syndromic surveillance system, Emergency Department Syndromic Surveillance System (EDSSS)). Symptom-based self-reported indicators typically have lower sensitivity and specificity than diagnostic tests and may suffer from biases.

[38] The sensitivity of a test is the proportion of true positives, the specificity is the proportion of true negatives. For RT-PCR based swab tests which are self administered, a diagnostic sensitivity of 0.65 and specificity of 100% is used in the Oxford REACT study.
[39] Laurance, J. and Alford, J. (2020) Home testing for coronavirus to track levels of infection in the community, Imperial College London News, 30 April 2020, available at: https://www.imperial.ac.uk/news/197217/home-testing-coronavirus-track-levels-infection/
[40] NIHR Oxford Biomedical Research Centre (2020) Large-scale COVID-19 infection and antibody test study launched, 23 April 2019, available at: https://oxfordbrc.nihr.ac.uk/large-scale-covid-19-infection-and-antibody-test-study-launched/
[41] See: https://covid.joinzoe.com/

(c) *Other types of data*, such as internet searches for specific symptoms, spikes in consumption of non-prescription medicines or sickness absences could potentially also be brought into the surveillance system to expand its detection of unusual events.

Data sources of types (b) and, more so, of type (c) should be used cautiously. At a minimum, they require careful calibration against high-quality data of type (a). Also, adding complexity to a predictive model risks losing, rather than gaining, precision if the signal content of the added data source is weak, and only weakly associated with the primary outcome of interest.

Design

Here, we assume that a method of locating an as-if-random sample of individuals has been agreed, the choice of diagnostic has been made and its performance characteristics are well understood. The remaining design considerations are: the selection of strata based on combinations of sub-population characteristics; the frequency of sampling; the individual-level characteristics to be recorded on sampled individuals; the sample size(s) to be taken in each stratum. With respect to the last of these, we need either to set a performance target and derive a set of sample sizes that will achieve this, or to set an achievable limit on total sample size, optimise their disposition across strata and evaluate the performance of the resulting surveillance system. Understanding the limitations of a range of affordable designs is more useful than setting a single performance target that is unattainable. Examples of suitable measures of performance might be: the maximum width of a 95% predictive interval for LSOA-level incidence within any stratum; or the ROC curve for predicting exceedance of a specified LSOA-level incidence.

As with any sample size calculation, an initial sampling design can only be constructed by assuming a specific statistical model for the underlying spatio-temporal incidence surface. However, data accruing in the early operation of the system can be used to assess the goodness-of-fit of modelling assumptions, estimate model parameters, and to adapt the sampling design accordingly. This will be particularly the case if resource constraints severely limit the proportion of probable or confirmed cases that can be followed up.

Analysis

In a surveillance system of the kind described here, taking account of spatial and/or temporal correlation in the underlying incidence process can materially improve predictive precision, sometimes by an order of magnitude[42]. Combining a relatively small sample of data from a designed study based on a recommended diagnostic test with a much larger sample of routinely

[42] Fronterre, C., Amoah, B., Giorgi, E., Stanton, M.C. and Diggle, P.J. (2020). Design and analysis of elimination surveys for neglected tropical diseases. *Journal of Infectious Diseases*, (doi: 10.1093/infdis/jiz554)

collected data, typically based on self-reports, can also be a cost-effective way of making the best use of all available data.[43 44]

A suitable class of statistical models for problems of this kind is a generalized linear mixed model[45] with a latent spatio-temporal Gaussian process included in the linear predictor[46]. The appendix gives an example of a model of this kind for the joint analysis of designed and routinely collected data.

The end product of the surveillance system is the availability of a set of stratum-specific space-time surfaces, adjustable for individual-level risk-factors, that quantify the variation in disease incidence, with associated measures of uncertainty.

Link between surveillance and the TTI process

In incidence surveillance system can provide a useful first stage in a TTI system. TTI will be most cost-effective when the individuals at the start of a TTI chain are those most likely to be infective. Also, if surveillance and TTI use the same diagnostic, TTI-generated data can be fed back into the surveillance system to increases its local precision. Here we discuss two of the decision points in the TTI process where knowledge of the spatio-temporal incidence of disease that is provided by a surveillance system plays a role in informing the chosen course of action: the decision to test or not an individual who has either reported symptoms or contacted the primary health care system; and the decision to trace or not the contacts of this individual and when to initiate this.

Known routes of transmission of COVID-19 include transmission from asymptomatic, pre-symptomatic and symptomatic individuals through exhaled droplets, and environmental transmission through contaminated surfaces. Here we focus only on person-to-person transmission.

The surveillance system described thus far estimates the probability that an individual within any stratum is test positive (or is symptom positive if the data source is related to symptoms). We also need an understanding of the probability that an individual will have transmitted infection given that they are test positive, which will likely depend on the individual's stratum membership and on their measured personal attributes.

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[43] Giorgi, E., Sesay, S.S., Terlouw, D.J. and Diggle, P.J. (2015). Combining data from multiple spatially referenced prevalence surveys using generalized linear geostatistical models. *Journal of the Royal Statistical Society* A 178, 445-464 (doi: 10.1111/rssa.12069)

[44] Amoah, B., Giorgi, E. and Diggle, P.J. (2020). A geostatistical framework for combining spatially referenced disease prevalence data from multiple diagnostics. *Biometrics*, **76**, 158-170.(doi: 10.1111/biom.13142)

[45] Breslow, N.E. and Clayton, D.G. (1993). Approximate inference in generalized linear mixed models. Journal of the American Statistical Association 88, 9-25.(doi: 10.2307/2290687)

[46] Diggle, P.J., Rowlingson, B. and Su, T-L. (2005). Point process methodology for on-line spatio-temporal disease surveillance. *Environmetrics*, **16**, 423-434. (doi: 10.1002/env.712)

In a recent paper, Ferretti et al (2020)[47] quantify the relative contribution of different routes of transmission to the reproductive number, and estimate that the main transmission routes are from pre-symptomatic and symptomatic individuals, which altogether account for a large fraction of transmissions. This paper also shows that pre-symptomatic transmission is nearly sufficient for driving the epidemic, accounting for a proportion 0.9 of the total contribution to an R0 equal to 2.[48] Both the incubation time and the generation time between source and transmission are estimated to be around 5 days. This shows: (i) that the primary focus of TTI is on "capturing" both pre-symptomatic and symptomatic individuals; (ii) that there is a time constraint on the effectiveness of the TTI process, which might require contact tracing to begin before confirmation through a diagnostic test.

