The Incubation Period of Coronavirus Disease 2019 (COVID-19) From Publicly Reported Confirmed Cases: Estimation and Application

Stephen A. Lauer, MS, PhD*; Kyra H. Grantz, BA*; Qifang Bi, MHS; Forrest K. Jones, MPH; Qulu Zheng, MHS; Hannah R. Meredith, PhD; Andrew S. Azman, PhD; Nicholas G. Reich, PhD; Justin Lessler, PhD

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Abstract
Background: A novel human coronavirus, severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), was identified in China in December 2019. There is limited support for many of its key epidemiologic features, including the incubation period for clinical disease (coronavirus disease 2019 [COVID-19]), which has important implications for surveillance.
and control activities.

Objective: To estimate the length of the incubation period of COVID-19 and describe its public health implications.


Setting: News reports and press releases from 50 provinces, regions, and countries.
outside Wuhan, Hubei province, China.

Participants: Persons with confirmed SARS-CoV-2 infection outside Hubei province, China.

Measurements: Patient demographic characteristics and dates and times of possible exposure, symptom onset, fever onset, and hospitalization.

Results: There were 181 confirmed
cases with identifiable exposure and symptom onset windows to estimate the incubation period of COVID-19. The median incubation period was estimated to be 5.1 days (95% CI, 4.5 to 5.8 days), and 97.5% of those who develop symptoms will do so within 11.5 days (CI, 8.2 to 15.6 days) of infection. These estimates imply that, under conservative assumptions,
101 out of every 10,000 cases (99th percentile, 482) will develop symptoms after 14 days of active monitoring or quarantine.

**Limitation:**
Publicly reported cases may overrepresent severe cases, the incubation period for which may differ from that of mild cases.

**Conclusion:**
This work provides additional evidence for a
The median incubation period for COVID-19 of approximately 5 days, similar to SARS. Our results support current proposals for the length of quarantine or active monitoring of persons potentially exposed to SARS-CoV-2, although longer monitoring periods might be justified in extreme cases.

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In December 2019, a cluster of severe pneumonia cases of unknown cause was reported in Wuhan, Hubei province, China. The initial cluster was epidemiologically
linked to a seafood wholesale market in Wuhan, although many of the initial 41 cases were later reported to have no known exposure to the market (1). A novel strain of coronavirus belonging to the same family of viruses that cause severe acute respiratory syndrome (SARS) and Middle East respiratory syndrome (MERS), as well as the 4 human...
coronaviruses associated with the common cold, was subsequently isolated from lower respiratory tract samples of 4 cases on 7 January 2020 (2). Infection with the virus, severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), can be asymptomatic or can result in mild to severe symptomatic disease (coronavirus disease 2019 [COVID-19]) (3). On 30 January 2020,
the World
Health
Organization
declared that
the SARS-
CoV-2
outbreak
constituted a
Public Health
Emergency of
International
Concern, and
more than
80 000
confirmed
cases had been
reported
worldwide as
of 28 February
2020 (4, 5). On
31 January
2020, the U.S.
Centers for
Disease
Control and
Prevention
announced
that all
citizens
returning from
Hubei province, China, would be subject to mandatory quarantine for up to 14 days (6).

Our current understanding of the incubation period for COVID-19 is limited. An early analysis based on 88 confirmed cases in Chinese provinces outside Wuhan, using data on known travel to and from Wuhan to estimate the exposure interval,
indicated a mean incubation period of 6.4 days (95% CI, 5.6 to 7.7 days), with a range of 2.1 to 11.1 days (7). Another analysis based on 158 confirmed cases outside Wuhan estimated a median incubation period of 5.0 days (CI, 4.4 to 5.6 days), with a range of 2 to 14 days (8). These estimates are generally consistent with estimates from 10 confirmed
cases in China (mean incubation period, 5.2 days [CI, 4.1 to 7.0 days] [9]) and from clinical reports of a familial cluster of COVID-19 in which symptom onset occurred 3 to 6 days after assumed exposure in Wuhan (1). These estimates of the incubation period of SARS-CoV-2 are also in line with those of other known human coronaviruses, including SARS (mean, 5 days;
range, 2 to 14 days [10]),
MERS (mean, 5 to 7 days; range, 2 to 14 days [11]), and non-SARS human coronavirus (mean, 3 days; range, 2 to 5 days [12]).

The incubation period can inform several important public health activities for infectious diseases, including active monitoring, surveillance, control, and modeling. Active monitoring requires
potentially exposed persons to contact local health authorities to report their health status every day. Understanding the length of active monitoring needed to limit the risk for missing SARS-CoV-2 infections is necessary for health departments to effectively use limited resources. In this article, we provide estimates of the incubation period of COVID-19 and
the number of symptomatic infections missed under different active monitoring scenarios.

