Fast spread of COVID-19 in Europe and the US and its implications: even modest public health goals require comprehensive intervention

Authors: Ruian Ke, PhD[1,*], Steven Sanche, PhD[1,2], Ethan Romero-Severson, PhD[1], Nick Hengartner, PhD[1]

Affiliations:

[1]T-6 Theoretical Biology and Biophysics, Theoretical Division, Los Alamos National Laboratory, NM87545, USA.

[2]T-CNLS Center for Nonlinear Studies, Los Alamos National Laboratory, NM87545, USA.

[*]Correspondences should be addressed to:

Ruian Ke

Email: rke@lanl.gov

Phone: 1-505-667-7135

Mail: Mail Stop K710,

T-6 Theoretical Biology and Biophysics,

Los Alamos National Laboratory,

NM87545, USA.

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29 **Summary**
30
31 **Background** The COVID-19 pandemic caused more than 800,000 infections and 40,000 deaths
32 by the end of March 2020. However, some of the basic epidemiological parameters, such as the
33 exponential epidemic growth rate, are not well estimated, partially because of confounding
34 factors in data collection during a rapidly growing outbreak, such as underreporting, delays in
35 case confirmation and changes in surveillance intensities.
36
37 **Methods** We developed an inference approach using a mathematical model to control for these
38 confounding factors. We fitted the model to both infection incidence and death count data
39 collected from eight European countries and the US. Public health implications of empirical
40 estimates were examined using simulations.
41
42 **Findings** In all countries, the early epidemic period was characterized by exponential growth
43 with rates between 0·19-0·29/day (epidemic doubling times between 2·4-3·7 days). However,
44 the proportion of cases that had been detected was low (less than 20% of cases detected) except
45 for Germany (23·1%; CI: 5-85%). With such high epidemic growth rates, moderate intervention
46 efforts will have little impact on the public health outcome; high levels of efforts to achieve
47 greater than 77-86% reduction in transmission are needed, no matter the goal is to slowdown the
48 growth to protect a large fraction of population from infection within 18 months or to reverse the
49 growth all together.
50
51 **Interpretation** The extremely fast spread of COVID-19 in Europe and the US suggest a highly
52 infectious virus with a high R_0. Early, strong and comprehensive intervention efforts are
53 necessary, whether the aim is mitigation or containment.
54

Introduction

COVID-19 originated in Wuhan China in Dec, 2019[1]. It has spread rapidly and caused a global pandemic within a short period of time. As of March 31, 2020, the global pandemic lead to more than 800,000 total confirmed cases and 40,000 deaths. Estimation of the rate of early epidemic spread in Wuhan, China, lead to different conclusions. Initially, it was suggested that the epidemic grew at 0·1-0·14/day, leading to an epidemic doubling time of 5-7 days[2-5]. However, using domestic travel data and two distinct approaches, we estimated that the epidemic in Wuhan grew much faster than initially estimated, and the growth rate is likely to be between 0·21-0·3/day, translating to a doubling time between 2·3 to 3·3 days, and an R_0 approximately at 5·7 with a large confidence interval[6]. A fast epidemic spread is consistent with multiple other lines of evidence, such as the rapid increase of the epidemic curve by symptom onset published by China CDC[7] and the growth in the number of death cases in Hubei, China during late January 2020[6]. However, it was not clear whether COVID-19 can spread in other countries as fast as in Wuhan, China.

Accurate estimation of the rate of epidemic growth is important for many practical aspects. First, it is crucial for forecasting the epidemic trajectory, the burden on health care systems and potential health and economic damage, so that appropriate and timely responses can be prepared. Second, it sets the baseline for evaluation of effectiveness of intervention strategies. Third, it is important for accurate estimation of the basic reproductive number, R_0, which in turn is used for many control measures, including evaluation of the vaccine/herd immunity threshold needed to stop transmission[6,8]. However, a major challenge to the inference of the growth of COVID-19 is that as a result of a fast-growing outbreak and a sizable infected population with no or mild-to-moderate symptoms[9,10], case confirmation data is influenced by many factors in addition to the true epidemic growth, including substantial underreporting[11], i.e. low detection rate, changes in surveillance intensity and delays in case confirmation. Simply fitting an exponential curve to case confirmation data may lead to erroneous conclusions when confounding factors are not taken into account or estimated from other sources of data.

