INSIGHTS FROM MATHEMATICAL MODELS OF COVID-19

Jomar Fajardo Rabajante
[ANALYSIS] Coronavirus cases in PH could reach 26,000 by end-March if random spread not contained

We're worried because this number is not something we believe our healthcare system can handle

Christopher Monterola and Erika Fille Legara
Published 4:14 PM, March 17, 2020
Updated 9:41 AM, March 29, 2020

need to conduct mass testing
“this is a long-term war”
Rabajante also inferred that the COVID-19 epidemic in Metro Manila might have started around Valentine's Day.

...86% of all infections are undocumented.

What these numbers tell us is that plans and strategies for both the public and private sector must extend beyond the duration of the enhanced community quarantine...

"People should plan long-term because we're talking about a pandemic. If we go back to our normal practices after the enhanced community quarantine, there is a possibility of a rebound of the infection"
Impact of non-pharmaceutical interventions (NPIs) to reduce COVID-19 mortality and healthcare demand


On behalf of the Imperial College COVID-19 Response Team

WHO Collaborating Centre for Infectious Disease Modelling
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Abdul Latif Jameel Institute for Disease and Emergency Analytics
Imperial College London
Insights from early mathematical models of 2019–nCoV acute respiratory disease (COVID–19) dynamics

Jomar F. Rabajante

(Submitted on 13 Feb 2020 (v1), last revised 28 Feb 2020 (this version, v3))

In December 2019, a novel coronavirus (SARS–CoV–2) has been identified to cause acute respiratory disease in humans. An outbreak of this disease has been reported in mainland China with the city of Wuhan as the recognized epicenter. The disease has also been exported to other countries, including the Philippines, but the level of spread is still under control (as of 08 February 2020). To describe and predict the dynamics of the disease, several preliminary mathematical models are formulated by various international study groups. Here, the insights that can be drawn from these models are discussed, especially as inputs for designing strategies to control the epidemics. Proposed model–based strategies on how to prevent the spread of the disease in local setting, such as during large social gatherings, are also presented. The model shows that the exposure time is a significant factor in spreading the disease. With a basic reproduction number equal to 2, and 14–day infectious period, an infected person staying more than 9 hours in the event could infect other people. Assuming the exposure time is 18 hours, the model recommends that attendees of the social gathering should have a protection with more than 70 percent effectiveness.
$R_0$ - Basic reproduction number

**Ebola:**
- R-Naught of 2

**SARS:**
- R-Naught of 4

Patient Zero
Infected

For Philippines, my team’s estimate is 1.5 to 2.5 based on DOH COVID-19 confirmed cases (using exponential fitting; serial interval = 7.5)
Features of COVID-19 infection that affect how mitigation measures will influence the shape of the epidemic curve. Key is that the time to infectiousness (latency) is possibly shorter than the time to symptoms (incubation) and therefore the delay to care seeking or isolation is a crucial period.

https://www.thelancet.com/journals/lancet/article/PIIS0140-6736(20)30567-5/fulltext
## Chart 14: Transmission Rate during Coronavirus Stages in Patients

<table>
<thead>
<tr>
<th>Stage</th>
<th>Symptoms</th>
<th>Hospitalization</th>
<th>Ventilation / ICU</th>
<th>Recovery</th>
<th>Death</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asymptomatic (30%)</td>
<td>No symptoms</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mild / Moderate (56%)</td>
<td>No symptoms</td>
<td>Symptoms (mild/moderate)</td>
<td>Recovery</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Severe (10%)</td>
<td>No symptoms</td>
<td>Symptoms (Severe)</td>
<td>Hospitalization</td>
<td>Recovery</td>
<td></td>
</tr>
<tr>
<td>Critical (4%)</td>
<td>No symptoms</td>
<td>Symptoms (Severe)</td>
<td>Hospitalization</td>
<td>Ventilation / ICU</td>
<td>Death</td>
</tr>
</tbody>
</table>

Most cases are mild
Only one in five of those with the virus experienced severe or critical illness.

