Fundamental Limitations of Contact Tracing for COVID-19

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Abstract

Contact tracing has played a central role in COVID-19 control in many jurisdictions and is often used in conjunction with other measures such as travel restrictions and social distancing mandates. Contact tracing is made ineffective, however, by delays in testing, calling, and isolating. Even if delays are minimized, contact tracing can only prevent a fraction of onward transmissions from contacts. Without other measures in place, contact tracing alone is insufficient to prevent exponential growth in the number of cases. Even when used effectively with other measures, occasional bursts in call loads can overwhelm contact tracing systems and lead to a loss of control. We propose embracing approaches to COVID-19 control that broadly test individuals without symptoms, in whatever way is economically feasible – either with fast cheap tests that can be deployed widely, with pooled testing, or with screening of judiciously chosen groups of high-risk individuals. Only by ramping up testing of asymptomatic individuals can we avoid the inherent delays that limit the efficacy of contact tracing.

The effectiveness of contact tracing for any infectious disease is limited by how quickly contacts can be informed. If contact tracing teams reach an individual’s contacts only toward the end of their infectious period, very few further infections will be prevented. Several delays in the process make rapid contact tracing challenging: the time to develop symptoms, to seek a test, to get test results, and for contact tracing teams to reach contacts. Contact tracing is particularly challenging for COVID-19 because transmission often occurs before symptoms appear \cite{10} and some individuals can transmit who never develop symptoms at all \cite{5}.

Symptomatic testing followed by contact tracing, set in the context of ongoing widespread distancing measures, have been the primary means of controlling COVID-19 in many jurisdictions in Europe, the UK and North America. However, broad and restrictive distancing measures have been considered too costly to be palatable in the long term, both economically and in terms of unintended consequences for public health, mental health and inequality \cite{4,8,16}. This left most of North America, Europe and the UK, among others, in the difficult position of re-opening their economies following declines in COVID-19 numbers. This reopening has occurred in a context where COVID-19 immunity was very low, substantial costs had been incurred, but COVID-19 had not been eliminated and/or was continually re-introduced. In many areas, contact tracing capacity was dramatically increased to allow reopening.

Since reopening, almost all jurisdictions in North American and Europe have seen substantial resurgence of COVID-19 despite having testing and contact tracing in place. Some have overwhelmed their health care systems, for example exceeding ICU capacity, cancelling elective surgeries, diverting patients, and being depleted of nursing staff, leading in some cases to health care workers being asked to work while testing positive for COVID-19 \cite{11,7,13}. Groups of doctors have written open letters calling for wider shutdowns while politicians hesitate, knowing the costs and the unintended damages that these shutdowns will create \cite{1,3}. This has occurred despite symptomatic testing and contact tracing being in place. It is clear that the level of widespread distancing that is tolerable and sustainable is insufficient for robust COVID-19 control, with the testing and contact tracing systems currently in place.

NOTE: This preprint reports new research that has not been certified by peer review and should not be used to guide clinical practice.
Under normal patterns of social interaction with no contact tracing, $R_0$ for COVID-19 is estimated to be between 2 and 5 [14]. Social distancing and other NPIs without the use of contact tracing reduce the basic reproductive number $R_0$ to some lower value $R^{NCT}$, the basic reproductive number with no contact tracing. Contact tracing reduces this further to $R = (1 - \rho)R^{NCT}$, where $\rho$ is the fraction of cases a contact would infect that are prevented by contact tracing. This fraction depends on the capacity to contact trace and on the timing of symptoms and transmission. Two important features are the fraction of contacts that can be reached and who self-isolate (we call this fraction $\alpha$ or “coverage”) and the time from a positive test until the contacts are reached (we call this time $\tau$). When cases are rare, contact tracers can rapidly reach a large proportion of a case’s contacts. As the number of cases rises, contact tracing capacity can become increasingly taxed, reducing the ability to reach all contacts and lengthening the delay. In Figure 1 we illustrate the fraction of cases that contact tracing can prevent given the current tracing capacity, i.e. how $\rho$ depends on $\alpha$ and $\tau$.

If we already have contact tracing in place, we cannot observe $R^{NCT}$. But if we have estimates of $R$, the coverage and the delay, we can estimate $R^{NCT}$ from $R^{NCT} = R/(1 - \rho)$. Then we can determine the fraction of new cases ($\rho\text{crit}$) we would have to prevent to bring $R$ below 1 by solving $1 = (1 - \rho\text{crit})R^{NCT}$. As an example, in British Columbia, on Nov 1, 2020, we estimate $R = 1.22 ((1.13,1.35) 90\%$ range), with that $\tau$ approximately 5 days in ideal cases (roughly 1 day for symptom onset to test, 2 days for the test result to be available, and another 2 days for the contacts to be notified, though this varies from one to many days [7]). With coverage of $\alpha = 0.5$, our formula yields $\rho = 0.08$ and $R^{NCT} = 1.33$: contact tracing only prevents 8% of onward cases. To reduce $R$ to 1 we would need $\rho = 1 - (1/(1.33)) = 0.25$. This could be achieved by reducing delays in contacting from 5 to 2.8 days. Alternatively we could increase coverage, but $R$ is only reduced to 1.12 even if we reached 100% of contacts ($\alpha = 1$), which wouldn’t bring spread under control. In reality, a combination of decreasing delays ($\tau$) and increasing coverage ($\alpha$) would be optimal.

The fact that there is a critical value of the contact tracing delay beyond which contact tracing is not able to prevent a sufficient fraction of cases to bring COVID-19 under control is an example of a tipping point: a value of a parameter where a system has qualitatively different behaviour when the parameter is above or below it [12]. If the delay $\tau$ is above its critical value, we have exponential growth in the number of cases; otherwise cases decline. There is another tipping point for the coverage; increasing coverage (for example by expanding the definition of a contact to include more people, taking extra measures to insure compliance with self-isolation) could push $R$ below 1 if $\tau$ is sufficiently short and other measures are in place.