Here, we argue that because death and the cause of death are usually recorded reliably and are less affected by surveillance intensity changes or delay in confirmation than case counts, the time series of death counts reflects the growth of an epidemic reliably, with a delay in onset determined by the time between infection to death. Based on this idea, we designed a simple methodology to disentangle the epidemic growth from confounding factors, such as underreporting, delays in case confirmation and changes in surveillance intensity. We fit models to both case incidence data and death count data collected from eight European countries and the US in March 2020. We show that in most countries, the detection rate of infected individuals is in general low, and COVID-19 spreads very fast in these countries. For such a fast-epidemic growth, our results suggest that very strong and active control measures need to be implemented as early as possible regardless of the public health goal (e.g. mitigation versus containment), and that moderate control measures will not achieve measurable public health benefit.

Methods

Data

We collected daily case confirmation and death count data for the US and 8 countries in Europe from the John Hopkins CSSE (Center for Systems Science and Engineering) database

101   (https://github.com/CSSEGISandData/COVID-19). The data is accessed and extracted on March
102   31, 2020. The data consists of time series of numbers of case confirmations and deaths by
103   country (cumulative). Daily incidences were derived from the cumulative counts. We used data
104   from the following countries: France (FR), Italy (IT), Spain (SP), Germany (GR), Belgium (BE),
105   Switzerland (SW), Netherlands (NT), United Kingdom (UK) and the US (US).
106

107   We included a subset of case confirmation and death count data for inference based on the two
108   following criteria. First, to minimize the impact of stochasticity and uncertainty in early data
109   collection, we used case confirmation incidence data starting from the date when the cumulative
110   number of cases was greater than 100, and used daily new death count data starting from the date
111   when the cumulative death count is greater than 20 in each country. Second, to estimate the early
112   outbreak growth in each country before control measures were implemented and at the same time
113   maximize the power of inference, we allowed a maximum of 15 days of data points for the two
114   types of data, leading to a maximum of 30 data points for each country. Note that the end date of
115   incidence data used for inference is at or close to the date when strong control measures were
116   implemented in each country (Table S1). We tested the sensitivity of model predictions when
117   only 10, 13 days of data points are included for inference. The results are robust to this variation
118   (Table S1), suggesting that the choice of 15 days is reasonable and that the data shows consistent
119   exponential growth during this period.
120

121   **Model**
122   We construct a SEIR type model using ordinary differential equations (ODEs; see
123   Supplementary materials). We consider the exponentially growing phase of the outbreak and
124   thus make the common assumption that the susceptible population is constant over time. Then,
125   the total number of infected individuals $I^*(t) = E(t) + I(t)$ can be expressed as:

$$I^*(t) = I_0^* e^{rt} \qquad (1)$$

126   where r is the exponential growth rate of the epidemic (the growth rate for short below), and I_0^*
127   is the number of total infected individual at time 0, set as January 20, 2020. Note the choice of
128   the date of time 0 does not affect our estimation.
129

130   We solve the ODE model and derive the following expressions for the key quantities for model
131   inference (see Supplementary material). The descriptions and values used for the parameters in
132   the ODE model are summarized in Table 1.
133

134   The true daily incidence of infected individuals, $\Omega(t)$, is:

$$\Omega(t) = \frac{\beta(k+r)}{r(k+r+\beta)} I_0^* \left(e^{rt} - e^{r(t-1)} \right) \qquad (2)$$

135   where β and $1/k$ are the transmission potential of the virus and the latent period of infection,
136   respectively.
137

138   The daily new confirmed case count, $\Psi(t)$, is related to the true daily incidence, $\Omega(t)$ as:

$$\Psi(t) = \theta(t) \frac{g}{(g+r)} \Omega(t) \qquad (3)$$

139   where $\theta(t)$ is the detection rate, i.e. the fraction of newly individuals at time t who are later
140   detected by surveillance later on. $1/g$ is the average duration between infection and case
141   confirmation.

142

143 The daily new death count, $\Phi(t)$, is related to the true daily incidence, $\Omega(t)$ as:

$$\Phi(t) = \left(\frac{nd}{r+nd}\right)^n X \frac{k}{k+r} \Omega(t) \qquad (4)$$

144 where X is the infection fatality ratio (sometimes referred as case fatality ratio, CFR, depending
145 on definition). We assumed a realistic (Erlang) distribution for the period between onset of
146 infectiousness and death[6], where $1/d$ and n are the mean and the shape parameter for the
147 distribution.