Symptomatic individuals can be best captured rapidly through a range of symptom-related indicators (see details below), while pre-symptomatic and asymptomatic individuals might be captured only through the contact tracing process. Such individuals might also be captured through the designed surveillance system, but unless the designed testing strategy enrolled a substantial fraction of the whole population, focussing contact tracing on these would miss a large fraction of the infectives.

As is the case for surveillance, the definition of a minimum dataset needs care. However, as TTI will involve smaller numbers of individuals who are also more likely to be cases, the argument for recording individual characteristics is stronger. These could include age, sex, ethnicity and occupation. It is important to note that this approach considers only the general population, excluding special categories such as care-home residents, hospital in-patients and health workers, and assumes that resource constraints dictate a prioritisation of who should be tested as the first stage of TTI.

The testing strategy and the prioritisation of whom to test

Pragmatically, we want to maximise *the capture probability*, i.e. the probability for an individual of being found positive in the RT-PCR swab test *if selected to be tested:* Prob(RT-PCR+ | selected for testing). The steps to maximize the capture probability could be as follows:

- Derive and agree with PHE and PH experts a list of symptom indicators, which encompass the most common symptoms of COVID-19 and are adapted to each of the routine data resources (111 calls, GPIH, GPOH, Zoe app and NHSx app). Specific symptoms to COVID-19 such as loss of taste or smell are particularly useful as they will help to discriminate from influenza like symptoms;
- For each of these sources, run a pilot study on a suitably stratified sample of people for whom both the set of symptoms indicators and the PCR test are measured.

[47] Ferretti L et al (2020). Quantifying SARS-Cov-2 transmission suggests epidemic control with digital contact tracing. *Science* (doi: 10.1126/science.abb6936)
[48] see Ferrettti et al (2020), Figure 2

- Calibrate a predictive model of Prob (RT-PCR+ | indicators) using the pilot data for each data source. For example, Menni et al (2020)[49] used the symptoms reported in the zoe app to derive a symptom prediction model using stepwise logistic regression. This gave a sensitivity of 0.65 [0.62; 0.67], a specificity of 0.78 [0.76; 0.80] and a ROC-AUC of 0.77 [0.72; 0.82]. The strongest predictor was loss of smell and taste. The overall Positive Predictive value was estimated at 0.69 [0.66; 0.71]. The sample size where both symptoms and PCR test were measured in the UK was 15,638, with 6,452 PCR+ tests. The authors did not find notable differences by age and sex.
- Improve the positive predictive value of the symptom-based predictive model by adding external information from: (i) surveillance studies that predict the stratum-specific incidence surfaces of COVID-19; (ii) primary care EHR records of co-morbidities and other risk factors of sampled individuals.
- Derive the final predictive probability of infection for each person that enters the system through any one of the data sources. Individuals with high predictive probability of infection (e.g. a person having specific symptoms in an area where current incidence is on the rise) are more likely to be COVID-19 positive than an individual with low predictive probability.
- Embed the predictive probability into the first step of the TTI decision process so as to optimise allocation of testing resources to individuals most likely to be infected. The efficacy of different rules could be investigated through simulations.

The decision and timing of contact tracing

A predicted stratum-specific incidence surface provides a basis for deciding where and when to prioritise contact-tracing follow-up, with the ultimate goal of prioritising for follow-up those individuals most likely to have transmitted infection. This can be combined with the predictive probability of infection for the source individual to decide whether to immediately start tracing their contacts or to await confirmation through a positive test result. If the predictive probability of the source individual is high, it might be recommended that contact tracing is initiated immediately, since about 50% of transmission is in the pre-symptomatic period. Waiting for the result of the test would mean that the transmission chain is less likely to be broken, but this needs to be balanced against the opportunity-cost of contact-tracing individuals who subsequently test negative. Of course, if and when test results become available more quickly, this could be revisited. Timeliness of testing and manual contact tracing is also a key factor, as shown in the simulation scenarios considered in section 3. See also Ferretti et al (2020)[50], who discuss a quasi-instantaneous contact tracing scheme based on an app.

Discussion

Real time surveillance of incidence through surveys and TTI are two complementary components of public health action in the face of an emerging threat from an infectious disease.

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[49] Menni C et al (2020). Real-time tracking of self reported symptoms to predict potential COVID-19. *Nature Medicine* (doi: 10.1038/s41591-020-0916-2)
[50] Ferretti L et al (2020). Quantifying SARS-Cov-2 transmission suggests epidemic control with digital contact tracing. *Science* (doi: 10.1126/science.abb6936)

We have discussed how a designed surveillance study can be combined with self-reported symptom-based data to create an agile surveillance system that can track the spatial evolution of the disease in real time. If several self-reported symptom data sources are offered concurrently to the population, like zoe app and NHSx app, *we recommend that they all contain an agreed standardised minimum set of information on the symptoms recorded*, very much along the lines of the core outcome set which, by international agreement, is recorded in all clinical trials (COMET). This will allow information from diverse technologies to be meaningfully synthesised.

To be able to calibrate the link between designed diagnostic testing and self-reported symptom data, it is necessary to have records of both types of data on a subset of individuals. To prevent selection biases, it would be highly desirable that at least part of this subset is randomly chosen, rather than purely observational.

Steps in the TTI process can be informed by an agile, real-time surveillance system to prioritise testing for the individuals most likely to be infected, and to target the contact tracing accordingly. The algorithm used for this prioritisation can be refined and improved as the epidemic progresses, and more specific clinical characteristics of infected individuals are discovered. Finally, the TTI process can also feedback into the design of specific localised surveillance studies around hotspots.

Appendix 1 focuses on real time surveillance through a combination of designed testing studies and routine capture of self-reported symptoms or calls to the health system. As this framework develops, considering additional sources of data to detect unusual activity or behaviour might be beneficial to increase the agility of the surveillance system.

Appendix [see attached paper - Appendix 1]. *An example of a surveillance system combining designed and routinely collected data to reconstruct the underlying space-time incidence data.*

12. TD3 Modelling TTI Scenarios

See attached paper [TD3].

13. TD4. A Review of International Approaches to TTI

TTI strategies have been developed by countries across the world, including Germany, South Korea, Taiwan, Singapore, New Zealand and Iceland, as part of their efforts to lower the number of COVID-19 cases and minimise related deaths. A review of these international approaches around this strategy offers insights for the UK.

