COVID-19 Evidence Update

COVID-19 Update from SAHMRI, Health Translation SA and the Commission on Excellence and Innovation in Health

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Contact Tracing and COVID-19

Executive Summary

This review covers available evidence on the topics of COVID-19 and contact tracing effectiveness, contact tracing strategies (forward; backward; multi-generational; digital), workforce skills, responses with priority and vulnerable populations and international examples of successes and failures in contact tracing.

Body of evidence: The search yielded 127 papers. 52 papers were classified as in scope for this evidence update, of which 25 (48%) were peer reviewed publications. There were 5 systematic reviews, 16 modelling studies, 31 observational studies, commentaries and reports. The World Health Organization [1], the US Centres for Disease Control and Prevention [2] and the European Centre for Disease Prevention and Control [3] have released contact tracing instructions and guidelines.

Key findings:

- Nearly all studies that have assessed effectiveness (observational and modelling) indicate that **contact tracing**, in combination with other strategies (e.g. testing, isolation, social distancing), **is associated with better control of COVID-19.**
- Contact tracing has the most benefit when secondary cases are identified and isolated before they become infectious.
- A systematic review concluded that contact tracing effectiveness is maximised when the time from symptom development to isolation occurs **within 2-3 days** and **80% of close contacts are quarantined** [4].
- Contact tracing is less effective when there are delays to testing and obtaining results, when the case numbers surge beyond the capacity of the tracing system, and when most contacts cannot be traced.
- **Delays of 4+ days** or **less than 60% of contacts successfully quarantined** may not meaningfully control transmission [4].

Policy strategies that complement contact tracing:

- The effectiveness of contact tracing also depends on achieving high quarantine compliance [5].
- Limits on social gatherings can reduce the burden on contact tracing [6].
- Contact tracing multiple generations of contacts can reduce the size of an outbreak but comes at the cost of quarantining a large proportion of a local population (in essence, becoming a local lockdown).
- Physical distancing in conjunction with contact tracing may achieve similar results without needing to quarantine as many people [7].

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Technological complements

- Evidence on the effectiveness of automated or digital contact tracing is **scarce**.
- The available evidence suggests that high population uptake of apps is necessary, as both the case and the contact need to have the technology enabled, and it should be supplemented with manual tracing.
- Contact tracing apps are most useful when they allow instantaneous notification of contact with a positive case, with a rapid follow-up call by a public health official [8].
- Telecommunication provider-based measures are more efficient than voluntary-based digital tools (such as apps) [9].
- Trust in government and privacy concerns are barriers to digital tracing techniques, notably in Western countries.

International Experience:

- Contact tracing strategies have been used to control COVID-19 successfully in a number of countries, some of which are more technologically driven (e.g. South Korea, Taiwan) whereas others have invested heavily in manual contact tracing systems through the deployment of a range of people (e.g. university students) to help (e.g. New Zealand, Germany).
- Contact tracing has not worked effectively in the UK and the US for a range of reasons, including **under-resourcing**, **delays in testing and obtaining results**, **relaxing social distancing measures while extensive community transmission was still occurring.**

Prioritising groups:

- There is very little evidence discussing prioritising of different contacts. The US CDC recommend prioritising contacts when resources are scarce and provide a 4-tier hierarchy.
- Some difficulties have been reported when people have been reluctant to participate in contact tracing (e.g. outbreak in South Korea linked to nightclubs). There is an absence of evidence about novel strategies for contacts tracing during COVID-19, to minimise the impact of deliberate non-disclosure of contacts.

SUMMARY OF KEY EVIDENCE

Reviews of contact tracing effectiveness

- Juneau 2020 [4] (medRxiv preprint): Systematic review examining the effectiveness of contact tracing in the context of COVID-19. A total of 32 studies were included (14 observational, 18 modelling)
  - **Key findings**: To stop the spread of COVID-19, public health practitioners have 2-3 days from symptom onset to isolate the case and successfully quarantine at least 80% of their contacts. **Delays of 4+ days or less than 60% of contacts successfully quarantined may not effectively control transmission.**

    - *Inclusion criteria*: Only SARS-CoV-2 studies were included - abstracts, letters, protocols, preprints and other unreviewed research, and studies that were not representative of community transmission (e.g. hospitals, nursing homes, prisons) were excluded.
    - Quality of evidence judged as low due to all studies being observational or modelling in design and possible publication bias whereby results of ineffective tracing efforts were not published.
    - *Results*: **All observational studies and 89% of modelling studies reported that contact tracing** (alone or in combination with other interventions) **was associated with better control of COVID-19**.
    - *Observational studies*: **Independent contribution of tracing** (vs other interventions) **could not be assessed**. Studies were conducted in China, Hong Kong, Taiwan, Singapore, South Korea, Vietnam, France, the US, in African countries, and international comparisons.

- Authors report very little detail of the observational studies in the paper, but include a supplementary table summarising key findings. Most studies contained very little detail on how contact tracing occurred or quantified the effect. Noteworthy results included:
  - **Multi-country comparisons** (Wilasang; Davalgi): Countries with extensive testing and contact tracing showed better outcomes than those with limited testing and contact tracing.
  - **China** (Shenzhen, Bi): Contact-based surveillance was associated with 2.3 day decrease in time to confirmation and 1.9 day decrease in time to isolation.
  - **Singapore** (Ng): 53 of the first 100 COVID-19 patients were identified through contact tracing, of which 13 (24.5%) were contacted on or before the date of symptom onset.
  - **US** (Burke): First 10 travel-related COVID-19 cases had 445 close contacts, of which 2 developed COVID-19, resulting in an additional 146 close contacts [i.e. rapid increase in contacts to trace]
  - **South Korea** (Choi): Used extensive digital surveillance technologies to support their contact tracing (tracked mobile phone location data, analysed security camera footage in public and private spaces, tracked credit card statements).
  - **Hong Kong** (Wong): Some close contacts were monitored for compliance with self-quarantine using electronic wristbands.
  - **Vietnam** (Dinh): Tracing of contacts up to 5 generations.

- *Modelling studies*: Few studies assessed the unique contribution of contact tracing
  - Early data from the first outbreak in **China** showed that a combination of non-pharmaceutical interventions (NPIs) were effective; the unique contribution of contact tracing was not assessed. However, one study inferred that the number of contacts traced in Wuhan was insufficient compared to the population size and probably had limited impact on controlling the epidemic (Tang).
  - Studies from the **UK, Italy** and **Canada** showed that a combination of contact tracing, isolation and testing were effective in controlling COVID-19 (See Kucharski 2020 [6] below).
  - The quarantine rate was identified as an important factor associated with contact tracing success in numerous articles. One **US** study (Ngonghala) found only a small decrease in the burden of the pandemic at the highest level of contact-tracing during the peak.
  - Studies modelling contact tracing efforts found that tracing effectiveness depended on how many individuals in the community were infected, how fast new cases were tested and isolated, how many and how rapid their contacts were traced and quarantined, and effectiveness of quarantines in preventing further transmission. One **UK** study (Keeling) suggested that **71% of contacts** may be the minimum needed to decrease R0 to below 1. Another study using a hypothetical population (Ferretti) showed that the longer the delay in isolating cases, the greater proportion of contacts that need to be isolated (**3-day delay=ineffective; 2-day delay=80% of contacts traced and quarantined; 1-day delay=70% of contacts traced and isolated**). Two other studies (Hellewell; Peak) modelling different scenarios showed that under optimal conditions (e.g. rapid identification and quarantining of most [at least 80%] close contacts) contract tracing was effective. Hellewell also showed that achieving control within 3 months was possible (50% chance) if only 20% of contacts of 5 initial cases were traced. However, with 40 initial cases, 80% of contacts needed to be traced to get the situation under control within 3 months. **Kretzschmar [10] showed that the proportion of onward transmissions per index case that can be prevented depends on testing and tracing delays (e.g. 0-day delay=80%, 3-day delay=42%, 7-day delay=5%).**
  - Two studies modelled the adoption of a mobile phone tracing app (Yasaka; Currie), both showing that widespread population adoption was needed to obtain the greatest reduction in transmission.