148

149 The expressions above clearly establish that during the exponential growth of an epidemic, the
150 ratio between death counts Φ and the confirmed cases Ψ (i.e. two widely reported numbers in
151 public databases, publications and news reports) is not only dependent on infection fatality ratio
152 and the detection rate, but also a highly nonlinear relationship between the distribution of the
153 period from infection to death and the growth rate, r, as indicated by the $\left(\frac{nd}{r+nd}\right)^n$ term. Failure to
154 take this into account may lead erroneous conclusions.

155

156 We tested three different scenarios for surveillance intensity changes over time, modeled as the
157 detection rate, $\theta(t)$:

158   1) θ is a constant, i.e. no change over time;

159   2) $\theta(t) = p_{min} + (p_{max} - p_{min})\frac{t^m}{t^m + K^m}$, i.e. θ is a Hill-type function of t;

160   3) $\theta(t)$ is equal to p_{min} before t_1, increases linearly to p_{max} between t_1 and t_2 and stay
161   constant at p_{max} after t_2, i.e. θ is a semi-linear function of t.

162 Note that $1/g$ can be a time dependent function as we and others shown previously[6,12]. To keep
163 the model simple, we implicitly assume that the time dependent changes in g can be included in
164 the estimation of $\theta(t)$.

165

166 See supplementary materials for details of data collection, modeling analysis, parameter choice
167 and estimation and uncertainty quantifications.

168

169 **Results**
170 **Estimation of the epidemic growth rate and surveillance intensity**
171 We constructed an SEIR type model and fitted the model to both the incidence (case
172 confirmation) data and the daily new death count data from eight countries in Europe and the US.
173 We selected data from a period during early outbreak before or a few days after strong control
174 measures, such as school and work closure, and locking down cities etc., were implemented in
175 these countries (see Methods for details and Table S1). There are clear decreases in the rate of
176 exponential growth of infection incidence after the end dates of data selection in most of these
177 countries (Fig. 1), and this is likely to reflect the impact of the strong control measures
178 implemented[13].

179

180 We estimated that the exponential growth rate of early outbreaks, r, ranges between 0·19 and
181 0·29/day in the nine countries, translating to doubling times between 2·4-3·7 days (Fig. 1). The
182 two countries with the highest point estimates of the exponential rate are Spain and the US, at
183 0·29 and 0·28/day, respectively; whereas Switzerland and Netherlands have lower point
184 estimates at 0·19/day. Accounting for uncertainties in the parameter values (see Methods), we

185 found that the epidemic growth rates in France, Germany, Italy, Spain and the US are mostly
186 likely higher than 0·2/day (Fig. 2A).
187
188 By explicitly considering surveillance intensity, our model enables us to estimate the detection
189 rate, i.e. the probability of an infected person being identified by surveillance. Assuming a
190 constant detection rate during the period when data used for inference are collected, we
191 estimated that Germany has a point estimate of the detection rate at 23·1%. In 8 other countries
192 examined, the detection rates were relatively low, ranging between 2·2-9·3%. This provides a
193 natural explanation of the high number of reported cases compared to the relative low number of
194 deaths in March 2020.
195
196 We caution that unlike the epidemic growth rate which is constrained by data, the estimation of
197 detection rate is highly dependent on the fixed parameter values, such as the infection fatality
198 ratio assumed in the model. If the infection fatality ratio is lower than we assumed, we would
199 estimate even lower detection rates. To fully assess the uncertainties in the estimation, we
200 performed sensitivity analysis varying parameter values within ranges based on the best current
201 knowledge (see Supplementary Material). Taking into account these uncertainties, we estimate
202 that Germany has a detection rate between 5% and 86%, and Switzerland has a detection rate
203 between 2% and 26% (Fig. 2). The detection rates in other countries are likely between 1-10%.
204 Although large uncertainties exist, we find that the relative detection rates among countries are
205 robust to parameter uncertainties, i.e. the detection rate in Germany is much higher than the rates
206 in the other countries. Overall, we find that even in countries with well-developed medical and
207 public health infrastructures, the detection rate for COVID-19 is in general low, likely due to the
208 high percentage of infected individuals with no or mild-to-moderate symptoms[9,10]. Our results
209 emphasize the importance of wearing personal protective equipment to prevent transmission
210 from the large population of unidentified individuals, and more aggressive testing of infection
211 and contact tracing are needed to identify most infected individuals.
212
213 We further tested the possibility of changes in surveillance intensity, and found no statistical
214 support (Table S2). We emphasize that this conclusion only applies to the period when the
215 incidence data used for estimation were collected (Table S1). It is likely that the surveillance
216 intensity was different during other periods of the outbreaks. As shown in Fig. 1, in Belgium,
217 France, Italy and Netherland, and UK, the red open circles, i.e. data that were not used for
218 inference, are mostly below the red band predicted by our model during very early outbreak.
219 This indicates that in these countries, the detection rates were even lower than we estimated such
220 that there were very few cases detected, although thousands of infected individuals were already
221 infected. Some of the red open circles in the US seems during late March are above the red band,
222 suggesting increases in surveillance intensity.
223
224 **Implications to intervention strategies - 'hit hard, hit early'**
225 Using our empirical estimates of the growth rates, we explored the implications for public health
226 efforts needed to control the COVID-19 outbreak. We considered an outbreak scenario in a city
227 with a population size of 10 million. Because it may take at least one and a half years for an
228 effective vaccine to be developed and deployed, below we compared outbreak outcomes under
229 different scenarios at 18 months.
230