Methods

Data Collection

We searched for news and public health reports of confirmed COVID-19 cases in areas with no known community transmission, including provinces, regions, and countries outside Hubei. We searched
for reports in both English and Chinese and abstracted the data necessary to estimate the incubation period of COVID-19. Two authors independently reviewed the full text of each case report. Discrepancies were resolved by discussion and consensus.

For each case, we recorded the time of possible exposure to SARS-CoV-2, any symptom onset, fever onset, and case
detection. The exact time of events was used when possible; otherwise, we defined conservative upper and lower bounds for the possible interval of each event. For most cases, the interval of possible SARS-CoV-2 exposure was defined as the time between the earliest possible arrival to and latest possible departure from Wuhan. For cases without history of
travel to
Wuhan but
with assumed
exposure to an
infectious
person, the
interval of
possible SARS-
CoV-2
exposure was
defined as the
maximum
possible
interval of
exposure to
the infectious
person,
including time
before the
infectious
person was
symptomatic.
We allowed for
the possibility
of continued
exposure
within known
clusters (for
example,
families
traveling
together) when the ordering of transmission was unclear. We assumed that exposure always preceded symptom onset. If we were unable to determine the latest exposure time from the available case report, we defined the upper bound of the exposure interval to be the latest possible time of symptom onset. When the earliest possible time of exposure could not be
determined, we defined it as 1 December 2019, the date of symptom onset in the first known case (1); we performed a sensitivity analysis for the selection of this universal lower bound. When the earliest possible time of symptom onset could not be determined, we assumed it to be the earliest time of possible exposure. When the latest time of possible
symptom onset could not be determined, we assumed it to be the latest time of possible case detection. Data on age, sex, country of residence, and possible exposure route were also collected.

**Statistical Analysis**

Cases were included in the analysis if we had information on the interval of exposure to SARS-CoV-2 and symptom onset. We estimated the
incubation time using a previously described parametric accelerated failure time model (13). For our primary analysis, we assumed that the incubation time follows a log-normal distribution, as seen in other acute respiratory viral infections (12). We fit the model to all observations, as well as to only cases where the patient had fever and only those detected inside or outside
mainland China in subset analyses. Finally, we also fit 3 other commonly used incubation period distributions (gamma, Weibull, and Erlang). We estimated median incubation time and important quantiles (2.5th, 25th, 75th, and 97.5th percentiles) along with their bootstrapped CIs for each model.
Using these estimates of the incubation period, we quantified the expected number of undetected symptomatic cases in an active monitoring program, adapting a method detailed by Reich and colleagues (14). We accounted for varying durations of the active monitoring program (1 to 28 days) and individual risk for symptomatic infection (low
risk: 1-in-10 000 chance of infection; medium risk: 1-in-1000 chance; high risk: 1-in-100 chance; infected: 1-in-1 chance). For each bootstrapped set of parameter estimates from the log-normal model, we calculated the probability of a symptomatic infection developing after an active monitoring program of a given length for a given risk level. This model
conservatively assumes that persons are exposed to SARS-CoV-2 immediately before the active monitoring program and assumes perfect ascertainment of symptomatic cases that develop under active monitoring. We report the mean and 99th percentile of the expected number of undetected symptomatic cases for each active monitoring scenario.
All estimates are based on persons who developed symptoms, and this work makes no inferences about asymptomatic infection with SARS-CoV-2. The analyses were conducted using the coarseDataTools and activemonitr packages in the R statistical programming language, version 3.6.2 (R Foundation for Statistical Computing). All code and data are
available at
https://github.com/HopkinsIIDD/ncov-incubation
(release at
time of
submission at

Role of the Funding Source

The findings
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Results

We collected data from 181 cases with
confirmed SARS-CoV-2 infection detected outside Hubei province before 24 February 2020 (Table 1). Of these, 69 (38%) were female, 108 were male (60%), and 4 (2%) were of unknown sex. The median age was 44.5 years (interquartile range, 34.0 to 55.5 years). Cases were collected from 24 countries and regions outside mainland China (n = 108) and 25
provinces within mainland China \((n = 73)\). Most cases \((n = 161)\) had a known recent history of travel to or residence in Wuhan; others had evidence of contact with travelers from Hubei or persons with known infection. Among those who developed symptoms in the community, the median time from symptom onset to hospitalization was 1.2 days \((\text{range, 0.2 to} \ldots)\).
29.9 days) (Figure 1).