- Authors proposed guidelines based on the modelling studies

Table 2—Evidence-based guidelines for effective contact tracing of COVID-19				
	Guidelines			
Dimension of contact tracing programme	Highly efficient (can stop the spread)	Less efficient (can slow the spread)	Inefficient (may not contribute meaningfully)	Evidence base
How many individuals in the community are infected	5 or less	20 or less	40+	Hellewell et al. 2020
How fast new cases are tested and isolated*	1 day or less	1-2 days	2+ days	Ferretti et al. 2020; Kretzschmar et al. 2020
How many of their contacts are traced and quarantined	80% or more	71-80%	Less than 71%	Ferretti et al. 2020; Hellewell et al. 2020; Keeling et al. 2020; Kretzschmar et al. 2020
How fast those contacts are quarantined*	1-2 days	2-3 days	3+ days	Ferretti et al. 2020; Kretzschmar et al. 2020
How effective isolations and quarantines are at preventing transmission	100%	90-100%	Less than 75%	Ferretti et al. 2020; Hellewell et al. 2020; Peak et al. 2020; Kretzschmar et al. 2020

*Delays in isolation of cases and quarantine of contacts are combined in most studies. We break them down here as distinct steps of the contact tracing process. For highly efficient tracing, they should not exceed 2-3 days.

- Anglemyer 2020 [11] (**Cochrane review**): Systematic review of digital contact tracing technologies (i.e. devices or apps that are maintained by individual users; included tools for outbreak response, proximity tracing and symptom tracking) in epidemics (e.g. COVID-19, Ebola, tuberculosis, SARS, MERS). 12 studies were included (6 cohort, all pre-COVID-19 & 6 modelling, 4 simulating COVID-19, and 2 pre-COVID-19).

  - **Key findings**: The effectiveness of digital solutions is largely unproven due to a lack of studies in real-world outbreak settings. Modelling studies provide low-certainty evidence of a reduction in secondary cases if digital tracing is used with other public health measures such as self-isolation. Cohort studies provide low-certainty evidence that digital contact tracing may produce more reliable counts of contacts and reduce time to complete contact tracing. It is unlikely that digital technologies would be the sole method of contact tracing during an outbreak;
    - **Inclusion criteria**: studies of any design, included preprints, available from 1 Jan 2000 to 5 May 2020, no language restriction.
    - **Results**: The 4 COVID-19 specific studies were Kucharski, Ferretti, Yasaka, Hinch, only the first 2 assessed change in effective reproduction number.
    - Digital contact tracing with self-isolation probably reduces the number of secondary infections, but not as much as manual contact tracing with self-isolation (Kucharski, Ferretti).
      - Kucharski: digital contact tracing would achieve an 18% reduction in *R*eff compared to self-isolation alone while manual contact tracing would achieve a 35% reduction.
      - Ferretti: 26% reduction for digital compared to self-isolation vs 53% reduction for manual tracing compared to self-isolation.
      - Neither study models a scenario of combining manual and digital tracing.
    - Digital contact tracing found more close contacts in two outbreaks than manual (for pertussis in the USA and Ebola in Sierra Leone). Devices in non-outbreak settings can identify more close contacts than self-reported diaries or surveys.
    - An app may reduce the time to complete a set of close contacts (TB in Botswana). Digital systems were faster to use than paper systems for recording new contacts and monitoring known contacts, and possibly less prone to data loss.

- Braithwaite 2020 [12] (medRxiv preprint): Rapid systematic review of automated or partially automated contact tracing; 15 studies included.
  - **Key findings**: No empirical evidence of automated contact tracing's effectiveness (regarding contacts identified or transmission reduction) was identified. Four of seven modelling studies included, suggested that controlling COVID-19 requires high population uptake of automated contact-tracing apps (estimates from 56% to 95%), typically alongside other control measures. Studies of partially-automated contact tracing generally reported more complete contact identification and follow-up, and greater intervention timeliness (0.5-5 hours faster), than previous systems.
    - *Inclusion criteria*: Interventional, observational, modelling and case studies, included COVID-19, SARS, MERS, influenza, or Ebola or hypothetical infections. Both pre-print and peer-reviewed articles were included and the search was restricted to English.
    - *Results*: 7 modelling studies addressed automated contact tracing for COVID-19; 5 studies were descriptive observational or case studies of partially-automated contact tracing (none were specific to COVID-19); 3 studies assessed automated contact detection but without subsequent tracing or contact notification.
    - One **UK** study (Kurcharski) estimated that a median of four contacts per case (mean 14) would be quarantined under automated contact-tracing, compared to 28 (mean 39) with all contacts traced manually, assuming 90% adherence to quarantine. (See Kucharski 2020 below).
    - Another **UK** study (Hinch) estimated that approximately 10-15 million people would be quarantined (assuming 100% adherence to quarantine and 80% app uptake) but did not present numbers of contacts identified per case.
    - Another study (Kim) showed that 80% app uptake might enable approx. 64% of contacts who would be notified in an optimal contact tracing system (50% uptake corresponded to 25% of contacts).
    - *Discussion*: "Uptake is particularly important since both infectious cases and their contacts need to have and be using a system for it to have any effect, leading to a quadratic relationship such that effectiveness drops off steeply as participation falls."
    - "Whether quarantine adherence differs between automated and manual systems is unknown. Automated notification might be psychologically different from receiving a phone call from a human contact tracer who can give detailed information about what action to take and why, check understanding and address questions or concerns. A previous review found adherence to be extremely variable and influenced by multiple factors, including risk perception and social and financial protections."

Modelling studies

- Kucharski 2020 [6] (Lancet Infect Dis): Modelled different contact tracing and isolation scenarios using BBC pandemic data from 40162 UK participants (data collected in 2017-18); used a model of individual-level transmission stratified by setting (household, work, school, or other).

  - **Key findings**: Combined isolation and tracing strategies would reduce transmission more than mass testing or self-isolation alone, e.g. 29% for self-isolation alone of symptomatic cases within the household vs 64% for self-isolation and household quarantine with the addition of manual contact tracing of all contacts. Limits on gatherings outside the home would mean that manual contact tracing of acquaintances alone could have a similar effect to that of detailed contact tracing of all contacts.

    - *Definitions & assumptions*: Contact=face-to-face conversation or physical contact; assumed infected individuals had a certain probability of being symptomatic and being tested if symptomatic; assumed a mean delay of 2.6 days from onset of symptoms to isolation in baseline scenario and assumed that individuals became infectious 1 day before symptom onset. Duration of infectiousness=5 days; relative infectiousness of asymptomatic cases=50%; proportion of cases who are eventually symptomatic=30% children, 70% of adults; probability that symptomatic individuals will eventually self-isolate and be tested=90%; secondary attack rate in home=20%, among other contacts=6%; proportion of contacts who are acquaintances=100% in household, 90% at school, 79% at work, 52% in other settings; proportion with app=53%.

- Secondary attack rate data sources – note, all studies were done when effective R<1 in controlled scenarios, and might omit superspreading events and isolation outside of household:

	Secondary attack rate among household contacts (%)	Secondary attack rate among close contacts outside household (%)	Contacts traced per case	Observed reproduction number
Shenzhen[16]	12·9%	0·9%	3·0	0·4
USA[21]	10·5%	0·0%	44·5	0·20
Guangzhou[22]	10·1%	0·5%	14·3	0·34
Taiwan[23]	6·6%	0·4%	27·6	0·21
Ningbo[17]	13·3%	5·1%	11·2	0·69
Guangzhou[24]	19·3%	5·3%	9·8	0·62

Table includes two separate analyses of contact tracing data from Guangzhou and differing estimates are likely to be influenced by control measures in place at the time.

***Table 2:* Secondary attack rates estimated from COVID-19 contact tracing studies by location**

- *Results*:

	Self-Isolation	Contact tracing	Non-HH contacts who are potentially traceable (%)	Cases who have R>1 (%)	R_{eff}	Mean reduction in R_{eff}
No control	No	No	NA	50%	2·6	0%
Self-isolation within home	Yes	No	NA	40%	1·8	29%
Self-isolation outside home	Yes	NA	NA	37%	1·7	35%
Self-isolation plus HHQ	Yes	HH	NA	35%	1·6	37%
Self-isolation plus HHQ plus work or school contact tracing	Yes	HH and work or school	100%	27%	1·2	53%
Self-isolation plus HHQ plus manual contact tracing of acquaintances	Yes	All	90% school, 79% work, and 52% other	26%	1·1	57%
Self-isolation plus HHQ plus manual contact tracing of all contacts	Yes	All	100%	21%	0·94	64%
Self-isolation plus HHQ plus app-based tracing	Yes	All	53%	30%	1·4	47%
Self-isolation plus HHQ plus manual contact tracing of acquaintances plus app-based tracing	Yes	All	90% school, 79% work, and 52% other with manual tracing; 53% with app tracing	23%	1	61%
Self-isolation plus HHQ plus manual contact tracing of acquaintances plus limit to four daily contacts with other individuals	Yes	All	90% school, 79% work, and 52% other	21%	0·93	64%
Self-isolation plus HHQ plus manual contact tracing of acquaintances plus app-based tracing plus limit to four daily contacts with other individuals	Yes	All	90% school, 79% work, and 52% other with manual tracing; 53% with app tracing	20%	0·87	66%
Mass testing of 5% of population per week	No	NA	NA	49%	2·5	2%

Results from 20 000 simulated setting-specific secondary transmissions, assuming a secondary attack rate of 20% among household contacts and 6% among other contacts. Results under the assumption of some workplace restrictions remaining in place are shown in table 4. Estimates are shown to two significant figures. HH=household. HHQ=household quarantine. NA=not applicable. R_{eff}=effective reproduction number.