1. Each of these countries initiated this strategy as soon as the first COVID-19 cases were reported and have been consistently implementing it, with the three components of testing, contact tracing and isolation being implemented in tandem.
2. Each of these countries have an expanded testing criteria in place. All countries use polymerase chain reaction (PCR) tests for symptomatic cases, high risk individuals, and health workers. South Korea, New Zealand and Iceland have gone a step further by introducing mass testing for individuals at the community level regardless of symptoms. Germany and Iceland have also started conducting antibody testing. One area that needs to be further investigated is the consideration of repeat testing, especially for health workers as they have repeated risk of exposure.
3. Random community testing and antibody tests are being used to inform countries' future steps such as plans to exit from lockdowns.
4. All of these countries offer testing across traditional healthcare settings (clinics and hospitals) as well as novel locations (drive through centres, walk-through centres, mobile sites outside supermarkets).
5. These countries have managed contact tracing through a combination of physical teams (consisting of multisectoral public staff), big data analytics and mobile-based applications. Four countries (South Korea, Singapore, New Zealand and Iceland) initiate contact tracing after a confirmed positive test results; whereas in Taiwan, this process begins even within a suspected case. South Korea, for instance, leverages technology to aid its contact tracing efforts. The government has an ICT system that automatically integrates GPS data, credit card information and CCTV footage to create a moving history (transmission route) for the confirmed case in a span of 10 minutes. This data is verified by patient interviews, contacts are then identified and sent automated text messages on the same day. The transmission route of the confirmed patients (anonymised) is also uploaded on government websites, so that citizens can avoid these places to reduce the risk of transmission.
6. The total time for TTI (i.e. from testing, tracing and tracking contacts to instructing contacts to isolate) is around 2 to 3 days in South Korea, Singapore, Taiwan, and New Zealand. Test results in these four countries are available in 4 to 5 hours.
7. While digital applications can aid contact tracing teams, they can also raise privacy concerns, for example relating to the risk of personal data being repurposed for causes other than outbreak control, and concerns about location and duration of storage of personal data. Iceland has tried to address these privacy concerns before launching their contact tracing application, by gaining certification by an independent reviewer, making it voluntary for users to download the application and agree to share GPS information, and storing anonymised data on the user's device.
8. In all the six countries, close contacts, once identified, have to self-isolate for 14 days and seek testing on displaying any symptoms. Approaches to ensure isolation and quarantine measures vary across countries. While Germany, New Zealand and Iceland

have recommended isolation for certain individuals, South Korea, Taiwan and Singapore have made quarantine mandatory and enforce it through the use of smartphone applications and fines.

9. Countries made use of existing national capabilities in implementing this strategy. Germany and South Korea used their robust biotechnology industry and laboratory networks and Iceland employed a public-private partnership to ramp up testing. Singapore and Taiwan used big data and multisectoral response teams.
10. A range of challenges implementing TTI have already been reported, including staff fatigue (especially frontline and laboratory staff), logistical hurdles of sourcing testing materials, privacy concerns over smart phone applications, and public adherence to social distancing and isolation guidance.

The tables that follow give an overview of approaches to TTI in Germany, South Korea, Taiwan, Singapore, New Zealand and Iceland.

Germany		
Total population	82.79 million	
Date of first reported case of COVID-19[51]	25 February 2020	
Epidemiological situation[52]	Confirmed: 174,478 Deaths: 7,884 Recovered: 150,000	
Testing[53] [54] [55] [56] [57] [58]	Who gets tested?	Initially, those with symptoms, travel history and close contact with confirmed cases were tested. Since 25 March 2020, the testing criteria has been relaxed to include anyone who has symptoms including healthcare workers.
	What kind of tests are being used?	Real-time PCR assay is being used. Germany developed its first rapid PCR test on 16 January. Since February, a nationwide network set up between doctors' practices, normally used to monitor the flu, is being used for testing for COVID-19. Labs are also using pooled testing procedures that produce reliable results in short times, thereby increasing the overall testing capacity. Antibody testing is also being conducted, drawing from blood donation services, samples from regions with large outbreaks and representative samples from the broader population.

[51] Reuters (2020) Man infected with coronavirus in Germany after Italy trip -state ministry. 25 February 2020. Available at: https://www.reuters.com/article/us-china-health-germany-idUSKBN20J2K2

[52] Robert Koch Institut (2020) COVID-19 Dashboard. Available at: https://experience.arcgis.com/experience/478220a4c454480e823b17327b2bf1d4

[53] Focus (2020) Statistikerin fordert Tests, die endlich das wahre Corona-Ausmaß in Deutschland Zeigen, 25 March 2020. Available at: https://www.focus.de/gesundheit/news/es-grassiert-ungewissheit-repraesentative-tests-sollen-wahres-ausmass-in-deutschland-zeigen_id_11813688.html

[54] NPR (2020) Germany is conducting nation-wide covid-19 antibody testing. 21 April 2020. Available at: https://www.npr.org/sections/coronavirus-live-updates/2020/04/21/839594202/germany-is-conducting-nationwide-covid-19-antibody-testing

[55] The Spectator (2020) How Germany has managed to perform so many covid-19 tests. 6 April 2020. Available at: https://www.spectator.co.uk/article/how-germany-has-managed-to-perform-so-many-covid-19-tests

[56] Robert Koch Institut (2020) Täglicher Lagebericht des RKI zur Coronavirus, 22 April 2020. Available at: https://www.rki.de/DE/Content/InfAZ/N/Neuartiges_Coronavirus/Situationsberichte/2020-04-22-de.pdf?__blob=publicationFile

[57] Healthcare in Europe (2020) Corona 'pool testing' increases worldwide capacities many times over, 1 April 2020. Available at: https://healthcare-in-europe.com/en/news/corona-pool-testing-increases-worldwide-capacities-many-times-over.html#

[58] New York Post (2020) German hospital launches drive-thru coronavirus testing, 10 March 2020. Available at https://nypost.com/2020/03/10/german-hospital-launches-drive-thru-coronavirus-testing/

	Where are tests conducted?	• Healthcare facilities • Drive-through testing centres
	What is the daily testing capacity?	As of May 11, a total of 3,147,771 tests have been conducted. Daily testing capacity as of 21 April was reported at 1,20,000 tests a day. Tests per million: 37,857.
Contact tracing [59] [60] [61]	Under Germany's contact tracing policy, implemented as soon as first cases were recorded, every person who has come into contact with an infected patient in the last two weeks is tracked and tested. Public contact tracing teams use phone calls to trace and monitor close contacts. Contact tracing teams will soon be assisted with Germany's home-grown smartphone app, developed for the Robert Koch Institute, to trace infections. Further, mobile carriers in Germany have started to share cell phone location data with health officials in an aggregated, anonymized format. On 21 March, the German health ministry also drafted changes to the Infection Protection Act to allow, among other things, the tracking of people who were in contact with those infected with the coronavirus. North-Rhine Westphalia, the country's largest state and one of the worst affected by the coronavirus outbreak, currently has 3,385 people employed in contact tracing. The federal government announced that each state was expected to have at least one team of 5 contact tracers for every 20,000 people, and 11 of 16 states have met this target. The federal government has recruited 362 containment scouts (plus 130 are being trained) to operate alongside contact tracers in about 400 local health authorities spread across the country.	