231 We first calculated the length of time for the epidemic to reach epidemic peak, assuming only
232 one infected individual at day 0. When the growth rate is higher than 0·027/day, the epidemic
233 peak will occur in less than 18 months and a large fraction of the population (>80%) will be
234 infected. If our goal is that the total fraction of infected individuals is less than 10% at the end of
235 18 months, the growth rate has to be less than 0·025/day (i.e. an extremely slow growth rate with
236 a doubling time of more than 28 days; Fig. 3B). This suggests that moderate social distancing
237 efforts will be insufficient to delay the epidemic peak beyond 18 months. On the other hand, if
238 these targeted growth rates are achieved through very strong public health interventions, a little
239 more effort would lead to enormous public health benefit, i.e. the total infected fraction
240 decreases exponentially when r decrease beyond 0·023/day as shown in Fig. 3B.
241
242 To further corroborates our results, we calculated the efforts needed to achieve three goals in 18
243 months: 1) virus containment, i.e. epidemic stops growing, 2) the total infected population is
244 10%, and 3) the total infected population is 1%. We found that the efforts needed are similar,
245 especially when the population of infected individuals is already more than 100 (Fig. 3C), i.e. a
246 scenario that many cities around the globe are facing now. For example, when an outbreak grows
247 at rate 0·29/day, the levels of efforts needed to achieve the three goals are between 84% and 86%
248 reduction in transmission; whereas when the growth rate is 0·19 /day, the levels of effort needed
249 are between 77% and 80% reduction. These high levels of reduction needed argue for very
250 strong and comprehensive intervention efforts implemented as soon as possible, no matter
251 whether the goal is containment or mitigation - a strategy reminiscent of the 'hit hard, hit early'
252 paradigm in treating HIV infection in a patient[16].
253

Discussion

255 The epidemic growth rate for disease spread depends on many factors, including biological[17],
256 demographic, and social factors. In this work, we report high COVID-19 epidemic growth rates
257 between 0·19-0·29/day and short doubling times between 2·4-3·7 days across the eight most
258 affected countries in Europe and in the US (as of March 31, 2020). This is consistent with our
259 previous estimate for the early COVID-19 outbreak in Wuhan, China[6]. Altogether, these results
260 demonstrate COVID-19 to be a highly transmissible disease in the absence of strong control
261 measurements irrespective of heterogeneities in geographic and social settings. We also find that
262 most of infected individuals are not identified/detected, similar to findings in Wuhan, China[6,11].
263 This has important implications to both pharmaceutical and non-pharmaceutical interventions as
264 we discuss below.
265
266 First, with the global efforts to develop vaccines for COVID-19, it is important to have an
267 accurate measure of the basic reproductive number, R_0, to set the threshold level of herd
268 immunity needed to prevent transmission. Previously, R_0 for COVID-19 were estimated to be
269 between 2-3[2-5] and were widely reported in official documents[18] and public media. These
270 estimates are mostly based on an epidemic growth rate between 0·1 and 0·14/day[2-5], which we
271 now know to be inconsistent with many new lines of evidence and data as discussed in this paper
272 and a previous work[6]. The growth rates that we estimated in this paper are simply not consistent
273 with a low R_0. Previously we showed that with a mean serial interval, defined as the duration of
274 time between onset of symptoms in an index case and a secondary case, of 6-9 days[3,19] and an
275 epidemic growth rate between 0·19-0·29/day, the value of R_0 must be higher than 3[6]. Using the
276 same framework as in Ref. 6, we find that when the growth rate is 0·19/day, the median R_0 is