FIGURE 1.

SARS-CoV-2 exposure (blue), symptom onset (red), and case detection (green) times for 181 confirmed cases. Shaded regions represent the full possible time intervals for exposure, symptom onset,
and case
detection;
points
represent
the
midpoints
of these
intervals.
SARS-
CoV-2 =
severe
acute
respiratory
syndrome
coronavirus
2.

Table 1.
Characteristics
of
Patients
With
Confirmed
COVID-
19
Included
in This
Analysis
($n = 18$)

Fitting the
log-normal
model to all
cases, we estimated the median incubation period of COVID-19 to be 5.1 days (CI, 4.5 to 5.8 days) (Figure 2). We estimated that fewer than 2.5% of infected persons will show symptoms within 2.2 days (CI, 1.8 to 2.9 days) of exposure, and symptom onset will occur within 11.5 days (CI, 8.2 to 15.6 days) for 97.5% of infected persons. The estimate of the
dispersion parameter was 1.52 (CI, 1.32 to 1.72), and the estimated mean incubation period was 5.5 days.

FIGURE 2.

Cumulative distribution function of the COVID-19 incubation period estimate from the log-normal model. The estimated median incubation period of
COVID-19 was 5.1 days (CI, 4.5 to 5.8 days). We estimated that fewer than 2.5% of infected persons will display symptoms within 2.2 days (CI, 1.8 to 2.9 days) of exposure, whereas symptom onset will occur within 11.5 days.
(CI, 8.2 to 15.6 days) for 97.5% of infected persons. Horizontal bars represent the 95% CIs of the 2.5th, 50th, and 97.5th percentiles of the incubation period distribution. The estimate of the dispersion parameter is 1.52 (CI, 1.32 to 1.72). COVID-
To control for possible bias from symptoms of cough or sore throat, which could have been caused by other more common pathogens, we performed the same analysis on the subset of cases with known time of fever onset ($n = 99$), using the time from exposure to onset of fever as the incubation time. We estimated the
median incubation period to fever onset to be 5.7 days (CI, 4.9 to 6.8 days), with 2.5% of persons experiencing fever within 2.6 days (CI, 2.1 to 3.7 days) and 97.5% having fever within 12.5 days (CI, 8.2 to 17.7 days) of exposure.

Because assumptions about the occurrence of local transmission and therefore the period of possible exposure may be less firm
within mainland China, we also analyzed only cases detected outside mainland China ($n = 108$). The median incubation period for these cases was 5.5 days (CI, 4.4 to 7.0 days), with the 95% range spanning from 2.1 (CI, 1.5 to 3.2) to 14.7 (CI, 7.4 to 22.6) days. Alternatively, persons who left mainland China may represent a subset of persons with longer
incubation periods, persons who were able to travel internationally before symptom onset within China, or persons who may have chosen to delay reporting symptoms until they left China. Based on cases detected inside mainland China ($n = 73$), the median incubation period is 4.8 days (CI, 4.2 to 5.6 days), with a 95% range of 2.5 (CI, 1.9 to 3.5) to 9.2 (CI,
days. Full results of these sensitivity analyses are presented in Appendix Table 1.

<table>
<thead>
<tr>
<th>Percentiles of SARS-CoV-2 Incubation Period From Selected Sensitivity Analyses*</th>
</tr>
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</table>

We fit other commonly used parameterizations of the incubation period (gamma, Weibull, and Erlang distributions). The incubation
period estimates for these alternate parameterizations were similar to those from the log-normal model (Appendix Table 2).

### Appendix Table 2.
Parameter Estimates for Various Parametric Distributions of the Incubation Period of SARS-CoV-2 Using 181 Confirmed Cases

Given these estimates of the incubation period, we predicted the
number of symptomatic infections we would expect to miss over the course of an active monitoring program. We classified persons as being at high risk if they have a 1-in-100 chance of developing a symptomatic infection after exposure. For an active monitoring program lasting 7 days, the expected number of symptomatic infections missed for every 10 000 high-risk
The incubation period of COVID-19 from publicly reported confirmed cases is monitored is 21.2 (99th percentile, 36.5) (Table 2 and Figure 3). After 14 days, it is highly unlikely that further symptomatic infections would be undetected among high-risk persons (mean, 1.0 undetected infections per 10,000 persons [99th percentile, 4.8]). However, substantial uncertainty remains in the classification of persons as being at
“high,” “medium,” or “low” risk for being symptomatic, and this method does not consider the role of asymptomatic infection. We have created an application to estimate the proportion of missed COVID-19 cases across any active monitoring duration up to 100 days and various population risk levels (16).