[59] The Telegraph (2020) Contact tracing: how will the UK's test, track and trace plan help ease lockdown, 14 May 2020. Available at: https://www.telegraph.co.uk/news/0/contact-tracing-uk-lockdown/

[60] Science (2020) Cellphone tracking could help stem the spread of coronavirus. Is privacy the price?, 22 March 2020. Available at: https://www.sciencemag.org/news/2020/03/cellphone-tracking-could-help-stem-spread-coronavirus-privacy-price#

[61] Nardelli, A. (2020).Germany Has Shared The Details Of Its Coronavirus Contact Tracing Operation. The UK Won't. BuzzFeedNews. Published May 09, 2020. https://www.buzzfeed.com/albertonardelli/germany-uk-coronavirus-contact-tracing-compared

Isolation[62] [63]	Since late February, self-isolation for 14 days on becoming symptomatic or having close contacts with confirmed or suspected cases is a recommended measure. Visits and events in nursing homes are cancelled in an effort to isolate and shield the over 800,000 seniors who live in around 11,700 facilities across the country.
Facilitators[64] [65]	Early response, strong biotechnology industry and laboratory testing capacity, decentralised diagnostic system have been the major facilitators for Germany's test, trace and isolate strategy for COVID-19.
Challenges[66] [67]	Regional bodies have reported bottlenecks such as the struggle to recruit additional staff to deal with increased workload and backlog as well as coordinating with the limited number of global suppliers for testing materials. Privacy concerns have been raised around mobile-based applications, particularly on the location of the data storage viz. government hosted central servers versus decentralised on user phones, with the latter being recommended by privacy experts.

62 Business Insider (2020) Germany has remarkably few COVID-19 deaths. Its healthcare system shows how Germany prevented a runaway death toll, 2 April 2020. Available at: https://www.businessinsider.com/why-germany-has-a-low-covid-19-mortality-rate-2020-4?r=US&IR=T

63 DW (2020) German retirement homes isolate the elderly from COVID-19 threat, 9 April 2020. Available at:https://www.dw.com/en/german-retirement-homes-isolate-the-elderly-from-covid-19-threat/a-53082145

64 The Medical Futurist (2020) How Germany Leveraged Digital Health to Combat COVID-19, 9 April 2020. Available at: https://medicalfuturist.com/how-germany-leveraged-digital-health-to-combat-covid-19/

65 The Spectator (2020) How Germany has managed to perform so many covid-19 tests. 6 April 2020. Available at: https://www.spectator.co.uk/article/how-germany-has-managed-to-perform-so-many-covid-19-tests

66 The Guardian (2020) Germany told it needs to massively increase coronavirus testing, 2 April 2020. Available at: https://www.theguardian.com/world/2020/apr/02/germany-told-it-needs-to-massively-increase-coronavirus-testing

67 CNN Business (2020) Wary Germans hate sharing their data. Will they use a COVID-19 tracking app? 25 April 2020. Available at: https://edition.cnn.com/2020/04/25/tech/coronavirus-contact-tracing-germany-privacy/index.html

South Korea		
Total population[68]	51.47 million	
Date of first reported case of COVID-19[69]	20 January 2020	
Epidemiological situation[70]	Confirmed: 11,018 Deaths: 260	
Testing[71]	Who gets tested?	Mass testing began in February regardless of symptoms or travel history. Test results are delivered between 24 to 72 hours, via text messages or phone calls along with corresponding advice. Around 20% of all those who tested positive were found to be asymptomatic.
	What kind of tests are being used?	Real-time PCR assay is being used. As of 15 April 2020, five diagnostic reagent companies (Companies KogeneBiotech, Seegene, Solgent, SD Biosensor, and Biosewoom) have obtained emergency use approval from the Korean Center for Disease Control and are producing RT-PCR reagents in the country.
	Where are tests conducted?	• Primary health clinics and hospitals • Public health and environment research institutes • Private healthcare providers • Drive-through testing centres • Walk-through testing centres
	What is the daily testing capacity?	As of May 15 2020, 726,747 tests have been conducted, leading to nearly 11,000 tests per million.[72] Daily testing capacity increased from 200 in January to 20,000 in March. Tests per million: 14,055[73] [74]

[68] The World Bank (2020) Population, total, data catalogue. Available at: https://data.worldbank.org/indicator/sp.pop.totl

[69] Korean Centers for Disease Control and Prevention (2020) Press Release: The first imported case of the novel coronavirus (2019-nCoV) in Korea, 20 January 2020. Available at: https://www.cdc.go.kr/board/board.es?mid=a30402000000&bid=0030

[70] Ministry of Health, Government of South Korea (2020) Official Update of COVID -19 Situation in South Korea. 30 March 2020. Available at: http://ncov.mohw.go.kr/en/ & https://coronaboard.kr/

[71] Government of South Korea. How Korea responded to the pandemic using ICT, 16 April 2020. Available at: http://www.moj.go.kr/moj_eng/1765/subview.do;jsessionid=_lbCnPNdLFYNs-Kih5hWY48vT1aeaCIC-Zwk14oH.wizard-8-dpzr7?enc=Zm5jdDF8QEB8JTJGYmJzJTJGbW9qX2VuZyUyRjUxJTJGNTIyODIyJTJGYXJ0Y2xWaWV3LmRvJTNG

[72] Korean Centers for Disease Control and Prevention (2020) Coronavirus Disease-19 data. Accessed 14 May 2020. Available at: http://ncov.mohw.go.kr/en/