**Case severity**

- **Mild**: 80.9%
- **Severe**: 13.8%
- **Critical**: 4.7%

**The elderly are most at risk**
Early data suggests that the older people are, the more dangerous the virus is to them. Fatality rates in mainland China were higher among older patients.

**Fatality rate, by age**

<table>
<thead>
<tr>
<th>Age</th>
<th>Fatality Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-9</td>
<td>0%</td>
</tr>
<tr>
<td>10-19</td>
<td>0.2%</td>
</tr>
<tr>
<td>20-29</td>
<td>0.2%</td>
</tr>
<tr>
<td>30-39</td>
<td>0.2%</td>
</tr>
<tr>
<td>40-49</td>
<td>0.4%</td>
</tr>
<tr>
<td>50-59</td>
<td>1.3%</td>
</tr>
<tr>
<td>60-69</td>
<td>3.6%</td>
</tr>
<tr>
<td>70-79</td>
<td>8.0%</td>
</tr>
<tr>
<td>80+</td>
<td>14.8%</td>
</tr>
</tbody>
</table>

*Note: Analysis of the first 44,672 confirmed cases of Covid-19 in mainland China as of February 11, 2020. 0.6% of the cases in the study were missing this information.*

*Source: Chinese Center for Disease Control and Prevention
Graphic: Henrik Pettersson and Natalie Croker, CNN

Correction: A previous version of this graphic misstated the ratio of elderly patients who died. It is about one in 10.
Substantial undocumented infection facilitates the rapid dissemination of novel coronavirus (SARS-CoV2)

Abstract

Estimation of the prevalence and contagiousness of undocumented novel coronavirus (SARS-CoV2) infections is critical for understanding the overall prevalence and pandemic potential of this disease. Here we use observations of reported infection within China, in conjunction with mobility data, a networked dynamic metapopulation model and Bayesian inference, to infer critical epidemiological characteristics associated with SARS-CoV2, including the fraction of undocumented infections and their contagiousness. We estimate 86% of all infections were undocumented (95% CI: [82%–90%]) prior to 23 January 2020 travel restrictions. Per person, the transmission rate of undocumented infections was 55% of documented infections ([46%–62%]), yet, due to their greater numbers, undocumented infections were the infection source for 79% of documented cases. These findings explain the rapid geographic spread of SARS-CoV2 and indicate containment of this virus will be particularly challenging.
ABSTRACTION

"Real-world" problem

Model (mathematical representation)

Solution

impractical, difficult or impossible

justified assumptions

analysis; interpretation; sensitivity evaluation; "validation"
REMARKS:

- Mathematical modelers are not fortune tellers, and in fact, modelers do not wish their worst-case prediction to happen. Worst-case scenario models are not intended to cause panic, but they are formulated to help in planning and creation of strategies.

- Models can be used as intelligent input during decision-making but users of the model results should always check if the assumptions used fit the system or situation.

- Models and model results should be interpreted with guidance from experts.

- "All models are wrong, but some are useful". I hope my models will be useful to the different stakeholders.

- The model results are subject to updates as time progresses, and subject to peer-review.
TYPES OF MODELS

1. Phenomenological
<<Black box>>
TYPES OF MODELS

2. Mechanistic

<<White or transparent box>>
TYPES OF MODELS

"Hybrid"

<<Grey box>>
A flow chart of a simple epidemic model for COVID-19 of individual states and pathways with rates of transfer based on appendix 1. Top pathway (mild symptoms): individuals stay in the community and eventually recover. Bottom pathway (clear symptoms): individuals self-isolate (low effectiveness) or go into mandatory isolation (at home or in a care facility) with higher effectiveness.
Can we trust the Oxford study on Covid-19 infections?

*Adam Kucharski*

We don't know exactly how many people have already been infected with the virus, but there's no evidence it's half the population.

*Adam Kucharski is an epidemiologist and author*
Assuming a basic reproduction number $R_0$ between 1.5 to 4, it is predicted that the cumulative number of infected individuals in the country is around 600k to 1.4m, with 80% from Metro Manila.