***Table 3:* Mean reduction in R_{eff} under different control measures**

CT=contact tracing. HHQ=household quarantine. SI=self isolation.

	Median number of people quarantined per detected case (90% prediction interval)
SI and HHQ	2 (0–4)
SI plus HHQ plus work or school CT	13 (1–110)
SI plus HHQ plus manual CT of acquaintances	22 (1–120)
SI plus HHQ plus manual CT of all contacts	29 (1–140)
SI plus HHQ plus app-based CT	4 (1–69)
SI plus HHQ plus manual CT of acquaintances plus app-based CT	25 (1–130)
SI plus HHQ plus manual CT of acquaintances plus limit to four daily contacts with other individuals	17 (1–110)
SI plus HHQ plus manual CT of acquaintances plus app-based CT plus limit to four daily contacts with other individuals	21 (1–110)

- Automated tracing was not as effective as manual tracing of all contacts to reduce Reff (47% vs 61%).
- *Discussion*: "The effectiveness of manual contact tracing strategies was highly dependent on how many contacts were successfully traced... If contact tracing was combined with a maximum limit to daily contacts made in other settings (e.g, by restricting gatherings), we found that this limit would have to be small (i.e., fewer than ten or 20 contacts) before a discernible effect could be seen on Reff."
- "The effectiveness of these isolation and tracing strategies was further enhanced when combined with physical distancing measures, such as a reduction in work contacts, or a limit to the number of contacts made outside of home, school, or work settings. Not only does physical distancing reduce transmission, but it is also likely to reduce the number of unknown contacts who can be harder to trace."
- "If limits were placed on gatherings outside of home, school, or work, then manual contact tracing of acquaintances alone could have an effect on transmission reduction similar to that of detailed contact tracing."

- He 2020 [13] (Technical report, non-peer reviewed, Royal Society DELVE initiative): Uses an individual-level transmission and contact simulation model to explore the effectiveness and resource requirements of various test-trace-isolate (TTI) strategies for reducing COVID-19 transmission in the **UK**. The model builds upon the individual-level model of Kucharski (described above) and stratifies transmission by setting (household, work, school, other) using the BBC Pandemic data of 40,162 participants. **Three strategies were assessed: symptom-based contact tracing, test-based contact tracing, and additional testing of asymptomatic contacts**, all of which trade-off speed, required number of test and contacts traced, and number of person-days spent under quarantine.
  - **Key findings**:
    - TTI has a moderate effect on R and implementation along with other strategies will be necessary to control COVID-19 in the UK. Test-based TTI strategies reduce R between 10-15%, while symptom-based TTI strategies reduce R between 15-20%.
    - The most significant reduction in transmissions of a TTI system is due to **prompt self-isolation of a symptomatic case and the quarantining of their household**. **Reducing the tracing time from 5 to 3 days leads to a 60-70% improvement in effectiveness** of a test-based TTI strategy.
    - TTI performance is strongly dictated by its coverage of transmission chains and compliance of the general population with its guidance. Leakages occur from asymptomatic COVID positive cases,

symptomatic cases who do not report symptoms, imperfect contact tracing (e.g. unknown contacts to the primary case).

- Resource requirements: Symptom-based TTI has low specificity (due to high level of COVID-like symptoms in the COVID negative population) and requires significantly higher numbers of manual contact tracings and person-days quarantined. In a test-based TTI strategy, additional testing contacts has a marginal impact on R (through identifying asymptomatic COVID positive contacts) but can significantly reduce the number of person-days of contacts quarantined. However, cases may be missed if not tested at the right time.
- Limitations: Only simulates 1 generation of transmission and assumes case isolation is 100% effective; inputs regarding dynamics of COVID transmission are not yet fully understood.

- James 2020 [5] (medRxiv preprint): Modelled a range of scenarios to assess each aspect of test, trace, isolate on the effective reproductive number.
  - **Key findings**: People's ability to quarantine and isolate effectively is critical; **80% of cases need to be quarantined or isolated within 4 days of isolation of index case for contract tracing to be effective**.
    - *Definitions and assumptions*: Quarantine=separation of individuals exposed to a case but are currently asymptomatic; isolation=the separation of symptomatic or confirmed cases. Previous models have assumed that isolation is 100% effective (i.e. no further onward transmission). This study models different levels of isolation effectiveness **based on data from New Zealand**. Used a continuous-time branching process model. Key input parameters were 1) proportion of contacts successfully traced (0%, 50%, 100% traced); 2) mean time taken to trace contacts following a positive test result (0 to 6 days); 3) effectiveness of contact quarantine and case isolation in reducing onward transmission (50%, 75%, 100%). Output was reduction in R_{eff} relative to no-control scenario. Assumed that 35% of infections are subclinical and 35% of all onward transmission occurs during the pre-symptomatic phase. Model does not distinguish between different types of contact (e.g. household vs work).
    - Contact tracing schematic

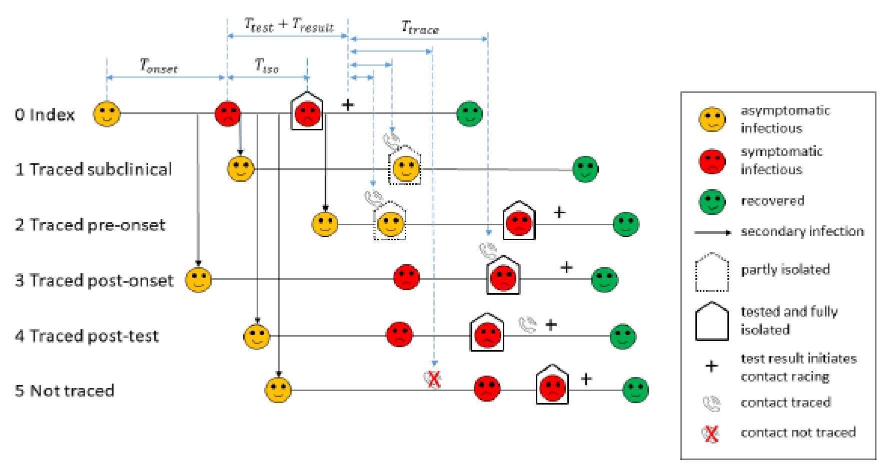

Figure 1. Schematic diagram of the contact tracing model. Infectious individuals are initially asymptomatic (yellow). For the index case who was not traced (0), there is a delay between onset of symptoms (red) and getting tested. Isolation occurs at some point between symptom onset and testing. There is a subsequent delay to the test result and tracing of contacts. Traced contacts (1-4) are quarantined when contacted by public health officials (phone icons) and isolated and tested immediately on symptom onset. Traced contacts (3) who are already symptomatic prior to being traced are isolated immediately when contacted. Traced contacts (4) that have already isolated prior to being traced are not affected. Contacts that cannot be traced (5) may still get tested and isolated, but this is likely to take longer. Asymptomatic individuals (1) do not get tested or isolated, but will be quarantined if they are a traced contact.

- *Results*: If quarantine is only 50% effective, instantaneous tracing provides the same reduction in R_{eff} as a mean tracing time of 2–3 days with 100% effective quarantine. If isolation of cases is only 50% effective, improving isolation may be more impactful than faster or more complete contact tracing. Tracing 50% of contacts with 100% quarantine and isolation effectiveness is significantly more effective than tracing 100% of contacts with 50% isolation and quarantine effectiveness.
- *Assessment of performance indicator*: While the average tracing time is the easiest parameter to measure, it is not the most robust. **A more robust performance indicator is "proportion of cases that were quarantined or isolated within 4 days of quarantine or isolation of the index case**".
- *Discussion*: "Our results show that a high-quality, rapid contact tracing system, combined with strong support systems for people in quarantine or isolation, can reduce R_{eff} by at most 60%...implying that some level of moderate social distancing will likely be required in addition to case targeted interventions."
- "The New Zealand contact tracing system is well-established and run by highly trained public health staff. Their work has been critical to the success of New Zealand's elimination strategy for COVID-19. However, even this well-established system suffers from noisy data and the difficulties of establishing index-case pairs."
- "For countries with large outbreaks where contact tracing is either not well-established or does not have sufficient capacity to deal new daily cases, our results show that improving the effectiveness of case isolation may be better strategy initially."