[73] Ministry of Health and Family Welfare, Government of South Korea (2020) Press Release: IMS meeting for Novel Coronavirus presided over by the Prime Minister, 13 February 2020. Available at: https://www.mohw.go.kr/eng/nw/nw0101vw.jsp?PAR_MENU_ID=1007&MENU_ID=100701&page=1&CONT_SEQ=352865

[74] BBC (2020) Coronavirus in South Korea: How 'trace, test and treat' may be saving lives, 12 March 2020. Available at: https://www.bbc.co.uk/news/world-asia-51836898; https://coronaboard.kr/

Contact tracing[75]	Korean public health authorities, national police agency, financial services commission, and local governments collaborated for contact tracing through interviews, analysis of closed-circuit television, credit card and smartphone GPS data, and publicizing the moving histories of anonymised COVID-19 patients on the Ministry of Health website (all measures are legally sanctioned by the government).The effective contact tracing system, known as the COVID-19 Smart Management System, is run by the Korean Centers for Disease Control and Prevention and can analyse a person's movements in just 10 minutes. This moving history (i.e. transmission route) of the confirmed case is verified with the patient interview and then contacts are identified and notified through automated text messages.
Isolation [76] [77] [78] [79]	South Korea uses a combination of local teams, mobile-based applications and fines to ensure mandatory 14-day quarantine for asymptomatic cases, those with minimal symptoms, close contacts of confirmed cases, as well as those who have tested negative. The primary case is classified based on the severity (mild, moderate, severe and extremely severe). Mild cases are isolated at local specialised clinics called 'living and treatment support centres'. Moderate, severe and extremely severe are hospitalised at national infectious disease hospitals and hospitals that were designated specifically for this at each location. The government-endorsed Corona 100m (Co100) application, launched on February 11, using government data, alerts users when they come within 100 metres of a location visited by a confirmed case. Another government GPS-based application named 'self-quarantine safety protection' launched on March 7, enforces self-quarantine measures. South Koreans are encouraged to download this application after getting tested. If they are advised to self-quarantine based on test results, then they have to input their symptoms into the mobile application twice a day for the period of the quarantine, and the application will monitor their locations and set off an alarm if they leave their designated quarantine location. For those who do not use the application, a local monitoring team calls twice daily to make sure the quarantined stay put and check for symptoms. Citizens and international visitors are also encouraged to use a government-based self-diagnosis mobile application, launched on February 12, allows users to monitor health conditions and access readily available information on follow-up actions such as physical check-ups, using helplines and finding clinics. Quarantine violators face up to 3 million won ($2500) fines. If a recent bill becomes law, the fine will go up to 10 million won and as much as a year in jail.

[75] Korea Centers for Disease Control and Prevention (2020) Contact Transmission of COVID-19 in South Korea: Novel Investigation Techniques for Tracing Contacts, Osong Public Health Res Perspect 2020;11(1):60-63 (doi: 0.24171/j.phrp.2020.11.1.09)

[76] Asian Boss (2020) Interview with Professor Kim Woo-joo from Korea University Guro Hospital. 27 March 2020. Available at: https://www.youtube.com/watch?time_continue=1903&v=gAk7aX5hksU&feature=emb_logo

[77] Zastrow, M. (2020) South Korea is reporting intimate details of COVID-19 cases: has it helped? Nature News, 18 March 2020. Available at: https://www.nature.com/articles/d41586-020-00740-y

[78] Normile, D. (2020) Coronavirus cases have dropped sharply in South Korea. What's the secret to its success? Science, 17 March 2020. Available at: https://www.sciencemag.org/news/2020/03/coronavirus-cases-have-dropped-sharply-south-korea-whats-secret-its-success#

[79] Juhwan Oh, Jong-Koo Lee, Dan Schwarz, Hannah L. Ratcliffe, Jeffrey F. Markuns & Lisa R. Hirschhorn. National Response to COVID-19 in the Republic of Korea and Lessons Learned for Other Countries. Health Systems & Reform, 2020, Vol. 6.

Facilitators[80]	Preparedness, early response, government leadership and transparent communication, and innovations have been the key facilitators for ensuring that the test, trace and isolate strategy works. Following the 2015 MERS outbreak, the government invested in its research and development for PCR testing kits, creating financial incentive for competition among private biomedical companies to develop rapid diagnostic tools. In the last week of January 2020, South Korean health officials convened a meeting with representatives from more than 20 medical companies on developing rapid testing kits, and by early February, two companies received approval for PCR tests. Transparent government communication has been demonstrated by daily press briefings and emergency texts to all citizens. Innovations including drive-through and walk-in test centres have speeded up the testing and have been adopted around the world.
Challenges[81] [82] [83]	Challenges have included privacy concerns owing to publicising people's movements, health worker fatigue, unintended negative economic consequences on businesses as people avoid places that have been visited by confirmed or suspected cases, and hardships for vulnerable groups due to mandatory quarantine.

[80] Fendos J. (2020) Lessons From South Korea's COVID-19 Outbreak: The Good, Bad, and Ugly. 10 March 2020. The Diplomat. Available at: https://thediplomat.com/2020/03/lessons-from-south-koreas-covid-19-outbreak-the-good-bad-and-ugly/

[81] Al Jazeera (2020) Testing times: Why South Korea's COVID-19 strategy is working. 21 March 2020. Available at: https://www.aljazeera.com/programmes/upfront/2020/03/testing-times-south-korea-covid-19-strategy-working-200320051718670.html

[82] Yonhap News Agency (2020) Medical staff under pressure amid spiking virus cases in S. Korea. 2 March 2020. Available at: https://en.yna.co.kr/view/AEN20200302002500320

[83] Ryall J. (2020) Coronavirus: Doctors collapse from exhaustion as virus spreads through South Korea. 3 March 2020. The Telegraph. Available at: https://www.telegraph.co.uk/news/2020/03/03/coronavirus-doctors-collapse-exhaustion-virus-spreads-south/

Taiwan		
Total population	23.78 million	
Date of first reported case of COVID-19[84]	21 January 2020	
Epidemiological situation[85]	Confirmed: 440 Deaths:7 Recovered: 383	
Testing[86 87 88 89 90]	Who gets tested?	Targeted testing for symptomatic individuals with travel history, close contact with suspected or confirmed cases, and vulnerable individuals including patients with severe respiratory symptoms and healthcare workers with pneumonia. Most recently, any patients who report a loss of the sense of smell or taste are mandated to be tested.
	What kind of tests are being used?	PCR tests began in January. In early March, Taiwanese genome researchers developed a rapid COVID-19 diagnostic test, which reduces time to test from the current 4 hours to 15 minutes. With funding from Taiwan, in early April, Taiwan and Denmark jointly developed ViroTrack, a diagnostic test that can produce a result within 12 minutes, indicating whether the person is carrying the virus or has recovered from a COVID-19 infection.
	Where are tests conducted?	• Taiwan Centers for Disease Control • Designated hospitals