FIGURE 3.

Proportion of
known symptomatic SARS-CoV-2 infections that have yet to develop symptoms, by number of days since infection, using bootstrapped estimates from a log-normal accelerated failure time model.

Table 2.
Expected Number of Symptomatic
SARS-CoV-2 Infections That Would Be Undetected During Active Monitoring, Given Varying Monitoring Durations and Risks for Symptomatic Infection After Exposure*

Discussion

We present estimates of the incubation period for the novel coronavirus disease (COVID-19) that emerged in Wuhan, Hubei province,
China, in 2019. We estimated the median incubation period of COVID-19 to be 5.1 days and expect that nearly all infected persons who have symptoms will do so within 12 days of infection. We found that the current period of active monitoring recommended by the U.S. Centers for Disease Control and Prevention (14 days) is well supported by the evidence (6).
Symptomatic
disease is
frequently
associated
with
transmissibility
of a pathogen.
However,
given recent
evidence of
SARS-CoV-2
transmission
by mildly
symptomatic
and
asymptomatic
persons (17,
18), we note
that time from
exposure to
onset of
infectiousness
(latent period)
may be shorter
than the
incubation
period
estimated
here, with
important
implications for transmission dynamics.

Our results are broadly consistent with other estimates of the incubation period (1, 7–9). Our analysis, which was based on 181 confirmed COVID-19 cases, made more conservative assumptions about the possible window of symptom onset and the potential for continued exposure.
through transmission clusters outside Wuhan. Of note, the use of fixed times of symptom onset, as used in 3 of the 4 prior analyses, will truncate the incubation period distribution by either decreasing the maximum possible incubation period (if the earliest possible time of symptom onset is used) or increasing the minimum possible incubation period (if the
midpoint or latest possible time of symptom onset is used). Therefore, using a symptom onset window more accurately accounts for the full distribution of possible incubation periods.

Although our results support current proposals for the length of quarantine or active monitoring of persons potentially exposed to SARS-CoV-2,
longer monitoring periods might be justified in extreme cases. Among those who are infected and will develop symptoms, we expect 101 in 10,000 (99th percentile, 482) will do so after the end of a 14-day monitoring period (Table 2 and Figure 3), and our analyses do not preclude this estimate from being higher. Although it is essential to weigh the costs of extending
active monitoring or quarantine against the potential or perceived costs of failing to identify a symptomatic case, there may be high-risk scenarios (for example, a health care worker who cared for a COVID-19 patient while not wearing personal protective equipment) where it could be prudent to extend the period of active monitoring.

This analysis
has several important limitations. Our data include early case reports, with associated uncertainty in the intervals of exposure and symptom onset. We have used conservative bounds of possible exposure and symptom onset where exact times were not known, but there may be further inaccuracy in these data that we have not considered. We have
exclusively considered reported, confirmed cases of COVID-19, which may overrepresent hospitalized persons and others with severe symptoms, although we note that the proportion of mild cases detected has increased as surveillance and monitoring systems have been strengthened. The incubation period for these severe cases may differ from
that of less severe or subclinical infections and is not typically an applicable measure for those with asymptomatic infections.

Our model assumes a constant risk for SARS-CoV-2 infection in Wuhan from 1 December 2019 to 30 January 2020, based on the date of symptom onset of the first known case and the last known possible exposure within Wuhan.
in our data set. This is a simplification of infection risk, given that the outbreak has shifted from a likely common-source outbreak associated with a seafood market to human-to-human transmission. Moreover, phylogenetic analysis of 38 SARS-CoV-2 genomes suggests that the virus may have been circulating before December 2019 (19). To test the
sensitivity of our estimates to that assumption, we performed an analysis where cases with unknown lower bounds on exposure were set to 1 December 2018, a full year earlier than in our primary analysis. Changing this assumption had little effect on the estimates of the median (0.2 day longer than for the overall estimate) and the 97.5th quantile (0.1 day longer) of
the incubation period. In data sets such as ours, where we have adequate observations with well-defined minimum and maximum possible incubation periods for many cases, extending the universal lower bound has little bearing on the overall estimates.

This work provides additional evidence for a median incubation period for COVID-19 of
approximately 5 days, similar to SARS. Assuming infection occurs at the initiation of monitoring, our estimates suggest that 101 out of every 10,000 cases will develop symptoms after 14 days of active monitoring or quarantine. Whether this rate is acceptable depends on the expected risk for infection in the population being monitored and considered judgment
about the cost of missing cases (14). Combining these judgments with the estimates presented here can help public health officials to set rational and evidence-based COVID-19 control policies.

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