- Firth 2020 [7] (**Nature Medicine**): Simulated control strategies using real-world social network data.
  - **Key findings**: Tracing 'contacts of contacts' reduced the size of the simulated outbreaks more than tracing of only contacts, but a consequence was that almost half of the local population was quarantined at a single point in time. **Quarantine in conjunction with contact tracing was an effective 'local lockdown' strategy**, but **physical distancing in conjunction with contact tracing was an alternative** to controlling the epidemic without needing to quarantine so many people.
    - *Definitions and assumptions*: Used pre-COVID-19 data: the BBC 'Contagion' dataset based on a town in the UK giving 1616 daily contact events, 1257 unique social links among 468 individuals. Assumed that 10% of contact tracing attempts were missed. Sensitivity analyses were performed for different input parameters but showed similar results.
    - *Results*: An uncontrolled outbreak resulted in 75% of the population infected after 70 days. Isolation of individuals when they became symptomatic resulted in 66% of the population infected, and primary contact tracing resulted in 48% infected. Secondary contact tracing resulted in 16% of the population infected after 70 days. With secondary contact tracing, 43% of the population was quarantined during the peak of the outbreak, and a substantial proportion (26%) of the population was still quarantined during the final (tenth) week of the simulation.
    - Results suggest that contact tracing would be most effective when the proportion of traced contacts is high, when the delay from notification to quarantine is short, and when the number of starting cases and the rate of movement into the network are low. Importantly, outbreak control was only achieved when there was a large number of quarantined individuals.
    - Estimated that increasing the testing capacity (and therefore testing and releasing more quarantined individuals) led to substantial increases in outbreak size, especially under secondary contact tracing (52%), suggesting that the increase in outbreak size with high testing rates is a result of increased transmission within the network, rather than the release of infected cases per se.
    - Depending on the scenario, the highest simulated levels of physical distancing (in conjunction with contact tracing) led to reductions of between 28% and 61% in the number of overall cases, and in some scenarios, dramatically reduced the number of people needing to be quarantined.

- Moon 2020 [14] (medRxiv preprint): Developed an individual-based contact-network model and a susceptible-exposed-infected-confirmed (SEIC) model to simulate transmission of COVID-19 upon reopening (0%, 25%, 50%, 75% and 100% reopening) following a 2-month lockdown in the **US**.
  - **Key findings**: Increasing the fraction of traced contacts decreases the size of the epidemic. Tracing 20% of contacts is enough to reduce the epidemic size in half in four reopening scenarios. Considering the costs of tracing as quarantining individuals, increasing from 5% to 20% of contacts traced results in higher numbers of quarantined susceptible people, but increasing from 20% to 60% decreases the number of quarantined people because the increment in mentioned contacts is balanced by a reduced number of confirmed cases.
    - *Definitions and assumptions*: Model has only 2 unknown parameters: the reproductive ratio and confirmed case rate; uses observed confirmed case data. Assume no change except reopening from pandemic lockdown.
    - *Results*: For any reopening situation, tracing more than 60% of contacts can reduce confirmed cases by more than 96.5% if all contacts are quarantined, and by more than 92% if infected cases are quarantined.

- Bilinski 2020 [15] (medRxiv preprint): Used simple epidemic model (deterministic Markov branching) to evaluate how contact tracing might enable modification of current physical distancing restrictions. Authors based in US but not clear what data underpins the analysis.
  - **Key findings**: Testing and tracing coverage need to exceed 50% to see substantial gains; if both are below 50%, contact tracing does not reduce transmission by more than 10%. With 90% testing and tracing as well as high isolation and quarantine efficacy, contact tracing could reduce overall transmission by >45%, which would allow for partial loosening of physical distancing measures.
    - *Definitions and assumptions*: Parameters adapted from prior modelling studies; assumed that 40% of infections are asymptomatic, and that confirmed cases have 50% lower rates of transmission than unconfirmed cases, and that symptomatic cases became infectious prior to emergence of symptoms. Different scenarios were represented by the fraction of contacts successfully traced, the isolation and quarantine efficacy among traced but undetected contacts, and whether testing was restricted to those with symptoms or includes all traced contacts.
    - *Other results*: Testing asymptomatic contacts increased the benefit of contact tracing by a median factor of 1.3 and benefits were larger when isolation and quarantine was less than 90%.
    - The overall impact of contact tracing depends strongly on isolation and quarantine efficacy. Median reductions in Rt assuming isolation and quarantine efficacy of 30%, 60% or 90% were 11%, 21% and 29% respectively, for strategies that tested only symptomatic contacts, and 21%, 26% and 30% for strategies that tested all contacts. The contact tracing scenario with the greatest impact overall—defined by high levels of symptomatic detection and successful tracing, high isolation and quarantine efficacy, and testing of all contacts irrespective of symptoms—reduced Rt by 46%.
    - Also evaluated the combined effect of scaling up both testing and contact tracing against the counterfactual of persistently limited testing at 20% of symptomatic cases and 5% of symptomatic cases and no contact tracing: Accounting for both expanded testing and contact tracing together, the maximum reduction in Rt increased to 57%, and the benefits in many scenarios were at least 10 percentage points greater than the benefits of contact tracing alone.
    - With contact tracing, physical distancing measures could be applied at 52% of their current, full implementation effectiveness and still maintain the critical containment threshold of Rt<1.
    - *Discussion*: “To support containment, contact tracing must be implemented in concert with wide-scale community testing and must successfully track a high fraction of infected contacts. Our results indicate that contact tracing will support a partial relaxation of physical distancing measures but not a complete return to levels of contact prior to physical distancing.”

- Keeling 2020 [16] (J Epidemiol Community Health): This study was **included in the Juneau 2020 systematic review**; based on data from a population survey of UK residents (n=5802) reporting on social encounters in a given day, additional noteworthy findings include:
    - Each new case requires an average of 36 individuals to be traced, with 8.7% of cases having more than 100 close traceable contacts.
    - A stricter definition of a close contact (requiring more contact time) reduces the burden on the health services as fewer contacts need to be traced, but also increases the risk of cases being missed. Definitions requiring more than 4 hours of contact are unlikely to control an outbreak as the expected number of untraced second cases is greater than one. The added benefit from definitions shorter than 1 hour has relatively little impact on the mean number of untraced cases but does reduce the probability that some untraced contacts occur.
    - "For contact tracing to be an effective public health measure requires most secondary cases to be discovered and isolated before they become infectious; hence the time from the primary case becoming infectious to the tracing of their contacts needs to be shorter than the incubation period. Longer time scales would allow tertiary cases to be infected and potentially increase the scale of tracing required."

- Barrat 2020 [17] (medRxiv preprint): Combined manual and digital approach to contact tracing.
    - "The limitations of manual contact tracing (MCT), due to delays and imperfect recall of contacts, might be compensated by digital contact tracing (DCT) based on smartphone apps, whose impact however depends on the app adoption. To assess the efficiency of such interventions in realistic settings, we use here datasets describing contacts between individuals in several contexts, with high spatial and temporal resolution, to feed numerical simulations of a compartmental model for COVID-19. We find that the obtained reduction of epidemic size has a robust behaviour: this benefit is linear in the fraction of contacts recalled during MCT, and quadratic in the app adoption, with no threshold effect. The combination of tracing strategies can yield important benefits, and the cost (number of quarantines) vs. benefit curve has a typical parabolic shape, independent on the type of tracing, with a high benefit and low cost if app adoption and MCT efficiency are high enough. Our numerical results are qualitatively confirmed by analytical results on simplified models."

- Huang 2020 [18] (medRxiv preprint): Estimated effectiveness of contact tracing measures in **Singapore**.
    - **Key findings**: Based on analysis of 247 cases, contact tracing and self-awareness (known exposure to confirmed case or cluster) helped to reduce the delay from onset to isolation by an average of 2-4 days, which helped to reduce the average number of secondary cases.
    - Limitations are similar to other models described above (e.g. many inputs are estimates)

- Reich 2020 [19] (medRxiv preprint): Used an SEIR agent-based model to simulate variations in testing and tracing parameters: time from symptom onset until a patient is self-isolated and tested, the share of contacts of a positive patient who are successfully traced, and time of test analysis and contact tracing.
    - **Key findings**: Success of contact tracing is determined by increasing the share of contacts traced and reducing symptom onset to test time.
    - Limitations are similar to other models described above.