[84] Taiwan Centers for Disease Control (2020) Taiwan timely identifies first imported case of 2019 novel coronavirus infection returning from Wuhan, China through onboard quarantine, 21 January 2020. Available at: https://www.cdc.gov.tw/En/Bulletin/Detail/pVg_jRVvtHhp94C6GShRkQ?typeid=158

[85] Taiwan Centers for Disease Control (2020) COVID-19 Update. Available at: https://www.cdc.gov.tw/En

[86] Sui C. (2020) What Taiwan can teach the world on fighting the coronavirus. NBC News, 10 March 2020. Available at: https://www.nbcnews.com/health/health-news/what-taiwan-can-teach-world-fighting-coronavirus-n1153826

[87] Chiou, C. (2020) How Taiwan Battles the Coronavirus. The Diplomat, 6 April 2020 https://thediplomat.com/2020/04/how-taiwan-battles-the-coronavirus/

[88] Taiwan Centers for Disease Control (2020)
Recommendations for COVID-19: Case Definition, Specimen Collection, and
Diagnostic Tests, 12 April 2020. Available at: https://www.cdc.gov.tw/En/File/Get/r5dYouF4hPsyYAmt_mOkcQ

[89] Taiwan Healthcare (2020) Taiwanese Genome Researchers just Developed a Rapid 15-minute COVID-19 Diagnostic Testing, 9 March 2020. Available at: https://www.taiwan-healthcare.org/biob2b/breaking-news?articleSysid=BhsArticle20200310105046123664253&articleTypeSysid=A

[90] Focus Taiwan (2020) Taiwan, Denmark jointly develop 12-minute COVID-19 test kit, 8 April 2020. Available at: https://focustaiwan.tw/sci-tech/202004080025

	What is the daily testing capacity?	As of May 15,2020, 68,659 tests have been conducted. Daily testing capacity for COVID-19 is approximately 1,300 samples. Tests per million: 2909.
Contact tracing[91] [92]	Taiwan's contact tracing teams are heavily aided by big data analytics. The country leveraged its digital national health insurance database and integrated it with its immigration and customs database to generate real-time alerts during a clinical visit based on travel history and clinical symptoms to aid case identification. The government also creates real-time digital updates alerting citizens to avoid locations where infections had been detected. Once confirmed cases are identified, close contacts are traced, and then digital fencing is utilised to ensure mandatory quarantines. The example of case 19 indicates that from the active tracing of this person [a sweep of cases that showed influenza symptoms but tested negative for influenza] to tracing and testing their close contacts (mostly family members) 48-72 hours transpired.	
Isolation[93]	The government enforces a mandatory 14-day home quarantine through a mobile-based location-tracking application that essentially geofences those at high risk (travellers from high risk areas, close contacts of suspected or confirmed cases). Home quarantines are monitored by the police and flouting these rules can result in heavy fines.	
Facilitators[94] [95]	Taiwan effectively delayed and contained community transmission as a result of its preparedness owing to the SARS outbreak (including outbreak simulations), early and multisectoral response, transparent communication, big data analytics, and digital tracking. Public acceptance of its protective policies has been influenced by the SARS experience.	
Challenges	Taiwan will have to expand its testing criteria as community transmission spreads. Concerns have been raised regarding the digital tracking of those under quarantine as well as the heavy fines imposed. Finally, it is unclear if the current intensive nature of Taiwan's response can be maintained until the end of the epidemic.	

[91] Wang C., Ng C. and Brook R. (2020). Response to COVID-19 in Taiwan: Big Data Analytics, New Technology, and Proactive Testing. JAMA. 323, 14:1341-1342. (doi:10.1001/jama.2020.3151)

[92] Tech UK (2020) How Taiwan used tech to fight covid 19, 31 March 2020. Available at: https://www.techuk.org/insights/news/item/17187-how-taiwan-used-tech-to-fight-covid-19

[93] Bennett D. (2020) From phone-tracking to drive-thru testing: How Taiwan and Korea are crushing the COVID-19 crisis. ABS-CBN, 21 March 2020. Available at: https://news.abs-cbn.com/ancx/culture/spotlight/03/21/20/from-phone-tracking-to-drive-thru-testing-how-taiwan-and-korea-are-crushing-the-covid-19-crisis

[94] Kluth, A. (2020) Taiwan offers the best model for coronavirus data sharing. Bloomberg, 22 April 2020. Available at: https://www.bloomberg.com/opinion/articles/2020-04-22/taiwan-offers-the-best-model-for-coronavirus-data-tracking

[95] _Lin C, Braund WE, Auerbach J, Chou J-H, Teng J-H, Tu P, et al. (2020) Policy decisions and use of information technology to fight 2019 novel coronavirus disease, Taiwan. Emerg Infect Dis. (doi: 10.3201/eid2607.200574)

Singapore		
Total population	5.6 million	
Date of first reported case of COVID-19[96]	23 January 2020	
Epidemiological situation	Confirmed: 26,098 Deaths:21 Recovered: 5973	
Testing[97] [98] [99]	Who gets tested?	Any individual (citizens, migrants, visitors) who are symptomatic, or have been in contact with a confirmed case, or are at high-risk including healthcare workers and those with pneumonia regardless of symptoms.
	What kind of tests are being used?	PCR test. Singapore developed its first rapid diagnostic test in early February and since March, ten companies have received provisional government authorisation for COVID-19 tests that can be supplied to healthcare institutions, private hospitals, medical clinics and clinical laboratories.
	Where are tests conducted?	• Public hospitals • Public Health Preparedness Clinics (GPs)
	What is the daily testing capacity?	As of May 10, Singapore has tested 224,262 individuals, which accounts to 39,319 tests per million.