Without extensive distancing, contact tracing with realistic parameters will not be able to bring $R$ below 1 and we will have exponential growth in the number of cases. But the situation will become worse even for initially very mild exponential growth. As the number of incident cases increases, the contact tracing system will be put under a heavier load, with both $\tau$ increasing and $\alpha$ decreasing, meaning an even lower fraction of cases are prevented by contact tracing. $R$ increases even further, which in turn causes even faster growth in the number of incident cases. This positive feedback cycle unabated will lead to the contact tracing system being overwhelmed, since contact tracing capacity cannot be expanded as quickly as case numbers rise.

If a region does have COVID cases under control ($R < 1$), we can also determine how large an increase in call load can be handled before contact tracing will fail to limit spread. As the number of individuals who need to be contacted daily ($n$) rises above the tracing capacity ($c$), the best strategy is to reduce coverage without also adding further delays. In this case, coverage will decline in proportion to how far over capacity the call demand is (e.g., coverage will drop by half if twice as many people need to be called as can be called, $n/c = 2$). Solving for the call volume that will cause $R$ to rise above one, we find that contact tracing breaks down once $n/c > \rho R^{NCT}/(R^{NCT} - 1)$ or, equivalently, $n/c > (R^{NCT} - R)/(R^{NCT} - 1)$. For example, in a region brought down to $R = 0.9$ from $R^{NCT} = 1.33$, contact tracing will fail to prevent spread once the demand requires 33% more calls than can be placed in a day.

This is the best case scenario - only coverage was impacted. In reality, as the incidence or call volume rises, delays grow. Testing backs up so that fewer onward cases can be prevented. Thus, any event – a burst in transmission caused by a superspreading event, a cluster of importations, or changes in behaviour
Fig 1. Top: Contact tracing of an index case eliminates infections from a secondary case only after contact and self-isolation occur (blue dashed line). Bottom left: $\rho$ as determined by $\alpha$ and $\tau$. Bottom right: The maximum value of $R_{NCT}$ (basic reproductive number without contact tracing) for which contact tracing with a given $\alpha$ and $\tau$ can bring growth under control. Parameters and calculations: If a proportion $\alpha$ of contacts are reached and self-isolate, the fraction of tertiary infections averted (pink shading) is $\rho = \alpha \int_0^\infty f(t)[1 - F(t_{symp} + \tau - t)] dt$ where $f(t)$ is the distribution of the infectious period (red/pink curve; assumed to be Gamma distributed with a mean of 4 days and standard deviation of 1.5 days [9]) and $F(t)$ is its cumulative distribution. $\rho$ is calculated by assuming that the secondary case started at a random time $t$ while the index case was infectious (integrating over $f(t)$) and then calculating what fraction of the infectious period of the secondary case is averted (the $1 - F$ term), accounting for the time delay until the index case develops symptoms ($t_{symp} \approx 5$ days from infection [13]) and their contacts are traced ($\tau$).
around a holiday – that causes the call volume to rise above this limit cannot be reversed by contact tracing
alone. Importantly, the number of calls needed can rise either because of true increases in incidence or due to
increases in contacts per case – either can cause this kind of collapse. When cases rise, the effectiveness of
contact tracing declines just when it is most needed.

Where does this leave us? Heading into mid-winter, with relatively little immunity yet built up and months
until the newly approved vaccines become widely available, many jurisdictions must face up to the fact that
they cannot have what they so wanted – considerable reopening to avert the high costs of shutdowns – if their
primary COVID-19 controls are based on symptomatic testing and contact tracing. Either strong distancing
measures must be maintained until a vaccine has been widely deployed, or we must rethink our testing and
tracing approach. One option for considerably strengthening the power of contact tracing is to go beyond
merely instructing contacts to isolate, but to test all contacts of a known case as rapidly as possible, whether
or not they are symptomatic. This approach, which is used in New Zealand [15], has the advantage that if a
secondary contact tests positive, tracing for their contacts can be initiated much earlier than if testing only
occurs after symptom onset, which might never happen if the secondary contact remains asymptomatic. In
contrast, if we simply ask individuals to self-isolate, first this isolation is imperfect, and we do not obtain
information about their contacts early enough to prevent onward transmission from them.

Mass testing is another approach recently used in Slovakia, where two thirds of the country were tested
with rapid antigen tests over two days. 57,500 COVID-19 cases were identified, which is almost three quarters
the number of cases discovered by PCR tests in that country since the beginning of the pandemic [19]. These
tests are less accurate than standard PCR tests, but lower cost means that they can be deployed much more
widely. Pooled sample testing is another approach: samples are collected from a group and tested at once,
reducing the costs of testing [6]. A positive result can lead to instructions to isolate for the whole group
and/or to subsequent individual tests. In addition, when call load exceeds contact tracing capacity in a region,
mass testing and isolation of positive cases could be used to bring case numbers down to where contact
tracing would become effective again. What these have in common is that they aim to find cases, and even
contacts of those cases, before symptom onset, at the start of or before infectiousness (effectively reducing \( \tau \)).

Measures initiated by testing symptomatic individuals cannot “get ahead of transmission” in the same way.

We can either find ways to get ahead of transmission or continue to use symptomatic testing followed by
contact tracing as our primary COVID-19 control. But we now know that contact tracing that focuses on
symptomatic cases must be complemented with long, sustained and widespread distancing measures, and
these have extremely high economic, social and health costs. If we want to avoid continual shutdowns and
resurgences, we need to build robust testing strategies and capacity that can stop transmission much earlier.

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