Contact tracing strategies (multiple generations, forward & backward tracing, digital)

- Nguyen 2020 [20] (Int J Tuberc Lung Dis): Based on **evidence from TB**, and applicable to low community transmission settings, recommends a framework for testing that includes second and third degree close contacts [F0 is index case, F1 is close contact of index case, F2 is contact of F1 and F3 is a contact of F2]:

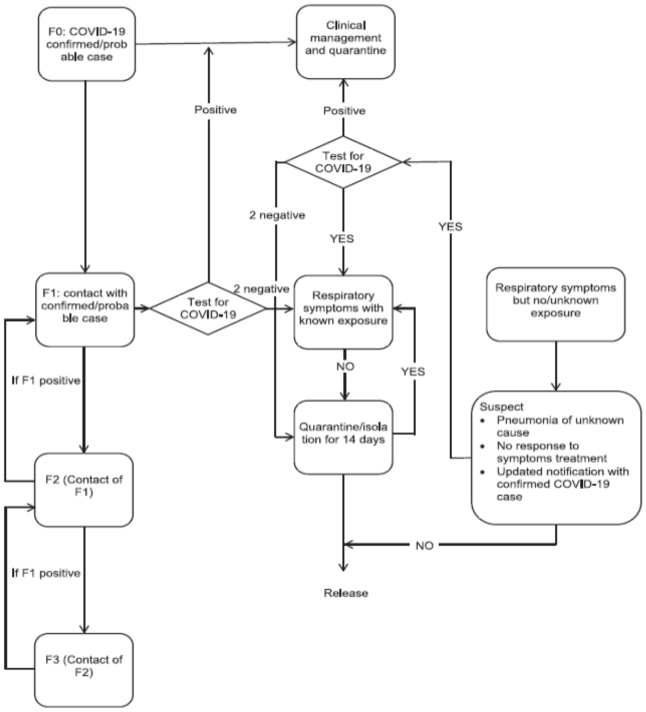

Figure Algorithm for investigation of COVID-19 contacts and symptomatic suspect cases.

- Bradshaw 2020 [21] (medRxiv preprint): Uses a stochastic branching-process model to compare the common 'forward-trace' protocol to the relatively uncommon 'bi-directional' tracing protocol.
  - **Key findings**: Bi-directional tracing robustly improves outbreak control, reducing the effective reproduction number by at least 0.3 while dramatically increasing resilience to low case ascertainment and test sensitivity. Adding smartphone-based exposure notification can further reduce R_{eff} by 0.25 but only if nearly all smartphones can detect exposure events.
    - *Assumptions*: 10% of transmission was assumed to be environmental (and therefore untraceable), 48% of transmission occurred pre-symptomatically, and 45% of cases were asymptomatic with reduced (50%) infectiousness. For the initial analysis we assumed a fixed basic reproduction number (R0) of 2.5. Other more optimistic and pessimistic values were also used.
    - *Results*: Manual forward tracing of contacts occurring up to 48 hours before symptom onset reduced R_{eff} but not enough to control the epidemic; extending tracing window to 7 days prior to symptom onset yielded a moderate improvement, and switching from forward-only to bidirectional tracing yielded a similar improvement gain. Digital exposure notification produced markedly superior outcomes, especially when using bidirectional tracing. However, even a small decrease in the proportion of individuals participating in digital tracing resulted in fragmentation of the tracing network, making R_{eff} comparable to, or even worse than manual tracing alone.
    - A hybrid approach whereby 80% of cases participated in the digital system, supplemented with bidirectional manual digital tracing substantially improved epidemic control.
    - Bidirectional tracing is robust to low case ascertainment and test sensitivity.
    - Hybrid bidirectional tracing robustly outperformed all other tracing strategies, with the greatest degree of outperformance observed when $1.75 \le R_0 \le 3.5$. When $R_0 \le 1.75$, manual and hybrid tracing both

achieved nearly 100% control, while when R 0 ≥ 3.5, no strategy achieved control probabilities over 10%. Even in these low-control scenarios, however, hybrid bidirectional tracing consistently reduced R_{eff} by roughly 20% relative to manual tracing alone.

- Endo 2020 [22] (medRxiv preprint): Used a branching process model to **compare the performance of forward and backward contact tracing** triggered by an index case found by symptom-based surveillance. Backward tracing first identifies the primary case that infected the index case to identify undetected cases at the same generation level as the index case, and then applies forward contact tracing.
  - Backward tracing has the potential to identify a large proportion of infections because of the observed overdispersion in COVID-19 transmission (i.e. super-spreaders).
  - Backwards tracing increases the maximum number of traceable individuals by a factor of 2-3, as index cases are more likely to come from clusters than a case is to generate a cluster.

- Davalbhakta 2020 [23] (J Med Sys): **Overview of mobile apps** currently utilised for COVID-19: identified 63 apps, of which 8 were dedicated to contract tracing and 9 included a contact tracing feature. Ten studies were identified that assessed the utility of smartphone applications and most focussed on app development, demonstrating that the development of a privacy preserving contact tracing technology enabled by a smartphone app is possible, but not evaluating its use in practice. One app (The COVID-19 symptom tracker) was evaluated for effectiveness.
  - Apps developed in the West tended to focus on information dissemination, with very few contact tracing or symptom checking apps. On the contrary, most apps developed in India have been created with the main purpose of contact tracing, or symptom checking. However, concerns about privacy and ethics have created issues with use.

- Vaithianathan 2020 [8] (report, not peer reviewed): A **primer for policymakers on digital contact tracing** for COVID-19. The rapidity and perfect scalability of digital contact tracing make it superior to manual contact tracing, however, digital contact tracing has to enable notification of contacts the instant a user becomes positive. Ideally, with a rapid follow-up call by public health officials. A number of contact tracing apps currently deployed, such as the **Australian COVIDSafe app**, do not allow instantaneous notification and are therefore very limited in their ability to achieve control. Digital tracing apps also require sufficient uptake to realise the benefits.
  - **South Korea** and **China** have used **mobile-phone and GPS data** to find contacts who were proximate to the index-case, often **without consent**.
  - Countries with strong traditions of individual liberty have explored low-energy Bluetooth technology rather than geo-location data.
  - The Bluetooth-based apps used in **Australia** and **Singapore** have limited functionality – they do not allow automated notification of contacts but are intended to make the job of manual tracing easier. As such, they offer **more comprehensive tracing** than manual systems alone, but are **not expected to greatly enhance speed**.
  - **Speed of contact tracing is more important early in the infection period than later**: reducing contact tracing from 4 to 2 days (with an R0 of 2.5) avoids 1 additional infection whereas the reduction from 8 to 6 days avoids less than 0.5. **Contact tracing after 8 days provides little additional protection against first-order transmission** (although may still help prevent second and subsequent order transmissions).
  - Digital contact tracing is beneficial if it speeds up isolation, but depends on high uptake, so may be best used in conjunction with manual tracing. For example, with 50% uptake of digital tracing app, then approx. 25% will be automatically notified (50% squared as both parties must have the app installed). The remaining 75% will need to be traced manually, as quickly as possible.

- A question for policymakers is whether it is easier to achieve a 60% uptake of digital and a 4 day manual tracing target or achieve manual tracing alone within 72 hours (which will become more difficult as cases grow or social-distancing rules are eased).

- Bianconi 2020 [24] (Phys Biol): Demonstrates that countries (**China, South Korea**) that selected and adopted advanced technologies (Lockdown, case finding, mandatory mobile phone contact tracing) **have been better at reducing both the peak and width of the epidemic dome** than countries that did not adopt mandatory mobile contact tracing and instead used the Lockdown Stop and Go policy (Italy, France, Spain, UK, USA).

- Altmann 2020 [25] (medRxiv preprint): An anonymous survey run in **France, German, Italy**, the **UK** and the **US** (n=5995) showed that there was strong support for contact tracing apps that automatically notified users of being in contact with a known COVID-19 case. Potential barriers to adoption were concerns about cyber security and privacy and lack of trust in government.

- Kurita 2020 [26] (medRxiv preprint): Assessed the effectiveness of COCOA, a contact reporting app used in **Japan**, compared to 'voluntary restrictions against going out' (VRG). Results indicated that COCOA alone is insufficient to halt an outbreak, however if VRG were about 15%, then 10% COCOA use by a population can reduce the reproduction number to less than one.

- Agbehadji 2020 [27] (Int J Environ Res Public Health): Reviewed potential models of nature-inspired computing, artificial intelligence and big data for contact tracing as a way of improving the efficiency and effectiveness.

- Chen 2020 [28] (J Med Internet Res): Used big data analytics (using digital technology, sensor data, claimed health insurance data) to track 627,386 Taiwanese people who potentially had contact with more than 3000 cruise ship passengers after a 1-day excursion to **Taiwan** on Jan 31 2020. Numerous locations where the cruise ship passengers may have visited were first identified by using passive mobile positioning data. Potentially exposed persons were sent syndrome monitoring and self-quarantine information via SMS messaging to their phones for mitigating the possible community spread. No confirmed COVID-19 cases in this contact population were ascertained.

