Quantifying dynamics of SARS-CoV-2 transmission suggests that epidemic control is feasible through instantaneous digital contact tracing

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COVID-19 impact on ICUs
(Imperial College report 9, Ferguson et al)

In this scenario, interventions can limit transmission to the extent that little herd immunity is acquired—leading to the possibility that a second wave of infection is seen once interventions are lifted.

Figure 2: Mitigation strategy scenarios for GB showing critical care (ICU) bed requirements. The black line shows the unmitigated epidemic. The green line shows a mitigation strategy incorporating closure of schools and universities; orange line shows case isolation; yellow line shows case isolation and household quarantine; and the blue line shows case isolation, home quarantine and social distancing of those aged over 70. The blue shading shows the 3-month period in which these interventions are assumed to remain in place.

Table 3 shows the predicted relative impact on both deaths and ICU capacity of a range of single and combined NPI interventions applied nationally in GB for a 3-month period based on triggers of between 100 and 3000 critical care cases. Conditional on that duration, the most effective combination of interventions is predicted to be a combination of case isolation, home quarantine and social distancing of those most at risk (the over 70s). Whilst the latter has relatively less impact on transmission than other age groups, reducing morbidity and mortality in the highest risk groups reduces both demand on critical care and overall mortality. In combination, this intervention strategy is predicted to reduce peak critical care demand by two-thirds and halve the number of deaths. However, this “optimal” mitigation scenario would still result in an 8-fold higher peak demand on critical care beds over and above the available surge capacity in both GB and the US.

Stopping mass gatherings is predicted to have relatively little impact (results not shown) because the contact-time at such events is relatively small compared to the time spent at home, in schools or workplaces and in other community locations such as bars and restaurants. Overall, we find that the relative effectiveness of different policies is insensitive to the choice of local trigger (absolute numbers of cases compared to per-capita incidence), $R_0$ (in the range 2.0–2.6), and varying IFR in the 0.25%–1.0% range.
Doubling times in China …

- \( r = 0.3 \) (0.21 – 0.39)  
  \( T_2 = 2.3 \)

- \( r = 0.35 \) (0.28 – 0.42)  
  \( T_2 = 2 \)

- \( r = 0.134 \) (0.121 – 0.146)  
  \( T_2 = 5.2 \)

- \( r = 0.44 \) (0.34 – 0.55)  
  \( T_2 = 1.6 \)

- \( r = 0.085 \) (0.078 – 0.093)  
  \( T_2 = 8.1 \)

**count type:**  
- ● symptom onset, linked to wet markets  
- ▲ symptom onset, not linked to wet markets  
- ■ confirmed case  
- + death

**log** \(_{10}\) (daily count)
... and Europe
An epidemiological classification of transmission modes for SARS-CoV-2

- Symptomatic (after symptom onset)
- Pre-symptomatic (before symptom onset)
- Asymptomatic (no symptom onset, or very mild symptoms)
- Environmental (fomites, ventilation systems...)

An epidemiological classification of transmission modes for SARS-CoV-2

- **Symptomatic**  (after symptom onset)
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  \[ \sim 40\% \text{ but low infectiousness ?} \]
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  - \(~40\% \text{ but low infectiousness?}\)
- **Environmental** (fomites, ventilation systems…)
  - \(~10-20\% ?\)
Incubation period and generation time

- Incubation period:
  how long it takes to develop symptoms

  versus

- Generation time (serial interval):
  how long it takes to transmit the disease
Inference of generation time distribution

Maximum Composite Likelihood estimate from *times of exposure* and *onset of symptoms* for infector-infected pairs
Pre-symptomatic transmission

About 30-45% of all transmissions from symptomatic cases are pre-symptomatic.
How to reach epidemic control: the reproduction numbers $R_0$ and $R_{eff}$

- $R_0$: average number of infections caused by an infected individual in a naive population
- $R_{eff}$: average number of infections caused by an infected individual in the presence of interventions

The critical condition to control the epidemic is $R_{eff} < 1$
Euler-Lotka equation

Classical renewal equation

\[ I(t) = \int_0^\infty I(t - \tau) \beta(\tau) d\tau, \]

Exponential ansatz with growth rate \( r \)

Classical Euler-Lotka equation

\[ R_0 = 1/ \int_0^\infty e^{-r\tau} w(\tau) d\tau \]
An epidemiological classification of transmission modes for SARS-CoV-2

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Decomposition of *infectiousness* (versus time post infection):

\[
\beta(\tau) = P_a x_a \beta_s(\tau) + (1 - P_a)(1 - s(\tau))\beta_s(\tau) + (1 - P_a)s(\tau)\beta_s(\tau) + \int_{l=0}^{\tau} \beta_s(\tau - l)E(l)dl
\]

- asymptomatic
- pre-symptomatic
- symptomatic
- environmental
Decomposition of infectiousness

About half of all transmissions are pre-symptomatic.