[96] Ministry of Health, Government of Singapore (2020) Official Update of COVID -19 Situation in Singapore. 29 March 2020. Available at: https://experience.arcgis.com/experience/7e30edc490a5441a874f9efe67bd8b89

[97] Singapore Ministry of Health (2020) Disease Outbreak Response System Condition, available at: https://www.moh.gov.sg/covid-19

[98] Fisher, D. (2020) Why Singapore's coronavirus response worked – and what we can all learn. The Conversation. 18 March 2020. Available at: https://theconversation.com/why-singapores-coronavirus-response-worked-and-what-we-can-all-learn-134024

[99] Lin, RJ., Lee, TH. And Lye, DCB (2020) Preprint: From SARS to COVID-19: the Singapore journey. Medical Journey of Australia, 6 April 2020, available at: https://www.mja.com.au/journal/2020/sars-covid-19-singapore-journey

Contact tracing[100] [101]	Public health staff have been working in partnership with police and detectives from the Criminal Investigation Department, in teams of 10, for 7 days a week, to trace, test and isolate contacts of patients with COVID-19. These teams have been using interviews, CCTV analysis, and the recently launched government mobile application 'Trace Together' for contact tracing. The government encourages the public to download this application on their mobile phones, which then uses Bluetooth technology to track and identify close contacts of a patient with COVID-19, including timestamps. Individual patients can choose to allow the Ministry of Health to access the data in the application to identify close contacts.
Isolation[102] [103]	Since 27 January, people returning to Singapore from hot zones (countries with widespread community transmission) were given a 'leave of absence', where they don't go to work but can leave their homes for meals and necessities. From 28 January, suspected carriers are being given a 'quarantine order' (QO) and have to be isolated at home or a government facility. On 18 February, the government announced the 'stay at home notice' (SHN), wherein all Singaporeans have to stay at home for 14 days and can leave their residence to purchase daily necessities and attend to important personal matters. Those who flout SHN or the QO may face penalties and can be prosecuted under Section 21A of the Infectious Disease Act. Singaporeans can also calculate the number of days of social distancing based on their arrival in the country, using a government-based website.
Facilitators	Multisectoral task force, early response, targeted testing and rigorous contact tracing, and timely and transparent communication have served as facilitators.
Challenges[104] [105]	It appears that Singapore was slow to test in the crowded dormitories leading to a large cluster of cases among migrant populations. Government enforced social distancing is difficult to follow in such crowded settings. More than half of the 43 registered dormitories have reported active viral clusters. The government has now responded by placing medical teams within the dormitories and enforcing quarantines.

[100] Teo YY. (2020) A systems-level approach to COVID-19 outbreak in Singapore. Usher Institute COVID-19 Webinar Series. 26 March 2020. Available at: https://www.youtube.com/watch?v=wNXvJ1v1_CU

[101] Ministry of Health, Government of Singapore (2020) Help speed up contact tracing with TraceTogether. 21 March 2020. Available at: https://www.gov.sg/article/help-speed-up-contact-tracing-with-tracetogether

[102] Hsu, L and Tan, M. (2020) What Singapore can teach the U.S. about responding to COVID-19. Stat News. 23 March 2020. Available at: https://www.statnews.com/2020/03/23/singapore-teach-united-states-about-covid-19-response/

[103] Ministry of Health, Government of Singapore (2020) Help speed up contact tracing with TraceTogether. 21 March 2020. Available at: https://www.gov.sg/article/help-speed-up-contact-tracing-with-tracetogether

[104] The Guardian (2020) Singapore outbreak surges with 3000 cases in three days, 21 April 2020. Available at: https://www.theguardian.com/world/2020/apr/21/singapore-coronavirus-outbreak-surges-with-3000-new-cases-in-three-days

[105] Asia Unbound (2020) Singapore and COVID-19: Strengths, Shifts, and Limits of National Response, 21 April 2020, available at: https://www.cfr.org/blog/singapore-and-covid-19-strengths-shifts-and-limits-national-response

New Zealand		
Total population	4.88 million	
Date of first reported case of COVID-19	28 February 2020	
Epidemiological situation[106]	Confirmed: 1498 Deaths:21 Recovered: 1421	
Testing[107 108]	Who gets tested?	Any individual with symptoms can be tested, including health workers and those at high risk. Random community testing started in April.
	What kind of tests are being used?	PCR tests.
	Where are tests conducted?	• Public health facilities • Mobile clinics (set up for community testing in settings such as supermarkets and car parks)
	What is the daily testing capacity?	As of May 13 2020, there have been 209,613 tests completed in total. Tests per million: 42,061
Contact tracing[109 110]	New Zealand has 12 public health units (PHU) that manage health services for clusters of its districts. Contact tracing is conducted by each PHU, which is supported by the centralised 'National close contact service' (NCCS) hub that sits within the Ministry of Health and has been operational since 24 March. PHUs continue to receive notifications of new confirmed or probable cases from laboratories and clinicians. PHUs experiencing heavy workloads can choose to divert parts of the workflow to the NCCS. PHUs inform the case of their result, arrange their home-isolation and identify close contacts.	

[106] Ministry of Health New Zealand (2020) COVID-19 - current cases. Available at: https://www.health.govt.nz/our-work/diseases-and-conditions/covid-19-novel-coronavirus/covid-19-current-situation/covid-19-current-cases

[107] Government of New Zealand (2020) Prime Minister's remarks on COVID-19 alert level decision, 20 April 2020. Available at: https://www.beehive.govt.nz/speech/prime-minister%E2%80%99s-remarks-covid-19-alert-level-decision-%E2%80%93-april-20

[108] Hayward, M. and Lines-MacKenzie, J. (2020) Coronavirus: Wider COVID-19 testing starts in Christchurch, Waikato, Stuff.co.uk, 17 April 2020. Available at: https://www.stuff.co.nz/national/health/coronavirus/121074955/coronavirus-wider-covid19-testing-starts-in-christchurch-community

[109] Ministry of Health, New Zealand (2020) Rapid Audit of Contact Tracing for COVID-19 in New Zealand, 10 April 2020. Available at: https://www.health.govt.nz/system/files/documents/publications/contact_tracing_report_verrall.pdf

[110] RNZ (2020) COVID-19: New Zealand contact tracing app due within two weeks, 27 April 2020, Available at: https://www.rnz.co.nz/news/national/415214/covid-19-new-zealand-contact-tracing-app-due-within-two-weeks

	Close contacts who live with the index case are managed by the PHU. Other contacts can be transferred to the NCCS for tracing. These lists of close contacts, which take various forms, are forwarded to the NCCS either via entry into REDCap (an existing web-based database used by some Public Health Units), secure file transfer, or email. The NCCS has developed a 'finding service' that seeks contact information from various health and other government datasets. NCCS staff call close contacts and advise they are contacts of a COVID-19 case and obtain the contacts' agreement to quarantine (commonly called self-isolation). As of April, contact tracing application is in the process of being developed.
Isolation[111]	Apart from self-isolation for close contacts of suspected or confirmed cases, on March 23, New Zealand imposed a lockdown requiring all citizens except essential workers to stay home at all times, unless they are accessing vital services or walking for exercise.
Facilitators[112]	Strong government leadership, early and coordinated government response, transparent and empathetic communication have been the major facilitators for ensuring New Zealand's test-trace-isolate strategy.
Challenges[113]	Logistical hurdles of sourcing kits and testing materials, challenges in contact tracing (to be offset by increased funding and staffing) and public breaches of lockdown measures have been reported as issues.