- Currie 2020 [29] (Public Health Res Prac): Assessed the potential contribution of the **COVIDSafe app in Australia**. Used Australian data to develop a system dynamic model (SEIR) to project future case counts under five scenarios that varied social distancing, testing, and uptake of the COVIDSafe app. The results show that app uptake of 27% may reduce case counts by 24% in the baseline scenario (decline of social distancing of 50% and decline in testing intensity of 5% every month). Greater reductions were observed with greater app uptake (40% app uptake=32% decline in case numbers; 61% uptake=55% decline). There were different rates of change depending on easing of social distancing and testing. The authors concluded that the maintenance of large-scale testing and maintaining social distancing was vital, and the COVIDSafe app is potentially valuable as an adjunct to testing and social distancing.

- Fateh-Moghadam 2020 [30] (medRxiv preprint): Developed open-source software ("Covid-19") to standardise data collection and facilitate surveillance of contacts and outbreaks and map the links between cases and contacts. The surveillance platform collected information on the contacts of confirmed and probable cases, collected by telephone interviews following a standard questionnaire. Note: setting was Italy during lockdown.
  - *Results*: 6,690 contacts were linked to 2,812 cases (mean 2.3 contacts per case; median 1, range 1 to 42). Over half of contacts (56%) were living in the same household.

- Although diligent efforts were made to trace contacts, community spread was not fully controlled and became increasingly difficult as the epidemic peaked. These findings suggest the need for an integrated data system where case information and laboratory results can be instantly notified, case investigations begun in a more timely way, and thus contact tracing also implemented earlier in the course of illness when the contacts may be transmitting to others. Surge capacity will be needed, however, since as the number of cases increases, the burden of work is likely to become rapidly overwhelming.

Digital systems in high risk settings

- Wilmink 2020 [31] (JMIR Public Health Surveill): Demonstrated the benefit of a specially developed digital contact tracing system that allows users to rapidly identify and isolate close contacts, store and track infection data, and identify contaminated rooms, for use in nursing homes and long term care facilities where manual contact tracing processes may be too slow.

- Ho 2020 [32] (J Med Internet Res): Compared real-time locating system (RTLS; i.e. radio-frequency identification tracking using tags and wireless readers) and electronic medical record (EMR) as methods of contact tracing at a hospital in **Singapore**. Results: Of 796 potential staff-patient contacts (between 17 patients and 162 staff members), 104 (13.1%) were identified by both the RTLS and EMR, 54 (6.8%) by the RTLS alone, and 99 (12.4%) by the EMR alone; 539 (67.7%) were not identified through either method. Compared to self-reported contacts, EMR reviews had a sensitivity of 47.2% and a specificity of 77.9%, while the RTLS had a sensitivity of 72.2% and a specificity of 87.7%. The highest sensitivity was obtained by including all contacts identified by either the RTLS or the EMR (sensitivity 77.8%, specificity 73.4%).

- Breeher 2020 [33] (Mayo Clin Proc): Newly developed electronic tools, additional expertise, and organisation into functional teams were able to reduce time from case identification to completion of exposure investigation to under 2 hours in a large multistate health system in the US.

Strategies for determining contact tracing effectiveness

- Mettler 2020 [34] (Int J Infect Dis): Proposes the use of the 'Diagnostic serial interval' (i.e. time between the diagnosis dates of the infector and infectee, based on PCR testing rather than symptoms). Short diagnostic serial intervals imply faster identification and isolation of new infection events and therefore less time for further transmission. Based on data from **South Korea**, the diagnostic serial interval was estimated to be 3.63 days (95% CI: 3.24, 4.01), which was shorter than the clinical onset serial interval. The short diagnostic serial interval in South Korea is likely due to the country's extensive contact tracing effort, meaning that potential infectees are identified prior to the onset of symptoms, thereby reducing the likelihood of further transmission.

Vulnerable populations

- Close 2020 [35] (**NEJM**): Describes a situation where **crowded home environments** were part of life for Indigenous Americans in Rural Arizona. As self-isolation was nearly impossible, the contact tracing team prioritised identifying high-risk patients (mostly grandparents and great-grandparents) who would benefit from early intervention and performed rapid testing of newly identified contact. Public health nurses called high-risk people throughout the incubation period to verify that they remained asymptomatic. **Visiting households** of high-risk people also resulted in everyone in the household getting assessed, resulting in the identification of cases that would have otherwise been missed. **This approach is staff-intensive**.

- Imbert 2020 [36] (Clin Infect Dis): **Homeless shelters** have high risk of transmission and there is limited utility in a public health response that focusses solely on identifying bedmates within six feet and reported close contacts due to vague close contact descriptions. Instead, **mass testing** may be a more effective response.
- Baggett 2020 [37] (Public Health Reports): Contact tracing efforts were reduced as the number of new COVID-19 cases among **homeless people** increased (Boston, **US**), based on the assumption of universal exposure across large congregate living environments. Instead **isolation and management of cases** was prioritised.

How other countries have implemented contact tracing

- Chung 2020 [9] (medRxiv preprint): **Rapid systematic review** and case study on test, contact tracing, testing, and isolation (TTI) policies for COVID-19 prevention and control; 48 studies included. Summarised different approaches taken across different countries.
    - **Telecommunication provider-based measures are more efficient than voluntary-based digital tools (such as Apps)**. Democratic nations adopt provider-based measures openly discuss its surveillance architectures, while less democratic nations tend not to or hide such information from the public. Types of telecommunication provider-based measures may include:
        - Mapping the amount of anonymized cell phone movement in a particular area (**Germany, Austria, Italy**)
        - Base station triangulation to approximate cell phone location (**Taiwan**)
        - Access the A-GPS data generated by the phone (**Israel**)
    - Voluntary provision of data including:
        - App recording device within a contact range via Bluetooth technique (**Singapore, Austria**)
        - App recording daily symptoms (**South Korea, Taiwan, Poland**)
        - QR code for entry or exit places (**China**).

- Klimburg 2020 [38] (Hague Centre for Strategic Studies): **Case studies of contact tracing.**
    - **Taiwan**: Provider-based mobile phone tracking, linking of databases, and segmenting of risk categories to streamline processing. Has extensive system of CCTV, has national health insurance databased which includes smart cards that track patient identity and medical history. Has dedicated outbreak response unit (arose from SARS experience). The Taiwanese approach has also been characterized by the **merging of datasets**, such as intersecting its National Health Insurance database with its immigrations and customs dataset.
    - **South Korea**: Characterized by high reliance on **GPS tracking** and location-based apps and widespread testing capabilities, supplemented by provider-based efforts; collaboration between its main telecom companies and law enforcement agencies, has a long history of domestic surveillance stemming from past military dictatorships. Example of an app is "Corona 100m", which makes use of provider-based (telecom) data and alerts users if they come within 100 meters of a location visited by an infected person.
    - **Singapore**: Characterized by **individual case tracing of contacts including the use of QR codes and making public exposure maps**. Singapore has publicly applied phone-based travel data tracking in conjunction with CCTV to back-track infection vectors. It follows a similar trajectory to South Korea, with **patient interviews and a review of CCTV footage**. In so-called "close contact" or otherwise "difficult" cases the patients may be asked to **voluntarily provide their mobile phones** so as to be able to extract historic GPS movement data and retrace subjects' movements. Singapore has put great public emphasis on the voluntary provider-based information. Singapore has made extensive use of

QR codes at all public buildings and most transport nodes (including taxis) to facilitate contact tracing if needed.
    - **China**: Considered to have one of the world's most elaborate internal surveillance capacities using vast systems of **artificial intelligence, CCTV and facial recognition technology, telecommunication monitoring** (both Internet access as well as cell-phone location tracking) and comprehensive bio-metric data to keep track of its citizens. Many of these measures were already bundled together under the **"Golden Shield" program**. The most well-documented case of app usage in China is the Alipay "Health Code" that uses color-coded QR systems for contact tracing and is effectively mandatory for any kind of movement.
    - **Israel**: Announced on March 18 an **emergency law** to allow for the use of the country's comprehensive **domestic surveillance apparatus** to combat the spread of the coronavirus. Telephone providers have been able to fully map **individual mobile phone user movements** at a very high level of detail. Also has "HaMagen" app, Hebrew for "The Shield". The voluntary app uses a phone's location history over the past 14 days and cross-references it with data from the epidemiological investigations of existing cases to determine if close contact was made.

- Choi 2020 [39] (Int J Environ Res Public Health): **South Korea**'s contact tracing approach combined self-report with digital surveillance technologies: **mobile phone data** (including location information), **credit card statements** and **security camera footage**.
    - Public health authorities conducted in-depth investigations on hotspots, which did not always go smoothly (e.g. outbreak in **nightclubs popular among LGBT communities** – almost 2000 club patrons left **false or incomplete contact information or avoided follow-up calls**. Digital tracing was used instead but was ill-received).