This estimate includes possible asymptomatic individuals and unreported cases. The high estimate for Metro Manila is mainly due to the high population size and density in the region.
ESTIMATED TOTAL NUMBER OF INDIVIDUALS INFECTED DURING THE WHOLE EPIDEMIC PERIOD

\[1-1/R_0\]

then include
- population size,
- population density,
- COVID-19 safe space
ESTIMATED TOTAL NUMBER OF INDIVIDUALS INFECTED DURING THE WHOLE EPIDEMIC PERIOD

It is possible that the peaks in the provinces are asynchronous due to the different outbreak initiation time.

Theoretically, in a large and homogeneous population, it requires at least 5-7 imported cases to have 95-99% chance of initiating an outbreak given $R_0 = 2$. Mobility in and out the provinces should be monitored and regulated to prevent an outbreak.
In a large and homogeneous population, \(-\log(c)/\log(R_0)\) initial cases are needed to have \(1-c\) chance of initiating an outbreak.

https://journals.plos.org/plospathogens/article?id=10.1371/journal.ppat.1003277
Cumulative (reported in media)

Active cases (those who are still sick; less recovered and deaths)
## ESTIMATED NUMBER OF BEDS AND ICUS NEEDED DURING THE PEAK OF THE EPIDEMICS

<table>
<thead>
<tr>
<th>REGION</th>
<th>MINIMUM NUMBER OF BEDS NECESSARY DURING PEAK (SEVERE + CRITICAL CASES)</th>
<th>MINIMUM NUMBER OF ICUS NECESSARY DURING PEAK (CRITICAL CASES)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R_0=1.5$</td>
<td>$R_0=2$</td>
</tr>
<tr>
<td>PHILIPPINES</td>
<td>28,636</td>
<td>42,954</td>
</tr>
<tr>
<td>NCR</td>
<td>23,827</td>
<td>35,741</td>
</tr>
<tr>
<td>REGION 1</td>
<td>155</td>
<td>232</td>
</tr>
<tr>
<td>REGION 2</td>
<td>27</td>
<td>41</td>
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<tr>
<td>REGION 3</td>
<td>754</td>
<td>1,131</td>
</tr>
<tr>
<td>REGION 4A</td>
<td>1,631</td>
<td>2,446</td>
</tr>
<tr>
<td>REGION 4B</td>
<td>27</td>
<td>40</td>
</tr>
<tr>
<td>REGION 5</td>
<td>137</td>
<td>206</td>
</tr>
<tr>
<td>REGION 6</td>
<td>447</td>
<td>670</td>
</tr>
<tr>
<td>REGION 7</td>
<td>891</td>
<td>1,336</td>
</tr>
<tr>
<td>REGION 8</td>
<td>79</td>
<td>118</td>
</tr>
<tr>
<td>REGION 9</td>
<td>72</td>
<td>107</td>
</tr>
<tr>
<td>REGION 10</td>
<td>137</td>
<td>206</td>
</tr>
<tr>
<td>REGION 11</td>
<td>121</td>
<td>181</td>
</tr>
<tr>
<td>REGION 12</td>
<td>125</td>
<td>187</td>
</tr>
<tr>
<td>BARMM</td>
<td>29</td>
<td>44</td>
</tr>
<tr>
<td>CARAGA</td>
<td>30</td>
<td>45</td>
</tr>
<tr>
<td>CAR</td>
<td>148</td>
<td>222</td>
</tr>
</tbody>
</table>
EPIDEMIC PEAK DYNAMICS

Number of active cases (those who are still sick less recovered and deaths)

shifted peak (to buy us more time to prepare)

community quarantine period

reproductive number after the community quarantine period

- R=0.9
- R=1.5
- R=2
- R=2.5
- R=3
- R=4
EPIDEMIC PEAK DYNAMICS

Number of active cases (those who are still sick, less recovered, and deaths)

extending the community quarantine will further shift the peak

reproductive number after the community quarantine period

- R=0.9
- R=1.5
- R=2
- R=2.5
- R=3
- R=4

community quarantine period
EPIDEMIC PEAK DYNAMICS

Number of active cases (those who are still sick less recovered and deaths)

Multiple strategies can do this coupled with socio-economic models

community quarantine period

reproductive number after the community quarantine period

- $R=0.9$
- $R=1.5$
- $R=2$
- $R=2.5$
- $R=3$
- $R=4$
WORST-CASE SCENARIO (PHILIPPINES)