[111] Government of New Zealand (2020) Staying at Home and Self-isolation guidance, available at: https://covid19.govt.nz/individuals-and-households/health-and-wel being/staying-at-home-and-self-isolation/#self-isolation-advice-if-you%E2%80%99re-unwell

[112] Brockett, M. (2020) New Zealand seeks to wipe out virus after early lockdown success, Bloomberg, 16 April 2020. Available at: https://www.bloomberg.com/news/articles/2020-04-16/new-zealand-seeks-to-wipe-out-virus-after-early-lockdown-success

[113] BBC (2020) Coronavirus: How New Zealand relied on science and empathy, 16 April 2020. Available at: https://www.bbc.co.uk/news/world-asia-52344299

Iceland		
Total population	3,64,164	
Date of first reported case of COVID-19[114]	28 February 2020	
Epidemiological situation	Confirmed: 1802 Deaths:10 Recovered: 1780	
Testing[115 116 117 118]	Who gets tested?	Targeted testing of persons living in Iceland who are at high risk for infection (mainly those who are symptomatic, with travel history to risk areas, or had contact with infected persons) began on 31 January. This targeted approach is supplemented with mass population screening (initiated on 13 March) using two strategies: issuing an open invitation to 10,797 persons and sending random invitations to 2283 persons. Nearly 50% of positive cases are asymptomatic.
	What kind of tests are being used?	PCR tests. Screening for antibodies started on 8 April 2020.
	Where are tests conducted?	• Symptomatic and those at high risk are tested at the national public hospital • Mass screening conducted in clinics by biopharma company deCODE genetics

114 Tómas, R. (2020) First Confirmed COVID-19 Case in Iceland, Iceland Review, 28 February 2020. Available at: ttps://www.icelandreview.com/news/first-confirmed-covid-19-case-in-iceland/

115 Gudbjartsson, D., Helgason, A., Jonsson, H., Magnusson, O., Melsted, P., Norddahl, G., Saemundsdottir, J., Sigurdsson, A., Sulem, P., and Agustsdottir, A., Eiriksdottir, B., Fridr ksdottir, R., Gardarsdottir, E., Georgsson, G., Gretarsdottir, O., Gudmundsson, K., Gunnarsdottir, T., Gylfason, A., Holm, H., Jensson, B., Jonasdottir, A., Jonsson, F., Josefsdottir, K., Kristjansson, T., Magnusdottir, D., le Roux, L., Sigmundsdottir, G., Sveinbjornsson, G. Sveinsdottir, K., Sveinsdottir, M., Thorarensen, E., Thorbjornsson, B., Löve, A., Masson, G., Jonsdottir, I., Möller, A., Gudnason, T., Kristinsson, K., Thorsteinsdottir, U. and Stefansson, K. (2020) Spread of SARS-CoV-2 in the Icelandic Population, New England Journal of Medicine (doi: 10.1056/NEJMoa2006100)

116 Government of Iceland Directorate of Health (2020) COVID-19 in Iceland - Statistics, available at https://www.covid.is/data

117 John, T. (2020) Iceland lab's testing suggests 50% of coronavirus cases have no symptoms, CNN, 3 April 2020, Available at: https://edition.cnn.com/2020/04/01/europe/iceland-testing-coronavirus-intl/index.html

118 Hjelmgaard, K. (2020) Iceland has tested more of its population for coronavirus than anywhere else. Here's what it learned, USA Today, 11 April 2020, available at: https://eu.usatoday.com/story/news/world/2020/04/10/coronavirus-covid-19-small-nations-iceland-big-data/2959797001/

	What is the daily testing capacity?	As of May 13, 55,075 people have been tested. The daily testing capacity is 2600. Tests per million: 151,197.
Contact tracing[119] [120]	Iceland's contact tracing team is about 160 members strong and operates from part of a hotel in the capital. This team includes public health staff, police and experts in counter-terrorism and organised crime. All individuals who tested positive for COVID-19 are contacted by telephone by a team designated by the public health authorities to track their infection and contacts. All registered contacts are interviewed by telephone, asked about their symptoms, and requested to go into 2 weeks of quarantine. Those with symptoms and those in whom symptoms developed in quarantine are tested for COVID-19. Contact tracing teams are also aided by a government-backed mobile application that was launched on 1 April.	
Isolation[121]	All individuals who test positive for COVID-19 are required to self-isolate until 10 days after fever had subsided or until they tested negative, and all contacts of these individuals are required to self-quarantine for 2 weeks. To protect the elderly and other groups who are at increased risk for serious illness, health authorities promoted self-isolation and banned visits to nursing homes and hospitals. Icelanders returning to the country must also go into quarantine.	
Facilitators	Early response, public-private partnership for wide scale testing and transparent government communication have been the key facilitators for Iceland's success in containing COVID-19.	
Challenges[122]	Logistical issues such as a shortage of tests at certain points have acted as barriers for Iceland's control and tracing efforts.	

[119] Clifford, M. (2020) Coronavirus: 'Test, trace, isolate' - Iceland PM says strict strategy has controlled outbreak, Sky News, 27 April 2020, available at: https://news.sky.com/story/coronavirus-test-trace-isolate-iceland-pm-says-strict-strategy-has-controlled-outbreak-11979125

[120] Logadóttir, F. (2020) An infection tracking app goes live on April 1st, Frettabladid, 31 March 2020, available at: https://www.frettabladid.is/frettir/smitrakningarapp-fer-i-loftid-fyrsta-april/

[121] See Gjudbarsson et al in footnote 113

[122] Ćirić, J. (2020) Iceland Slows COVID-19 Testing Due to Shortage of Swabs, Iceland Review, 23 March 2020, available at: https://www.icelandreview.com/society/iceland-slows-covid-19-testing-due-to-shortage-of-swabs/