$R_0 = 2.0$:
- $R_p = 0.9$ from pre-symptomatic
- $R_s = 0.8$ from symptomatic
- $R_e = 0.2$ from environmental
- $R_a = 0.1$ from asymptomatic
Generalised Euler-Lotka equation for contact tracing

Kermack-McKendrick equations for chains of infections with contact tracing:
(Fraser el al PNAS 2004)

\[
\frac{\partial Y(t, \tau, \tau')}{\partial t} + \frac{\partial Y(t, \tau, \tau')}{\partial \tau} + \frac{\partial Y(t, \tau, \tau')}{\partial \tau'} = 0
\]

\[
Y(t, 0, \tau) = \beta(\tau) (1 - \epsilon_I s(\tau)) \int_\tau^\infty \left( 1 - \epsilon_T + \epsilon_T \frac{1 - s(\tau')}{1 - s(\tau' - \tau)} \right) Y(t, \tau, \tau') d\tau'
\]

Efficiency of isolation / contact tracing & quarantine

The generalised (functional) Euler-Lotka equation corresponds to the eigenvalue equation (with eigenvalue 1) for this operator:

\[
\mathcal{N}_r y = e^{-r\tau} \beta(\tau) (1 - \epsilon_I s(\tau)) \int_0^\infty \left( 1 - \epsilon_T \frac{s(\rho + \tau) - s(\rho)}{1 - s(\rho)} \right) y(\rho) d\rho
\]
Is the COVID-19 epidemic controllable via realistic contact tracing?

![Graphs showing success in isolating cases and quarantining contacts for different delays and max $R_0$.](image)
Why instant contact tracing matters?
Why instant contact tracing matters?

*Isolation and contact tracing can stop the epidemic only with high efficiency and short response times*

<table>
<thead>
<tr>
<th>Delay to Isolation and Contact Quarantine</th>
<th>% Success in Isolating Cases</th>
<th>% Success in Quarantining Contacts</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 days (manual contact tracing)</td>
<td><img src="image1.png" alt="Graph" /></td>
<td><img src="image2.png" alt="Graph" /></td>
</tr>
<tr>
<td>No delay (instantaneous contact tracing)</td>
<td><img src="image3.png" alt="Graph" /></td>
<td><img src="image4.png" alt="Graph" /></td>
</tr>
</tbody>
</table>

Isolation and contact tracing can stop the epidemic only with high efficiency and short response times.
Why digital solutions?

Tools of classical epidemiology against COVID-19:

- **Physical distancing/isolation/quarantine**
  - Either insufficient or high social&economic costs

- **Mass screening/testing + contact tracing**
  - Hard to scale for a rapid response (HR, lab capacity)

- **Vaccination**
  - Development/trial phase + time to scale production

Alternative digital technologies are needed for a **fast, scalable** response
A mobile app for instant contact tracing

Subject A has COVID-19 infection. No symptoms

Day 1
- Home
- Train
- Work
- Home

Awakes with fever

Day 2
- Report symptoms
- Request home test

Positive Covid-19

Automated test request
Self-isolate - 14 days
Advice on social distancing (lower risk contact)

Decontaminate

Instant signal
Useful at all phases of the epidemic

- Prevent initial spread
- “Smart lockdown” to keep to economy afloat
- “Smart exit” from lockdown to prevent a second peak
- Control residual spread
Challenges

• Limitations in smartphone coverage and contact technologies (Bluetooth Low Energy). Integration of multiple approaches?

• >50% uptake required at population level

• Compliance with app recommendation to “stay at home” is key

• Scale-up of diagnostic testing across Europe is needed

• Some degree of physical distancing could still be required for the fast-growing European epidemic

• *Iterative improvements of app back-end and front-end, as well as the science and technology behind app tracing*
Ethical issues

• Building trust and confidence at every stage

• privacy and data usage concerns at the forefront

• adopting a transparent and auditable algorithm

• careful consideration of digital deployment strategies to support specific groups, such as health care workers, the elderly and the young

• deployed with individual consent
Challenges: voluntary uptake

Would you install the app?

- Definitely install
- Probably install
- Maybe

Currently
If an infection occurs in your community
If someone you know is infected
In lockdown, and displaying all-clear lifts restrictions
Challenges: voluntary uptake

Compliance with app recommendation to self-isolate

Would comply with recommendation to self-isolate

More or less likely to comply if promised a rapid test

Definitely comply

 Probably comply

Equally likely

More likely

Percent
Challenges: voluntary uptake

Main reasons for installing the app

- Protect family and friends: 19%
- Responsibility to the community: 15%
- Might stop the epidemic: 15%
- Let me know risk of infection: 15%
- Reduce deaths in older people: 13%
- Peace of mind: 11%
- Help me stay healthy: 11%
- Other: .88%
Challenges: voluntary uptake

Main reasons against installing the app

- Concerns about gov. surveillance after epidemic: 25%
- Would feel more anxious: 24%
- Phone might get hacked: 19%
- Other: 11%
- Don't want NHS to have location data: 7.4%
- Too much hassle installing: 5.9%
- I would not benefit: 4.7%
- I won't be infected: 2.5%
Recent developments

• Many privacy-preserving projects across the world - now mostly concentrated in two main consortia for Europe and North America (PEPP-PT and TCN)

• Bluetooth Low Energy as common choice of technology (hence interoperability/roaming possible)

• Much movement at European level, different countries at different stages

• Recent Google/Apple announcement: embedding contact tracing APIs in the OS. Technical and political pros and cons.
What can you do?

- App-based contact tracing could potentially control the epidemic and should be at the core of epidemic response.  
  *Optimised contract-tracing algorithms? Learning from contact networks?*

- It should not be a stand-alone solution! Must be part of an integrated strategy (with epidemiological surveillance, risk forecast, geolocation of hot spots, local lockdowns…).
  *Interplay with other interventions?*

- Widespread diagnostic testing is critical

- Physical distancing still important

- Please support European governments and institutions in their efforts towards app-based contact tracing within an integrated strategy of epidemic control
Based on: Ferretti, Wymant et al, Science 2020
Find out more about our research here:
http://www.coronavirus-fraser-group.org