Without Community Quarantine, R0=3

75k at peak

- Actual Active Cases
- Actual Active Cases Less Undetected Asymptomatics
- Total Detected Cases
- Total Detected Deaths

(Day 0 = around February 5)
WITH ECQ SCENARIO (PHILIPPINES)

Community Quarantine Period: Day 45 to Day 75
Max detection: 500; Asymp tested: 0.1%; No protection

Legend
R: before ECQ to during ECQ to after ECQ

ECQ
WITH EXTENDED ECQ SCENARIO (PHILIPPINES)

Legend
R: before ECQ to during ECQ to after ECQ

Community Quarantine Period: Day 45 to Day 75
Max detection: 500; Asymp tested: 0.1%; No protection

Community Quarantine Period: Day 45 to Day 90
Max detection: 500; Asymp tested: 0.1%; No protection

shifted peak
**WITH MULTIPLE STRATEGIES SCENARIO (PHILIPPINES)**

Flattening the curve until vaccine arrives (50% of the population should be vaccinated for $R_0=2$)

- Maintain social distancing and avoid mass gatherings (to reduce $R_0$ thus reduce beta)
- Increase detection and isolation (include % of mild and asymptomatic cases) to reduce infectious
- Increase protection and good personal hygiene/etiquette to reduce transfer from exposed to
WITH MULTIPLE STRATEGIES SCENARIO (PHILIPPINES)

What actionable strategies we can do after ECQ to:

• Reduce $R_0$ (e.g., physical distancing)?
• Increase detection and isolation (including % of mild and asymptomatic cases) to reduce people in the infectious class?
• Increase protection of susceptible class and improve community practice of good personal hygiene/etiquette to reduce transfer from exposed class to infectious class?
• etc.

Flattening the curve until vaccine arrives (50% of the population should be vaccinated for $R_0=2$)
CONTINUOUS MONITORING AND UPDATING OF FORECASTS MUST BE DONE UNTIL...

1-1/RO OF THE POPULATION ARE VACCINATED.
## Chart 13.b: NPI Measures per Country

<table>
<thead>
<tr>
<th>Measures (Non-Pharmaceutical Interventions, NPIs)</th>
<th>China</th>
<th>Singapore</th>
<th>South Korea</th>
<th>Taiwan</th>
<th>Italy</th>
<th>Spain</th>
<th>France</th>
<th>US</th>
<th>UK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Government</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Education</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Detection &amp; Isolation</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Public Decontamination</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Healthcare Resources</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Social distancing/isolating cases</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>Economics</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
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<td>Travel Bans</td>
<td>Yes</td>
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<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
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<td>Closure</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Source: Matt Bell, Elena Baillie, Genevieve Goo, Tomas Pueyo
Excess healthcare capacity during the peak of the epidemics

Number of detected cases per day

- Healthcare capacity = 10
- Healthcare capacity = 100
- Healthcare capacity = 200
- Healthcare capacity = 300
- Healthcare capacity = 400
- Healthcare capacity = 500
COVID-19 RELATED CROWD DYNAMICS

Proposal:
• increase clean and safe space (e.g., always clean the environment and wear mask)
• implement physical distance between random people, e.g., maximum of 10% crowd density

![Graph showing number of new infected vs crowd density with different exposure times]
COVID-19 RELATED CROWD DYNAMICS

Proposal (without protection):
- decrease the rate of patient encounter per frontline health care worker, e.g., maximum of three encounters per hour in a 12-hour work shift duration;
- decrease the interaction time between the frontline health care worker and the patients, e.g., less than 40 minutes for the whole day;
- identify potential “super-spreaders”
COVID-19 RELATED CROWD DYNAMICS

Proposal:
• provide effective protective gears and facilities, e.g., 95% effective, that the frontline health care workers can use during their shift
Infection fatality ratio in the Philippines is estimated at 0.61% (using age-dependent case fatality rate data from China), or around 1.94% (using age-dependent case fatality rates in the Philippines as of 29 March 2020).
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