- Reintjes 2020 [40] (BMJ, editorial): Reports on contact tracing in **Germany**
    - Contact tracing is the responsibility of local health authorities at city or county level, with support from state and national health departments when necessary.
    - **Civil servants were redeployed to public health** from elsewhere and extra staff employed to support local contact tracing. Inexperience was overcome by embedding them in experienced organisational structures.
    - As lockdowns were being lifted, authorities determined that there should be **five contact tracers for every 20,000 citizens.**
    - Technological solutions, including an anonymised and decentralised contact tracing app, were deployed, but privacy concerns led to a delay.

- Verrall 2020 [41] (report, non-peer reviewed): Rapid audit of contact tracing for COVID-19 in **New Zealand**.
    - The capacity of the 12 public health units (PHU) is the primary factor limiting New Zealand's ability to scale up its contact tracing response. In March, the workload exceeded their capacity on occasion, even though case numbers were less than 100 per day.
    - The 'National close contact service' (NCCS) hub, together with a technology solution (NCTS; cloud-based platform repurposes case management software designed for the National Screening Unit), was established to perform contact tracing at times of high demand. In this new model 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. Close contacts who live with the index case are managed by the PHU. Other contacts can be transferred to the NCCS for tracing. 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.
    - Initially, the timeliness of the process was poor with average time from referral to isolate being 2.3 days, but this was likely due to staff training and software changes.
    - Another concern was that only 60% of contacts could be easily reached by phone
    - Strategies, such as follow up text messages and using other contact information sources were utilised to improve the system.

- Sulaiman 2020 [42] (medRxiv): **India** – 250,000 volunteers were used for contact tracing. For the 300 positive cases reported in Kerala in April, close to 175,000 people were traced and quarantined.

- Nachega 2020 [43] (Clin Infec Dis): Contact tracing is a key strategy in various **African countries** including South Africa (provincially-based telephone teams), Rwanda, DRC, and Tanzania (CHCWs using mobile phone calls and SMS and home visits if necessary), Mozambique (done by skilled and trained health and medical staff and students).

Failures in contact tracing

- Baraniuk 2020 [44] (**BMJ; commentary**): Discusses different contact tracing approaches, from European perspective, particularly the **UK**.
    - Suggests that locally responsive contact tracing teams are better able to identify who in the local community are most vulnerable, but this was not possible in the UK because of the dismantling of the local health infrastructure and the reliance on centralised contact tracing.
    - Approaches taken in places like South Korea would be considered far too intrusive.
    - In Europe, most countries are working to expand the manual contact tracing workforce (e.g. Ireland is seeking to increase from 2000 calls a day to 5000 a day).
    - The UK conducted contact tracing until 12 March when it **stopped due to a lack of capacity** in the face of skyrocketing cases. The new contact tracing programme has not been made public but the government has committed to hiring 18,000 people, including 3,000 healthcare staff, to handle phone calls (to be appointed from 18 May).
    - The UK has also launched an app to gather data for contact tracing but it has some technical limitations and there are concerns from the public about privacy.

- Limb 2020 [45] (**BMJ; commentary**): A council in **England** set up its own contact tracing system because of a surge in local cases and frustration with the government's NHS Test and Trace Scheme.
    - **4 in 10 cases were going untraced**. The government's tracing system was **not working well in areas with diverse populations because of insufficient translation services**.
    - The test and trace system includes a national call centre and online system and is run by two private companies. In just seven weeks NHS Test and Trace has tested over 2.3 million people for coronavirus, identified nearly 39 000 with the virus and reached almost 200 000 of their close contacts.

- Ready 2020 [46] (**BMJ; commentary**): **United States** approach varies across the country; some states are investing heavily in contact tracing.
    - Massachusetts has announced an ambitious contact tracing programme that is based on well tested methods used internationally to contain outbreaks of Ebola and tuberculosis. They have hired students, public health professionals, and lay people who have started making phone calls.

- Across the United States, other state and local governments are also putting contact tracing in place, including in San Francisco and hard-hit New York, New Jersey, and Connecticut. But **some states**, including a few that are starting to lift limits on restaurants and other public services and events, **have not.**
- Massachusetts's move to put in place its contact tracing programme is budgeted at $44m (£36m; €41m). The estimated national cost is $3.6bn. Whatever the method, contract tracing will require a "massive" expansion of the public health workforce—100,000 to 300,000 tracers.
- At the time of the announcement in early April, only about 9000 people had tested positive in **Massachusetts**. By the time the **contact tracing programme got started in late April**, the number had reached **68,000.**

- Clark 2020 [47] (**Clin Infec Dis, viewpoint**): Discusses why testing-tracing efforts failed to sufficiently mitigate COVID-19 across much of the **United States**.
  - Noticeable lack of unified national leadership and coordination and **disregarding benchmarks for reopening**.
  - **Inadequate testing** supply resulting in **long delays** in obtaining results.
  - In states where the virus is currently surging, implementation and sustainable management of testing-tracing efforts became **virtually unfeasible** as transmission increased, and **capacity was exceeded** in some jurisdictions. Lack of clarity may have resulted in ineffective policies in states like Florida and Texas where the decision was to ease restrictions and instead rely on contact tracing in the midst of high levels of sustained ongoing transmission.
  - The US has substantial **regulations that preclude enforcement of compliance with contact tracing**, which implies that the public's participation will be voluntary, and therefore less likely to provide accurate and comprehensive information.
  - Most local health departments are left to manage the public health concerns of their own jurisdictions with little support, and most lack the resources needed to adequately fulfill this responsibility.

- Lanese 2020 [48] (Livescience, news): Discusses why contact tracing hasn't slowed COVID-19 in the United States. Apart from other weak points in the containment strategies (e.g. slow diagnostic testing, lack of social distancing), improvements to contact tracing programs are needed.
  - **Arizona**: By early July, the state began reporting about 3,500 new cases a day and has only grown steeper; the **health department has neither the human resources, capacity, equipment or training to carry out comprehensive contact tracing on a scale that would make a difference** at this point in the epidemic.
  - **San Francisco**: Contact tracers reached about **88% to 90% of contacts who needed to isolate within 24 hours,** backlogs in testing reduced the numbers slightly, and surge in cases related to loosening social-distancing requirements and imported cases from neighbouring regions made contact tracing more difficult.
  - **California** set a standard for each county to recruit at least **15 contact tracers per 100,000 residents**, and now employs more than 10,000 contact tracers, but they are not evenly distributed across counties.

- Steinhauer 2020 [49] (New York Times, news): Contact tracing is not going to work when so many parts of the prevention system are broken – **testing is too slow** and the **community transmission is too great**.
  - A survey of state health departments by National Public Radio last month found they had roughly 37,000 contact tracers in place, with an additional 31,000 in reserve for when they would be needed. The work force — a mix of government employees, volunteers and contract workers hired by outside

companies or nonprofit organizations — still falls short of the 100,000 people that the C.D.C. has recommended.

Workforce skills

- Korea Centers for Disease Control and Prevention [50] (Osong Public Health and Research Perspectives): Describes the process in South Korea of using objective data sources to overcome limitations in omissions and errors when interviewing patients.

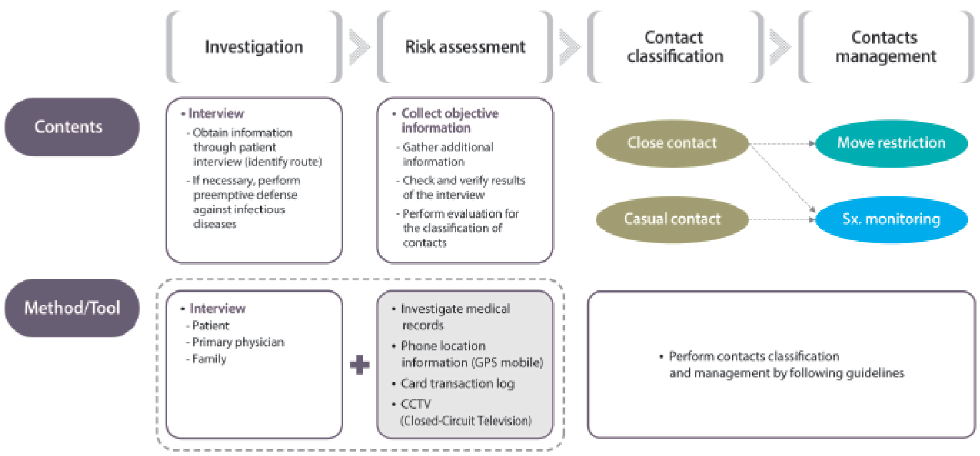

Figure 1. Stepwise approach in monitoring contacts when a patient with COVID-19 is detected.
GPS = global positioning system.