277   estimated to be 3·9 (95% CI: 3·1 and 5·0); whereas when the growth rate is 0·29/day, the median
278   R_0 is estimated to be 7·1 (95% CI: 5·1 and 9·6)[6]. Although shorter serial intervals are reported in
279   the literature[20,21], it was noted that this is likely due to strong intervention efforts[19,20]. Given the
280   potentially long infectious period in individuals with either mild or severe symptoms[22], the mean
281   serial interval during early outbreak in the absence of strong intervention (a likely scenario in
282   most countries examined here) is unlikely less than 6 days. Overall, our results imply that a large
283   fraction of the population needs to be vaccinated if an effective vaccine is to prevent the spread
284   of the virus. In addition, if the virus is allowed to spread through the population, a large fraction
285   of the population (>74%) will be infected even if the growth curve is flattened by control efforts.
286

287   Second, the awareness of the extraordinary high rates of COVID-19 spread during the current
288   outbreak is critically important for epidemic preparedness. This is because the short doubling
289   time means that health care systems can be overwhelmed in a couple of weeks rather than several
290   months in the absence of control. A recent report shows that the number of COVID-19 patients
291   admitted to intensive care units (ICUs) in Italy grew at a rate of approximately 0·25/day[23],
292   remarkably consistent with our estimates. With such a high growth rate, there was only a very
293   short window period for preparation[23]. Of course, heterogeneities in the growth rate may exist
294   among different areas within each a country. We note that our inference is largely driven by data
295   collected from highly populated areas, such as Wuhan in China, Lombardy in Italy, and New
296   York city in the US. Further work is needed to assess heterogeneity in the rate of spread across
297   areas with different population densities.
298

299   Third, the high epidemic growth rates suggest that moderate control efforts will not sufficiently
300   slow the virus spread to achieve measurable public health benefits. This may explain the
301   continuous growth of the outbreak in some countries despite measures, such as work and school
302   closures, were in place. We found that similarly high levels of efforts to reduce overall
303   transmission by 77-86% are needed to delay the epidemic peak and protect a large fraction of the
304   population from infection in 18 months (mitigation) or to reduce R_0 below 1 (containment).
305

306   Lastly, our finding that the majority of infected individuals are not identified suggests that in
307   most infected individuals, the symptoms are likely to be mild, and many of them may not be
308   aware of their infection status. Part of the higher detection probability in Germany is possibly
309   due to their early use of contact tracing, which will find asymptomatic and mild cases that might
310   otherwise not be detected. This argues for extensive, universally available testing to identify and
311   isolate most infected individuals as well as the use of personal protective equipment to prevent
312   potential transmission from individuals with no or mild symptoms.
313

314   Overall, in the absence of very strong control, the virus can cause high mortality and
315   morbidity[14,15] due to the high number of expected infections, which places an extremely heavy
316   burden on even the most advanced health care systems[15,24]. Thus, with COVID-19, half-
317   measures will not be effective in meeting public health goals. Even for more modest goals such
318   as "flattening the curve", we probably need all feasible tools available, i.e. extensive testing,
319   isolation and quarantine, use of personal protective equipment, coupled with comprehensive
320   social distancing. This is a strategy reminiscent of the 'hit hard, hit early' paradigm in treating
321   HIV infected individuals[16]. China, South Korea, and Singapore have proven that containment is
322   possible with appropriate measures. Because there will be extensive economic impacts of the

323 global COVID-19 pandemic regardless of how principled our response is, the question is not
324 balancing public health with damage to the economy, but rather how many lives can we save.
325
326

Acknowledgments

333

Declaration of interests

335 The authors declare no competing interests.
336

Author contributions

338 RK and NH conceived the project; RK performed literature search and designed the study; SS
339 collected data; RK, SS and ERS performed analyses; RK, SS, ERS and NH wrote and edited the
340 manuscript.

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Figure captions

Figure 1. Estimation of the exponential growth rate, doubling time of epidemics and detection rate of infected individuals in 8 European countries and the US. Red and black symbols show the daily counts of new case confirmation and new death, respectively. Dots denote data used for parameter inference; whereas open circles denote data that are not used for parameter inference. We simulated the exponential model using sampled parameter combinations that are able to explain the data shown in dots (see the Uncertainty Quantification section in the Supplementary Material). The colored bands denote the area between the lower and upper bounds of simulated/predicted true daily infection incidence (blue), daily case confirmation (red) and daily death (grey) assuming no intervention efforts nor changes in surveillance intensity. Deviation of open circles from the corresponding bands thus indicates either changes in surveillance intensity or impacts of control measures.

Figure 2. Point estimates and estimated ranges of the exponential growth rate, r and the detection rate, θ, in each country. BE: Belgium; FR: France; GR: Germany; IT: Italy; NT: Netherlands; SP: Spain; SW: Switzerland; UK: United Kingdom; US: United States.

Figure 3. Strong control measures are needed to achieve measurable benefits, no matter the goal is mitigation ('flatten the curve') or containment. (A) Predicted time to epidemic peak for different growth rates. To delay epidemic peak beyond 18 months, a growth rate less than 0·027/day is needed. This threshold is denoted by dashed lines. Red area shows the ranges of growth rates estimated for the eight European countries, the US and Wuhan, China. **(B)** Final fraction of infected individuals after 18 months. A growth rate less than 0·023/day (doubling time more than 30 days) is needed to achieve the goal that less than 10% of individuals are infected (dashed lines). However, the benefit, i.e. fraction of uninfected individuals, increases exponentially when the growth rate is further reduced beyond the threshold. **(C)** Similar levels of efforts, measured as fractions of transmission reduction, are needed to achieve containment, i.e. reverting epidemic growth (dots), or mitigation, i.e. the final fraction of infected individuals is 1% (x) or 10% (open circle). We assumed epidemic growth rates of 0·19 (red) or 0·29/day (blue).

448 **Table 1. Description of parameter and their values.** See the supplementary material for
449 discussions of choice of parameter values.

Parameters	Description	Value	Ranges used in uncertainty analysis	References
r	Exponential growth rate	Estimated from data	$0·1 – 0·35$ /day	
I_0^*	I_0^* is the number of total infected individual at time 0 (Jan. 20)	Estimated from data	$0·0001 – 10$ on a log scale	
β	Infectivity in the SEIR model	Calculated from r		See Supplementary material
$1/k$	The mean latent period, i.e. from infection to becoming infectious	3 days	2-5 days	[6,25]
$1/g$	The mean duration from infection to case confirmation	8 days	6-10 days	[6,12]
n	Shape parameter for the duration from symptom onset to death.	4	4-5	
$1/d$	Mean duration from onset of infectious period to death	18·5 days	$16·5 – 20·5$ days	[6,26]
X	Infection fatality ratio	0·01	$0·004 – 0·015$	[14,15]

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A Belgium
Growth rate, r: 0.20 /day
Doubling time: 3.5 days
● Cases
● Deaths

B France
Growth rate, r: 0.22 /day
Doubling time: 3.1 days
● Cases
● Deaths

C Germany
Growth rate, r: 0.24 /day
Doubling time: 2.9 days
● Cases
● Deaths

D Italy
Growth rate, r: 0.24 /day
Doubling time: 2.8 days
● Cases
● Deaths

E Netherlands
Growth rate, r: 0.19 /day
Doubling time: 3.6 days
● Cases
● Deaths

F Spain
Growth rate, r: 0.29 /day
Doubling time: 2.4 days
● Cases
● Deaths

G Switzerland
Growth rate, r: 0.19 /day
Doubling time: 3.7 days
● Cases
● Deaths

H UK
Growth rate, r: 0.20 /day
Doubling time: 3.4 days
● Cases
● Deaths

I US
Growth rate, r: 0.28 /day
Doubling time: 2.5 days
● Cases
● Deaths

A
Months to Peak (y-axis, 0–25)
Growth rate, r (/day) (x-axis)
r=0.027/day

B
Final fraction (y-axis, 0.1%–100.0%)
Growth rate, r (/day) (x-axis)
r=0.025/day

C
Reduction in transmission (y-axis, 0.2–1.0)
Initial infected population (x-axis, 1–10000)
r=0.29/day
r=0.19/day
● Containment
✕ 1% infected
○ 10% infected