- US CDC [51] has the resource "**Ensuring High Quality and Continuous Improvement of COVID-19 Case Investigators' Interviewing Skills**" for improving the skills of interviewers. The report states "Developing trust and a warm, empathetic rapport, while maintaining a professional relationship is key to providing the most effective support and collecting the most accurate information to inform the next steps in contact tracing. The quality of one's interviewing skills have a direct impact on these goals. Therefore, it is essential that all designated Case Investigators are trained in the skills of interviewing."

- New Hampshire (United States) case investigation and contact tracing plan [52]:
  - Since the beginning of COVID-19, DPHS has investigated and monitored every case of COVID-19.
  - Case investigation and contact tracing requires **staff with adequate training, language skills, cultural sensitivity, supervision, and access to social and medical support for cases and their contacts**.
  - 3 primary roles: case investigation, contact tracing, health monitoring; in New Hampshire, these roles are undertaken by different staff members.
  - Staff include highly skilled DPHS and contracted **public health professionals including public health nurses, infectious disease care coordinators, epidemiologists, data analysts, medical assistants, advanced practice registered nurses, physician assistants, public health program managers, public health section chiefs, and infectious disease physicians**.
  - The workforce has expanded over time as demand increased.

Table. Historic Approximate Number of COVID-19 Case Investigation and Contact Tracing Staff

February 2020 (Initial Response)	March 2020	April 2020	May 2020	June 2020
15	40	80	105	120

GUIDELINES

WHO Guidelines

- Public health criteria to adjust public health and social measures in the context of COVID-19 Annex to Considerations in adjusting public health and social measures in the context of COVID-19 12 May 2020

  Contact tracing
  - **At least 80% of new cases have their close contacts traced and in quarantine within 72 hours of case confirmation**. These indicate that the capacity to conduct contact tracing is sufficient for the number of cases and contacts.
  - **At least 80% of contacts of new cases are monitored for 14 days**. Contacts should be contacted each day during the 14-day period and ideally no more than two days should elapse without feedback from a contact.
  - Information and data management systems are in place to manage contact tracing and other related data. While contact tracing data can be managed on paper at a small scale, large-scale contact tracing can be **supported by electronic tools such as the Go.Data** contact tracing software.

- Contact tracing in the context of COVID-19. 10 May 2020 | COVID-19: Surveillance, case investigation and epidemiological protocols

  This document provides guidance on how to establish contact tracing capacity for the control of COVID-19. WHO recommends voluntary participation by cases and their contacts.
  1. **No cases**: A well-trained contact tracing workforce should be identified, trained and on standby ready to respond to first cases.
  2. **Sporadic cases or clusters**: **Exhaustive** contact tracing is essential for rapidly suppressing transmission.
  3. **Clusters**: Contact tracing is essential for suppressing transmission and reducing transmission within clusters.
  4. **Community transmission**: Contact tracing may be difficult when transmission is intense but should be carried out as much as possible, focusing on **household contacts, health care workers, high-risk closed settings (dormitories, institutions, long term-care homes), and vulnerable contacts**, as well as maintaining strong contact tracing capacity in areas with smaller clusters of cases.

  Other groups
  - Contact tracing may be further adapted for jurisdictions with limited human resources and technological capacity, including very low-income settings or humanitarian contexts: this may entail focusing only on high-risk contacts and on areas not experiencing community-wide transmission. Additional guidance on public health and social measures for COVID-19 preparedness and response in low capacity and humanitarian settings, including contact tracing is available here. In settings with limited resources, the provision of essential commodities for infection control among contacts, such as soap and clean water, must also be ensured.

  Profile of contact tracers
  - Ideally, contact tracers are recruited from their own community and have an appropriate level of literacy, strong communication skills, local language proficiency, and an understanding of context and culture.
  - They should be familiar with and trained on the basics of COVID-19 transmission, prevention and control measures, how to monitor signs and symptoms, as well as the ethics of public health surveillance and quarantine.
  - Contact tracers workforce can be drawn from many settings, including local government, civil society, and non-governmental organizations, university students, community volunteers, etc. **Medical personnel should not be assigned to perform contact tracing unless circumstances require** Supervisors should be assigned to all contact tracing teams to allow for technical and logistics support, problem solving, and quality monitoring.

US CDC Guidelines

- Interim Guidance on Developing a COVID-19 Case Investigation & Contact Tracing Plan: Overview Updated May 26, 2020.
    - **Case investigation and contact tracing are well-honed skills that adapt easily to new public health demands and are effective tools to slow the spread of COVID-19 in a community.** This guidance aims to provide a foundation for state, territorial, local, and tribal development of case investigation and contact tracing plans. It is important to note that COVID-19 case investigation and contact tracing activities will vary based on the level of community transmission, characteristics of the community and their populations, and the local capacity to implement case investigation, contact tracing, and COVID-19 testing.

- Contact Tracing for COVID-19 Updated 22 July 2020.
    - **Box 4. Close Contact Evaluation and Monitoring Hierarchy**
    - ***EVALUATE/MONITOR CLOSE CONTACTS WHO ARE:***

PRIORITY 1
- Hospitalized patients
- Healthcare personnel (HCP)
- First responders (e.g., Emergency Medical Services (EMS) personnel, law enforcement, firefighters)
- Individuals living, working or visiting acute care, mental health, and long-term care facilities
- Individuals living, working or visiting community congregate settings (e.g., correctional facilities, homeless shelters, educational institutions, mass gatherings, and crowded workplaces including production plants)
- Members of a large household living in close quarters especially with a resident with co-morbidities
- Individuals known to live in households with a higher risk individual or to provide care in a household with a higher risk individual

PRIORITY 2
- Critical infrastructure workers*
- Individuals 65 years of age and older
- Individuals at higher risk for severe disease
- Pregnant women

PRIORITY 3
- Individuals with symptoms who do not meet any of the above categories
- Deceased cases

PRIORITY 4
- Individuals without symptoms who do not meet any of the above categories

**Consider moving to Priority 1 critical infrastructure workers who works closely with other critical infrastructure workers or is in close contact with large numbers of people (e.g., transportation, food service).*

- **Case Investigation and Contact Tracing: Part of a Multipronged Approach to Fight the COVID-19 Pandemic. Updated Apr. 29, 2020**
    - Includes principles of contact tracing

European Centre for Disease Control Guidelines

- ECDC. Contact tracing for COVID-19: current evidence, options for scale-up and an assessment of resources needed. April 2020. European Centre for Disease Prevention and Control.

    - **Summary**
    Contact tracing is an effective public health measure for the control of COVID-19. The prompt identification and management of the contacts of COVID-19 cases makes it possible to rapidly identify secondary cases that may arise after transmission from the primary cases. This will enable the interruption of further onward transmission. Contact tracing, in conjunction with robust testing and surveillance systems, is central to control strategies during de-escalation. Contact tracing has been a key part of the response in several Asian countries that have successfully reduced case numbers. It is possible to scale up contact tracing by adapting traditional contact tracing approaches to available local resources and by using a number of resource-saving measures. This document outlines a number of resource measures including the use of well-trained non-public-health staff and volunteers; repurposing existing resources such as call centres; reducing the intensity of contact follow-up and using new technologies such as contact management software and mobile apps.

    - Includes further information of:
        - Evidence base for contact tracing
        - Scaling up contact tracing
        - Using non-public-health staff and volunteers
        - Repurposing existing resources
        - Reducing the intensity of follow up of contacts:
            - As the number of cases increase, the number of contacts will also increase and this intensity of follow-up activities may not be feasible. Options for changing the intensity of follow-up are listed below.
            - Instead of an initial phone call, all or some contacts (e.g. low-risk exposure contacts) can be notified by text message or pre-recorded voicemail, with full instructions on what to do and a phone number to call if they have questions.
            - Instead of a daily follow up phone call, high-risk exposure contacts can receive a text message every day, or no follow-up if the instructions given initially are clear.
            - Instead of following up all contacts, the tracing of **high-risk exposure contacts** and contacts who are **healthcare workers** or **work with vulnerable populations** should be prioritised [20].
            - Prioritising the follow-up of cases in specific settings (e.g. **long-term care facilities, prisons, refugee camps,** etc.) is important in order to mitigate the impact on vulnerable populations. Contact tracing should also be prioritised for contacts who are healthcare workers or work with vulnerable populations.
            - **The above measures will save staff resources, although they may reduce the effectiveness of contact tracing**.
        - Using technology

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