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BRIEF REPORT

Coronavirus Disease 2019 Epidemic Doubling Time in the United States Before and During Stay-at-Home Restrictions

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Background. Coronavirus disease 2019 (COVID-19) has spread rapidly in the United States since January 2020.

Methods. We estimated mean epidemic doubling time, an important measure of epidemic growth, nationally, by state, and in association with stay-at-home orders.

Results. The epidemic doubling time in the United States was 2.68 days (95% confidence interval [CI], 2.30–3.24 days) before widespread mitigation efforts, increasing by 460% to 15 days (12.89–17.94 days) during the mitigation phase. Among states without stay-at-home orders, the median increase in doubling time was 60% (95% CI, 9.2–223.3), compared with 269% (95% CI, 277.0–394.0) for states with stay-at-home orders.

Conclusions. Statewide mitigation strategies were strongly associated with increased epidemic doubling time.

Keywords. COVID-19; coronavirus; SARS-CoV-2; epidemic doubling time.

Over the last 2 decades, 3 novel coronaviruses have emerged: severe acute respiratory syndrome (SARS) in 2002 [1–3], Middle East respiratory syndrome in 2012 [4], and a second, different respiratory syndrome, coronavirus disease 2019 (COVID-19), caused by SARS coronavirus 2 in 2019 [5]. By the end of April 2020, there were 3 256 846 confirmed COVID-19 cases worldwide [6]. The first case in the United States was reported in Washington on 20 January 2020 [7], and the first suspected occurrence of community spread was reported by the US Centers for Disease Control and Prevention on 26 February [8], for a total of 15 reported cases in the country. By 4 March 2020, all states reported at least 100 cases [6] and by the end of April the United States, with just over 4.2% of the global population, accounted for 32.8% of all reported infections [6].

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Understanding the rapid transmission within the United States is critical to informing interventions, but calculating the basic reproductive number, R_0, which describes transmission on an individual level, is relatively complex, and relevant only in a largely susceptible population. However, current data allow for an understanding of transmission on a population level by calculating the epidemic doubling time: the amount of time in which the cumulative incidence doubles [9, p 370]. The doubling time measures the rate at which the epidemic is growing, and an increase in doubling time indicates that transmission is decreasing. Little is known about the geographic variation of the doubling time in the United States before and after state-specific stay-at-home orders were enacted in an effort to reduce transmission.

METHODS

Data Sources

We used US COVD-19 surveillance data reported by the COVID-19 Data Repository at Johns Hopkins University, which sources data from multiple institutions, including the World Health Organization, several countries' centers for disease control, and ministries of health, to enumerate the official daily number of cases nationally and by state [6]. We determined the timing of state stay-at-home orders based on previous reports [10]. We used a "stringency index" to summarize the collective states' interventions, as developed by the University of Oxford Coronavirus Government Response Tracker. The tracker created the index from 8 indicators that capture policy measures to restrict, contain, or eliminate opportunities for transmission (eg, closure of nonessential businesses). It is noted that these indicators reflect the quantity and strictness of these policies, but cannot be used as a measure of the effectiveness of a state or country's policies [11].

Analysis

The epidemic doubling time was calculated using the following equation for national and state estimates in both time periods: $\log_e(2)/r$. This assumes a constant growth rate, r, within a given time period. The growth rate was calculated for changing incidence at each day by state. The harmonic mean doubling time and 95% confidence intervals (CIs) for both the national- and state-level cases were then calculated.

Rather than calculating epidemic doubling time over the entire 4-month period, we divided the time frame into 2 distinct periods: before and during the intervention (ie, stay-at-home order). This allowed us to compare epidemic doubling time between these 2 periods.

On the national level, we defined the 2 time periods as follows. Phase 1 was before heightened stringency, from 4 March

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(the date when 100 cumulative cases were reported nationwide), until 4 April 2020 (14 days after the states collectively reached a heightened stringency index of 67 [out of a possible total of 100]). Phase 2 was during heightened stringency, from 5 to 30 April 2020.

On the state level, we defined the 2 time periods as follows. Phase 1 was before a stay-at-home order, beginning on the date by which 100 cumulative cases were reported in that state and extending until 14 days after implementation of that state's stay-at-home order . Phase 2 was during the stay-at-home order, from the 15th day after the stay-at-home order until 30 April 2020.

For both national-level and state-level estimates, we added the 14-day buffer to the first time period to allow for the minimum time period that policy changes could potentially affect the number of new cases. Three states—Oklahoma, Utah, and Wyoming—enacted stay-at-home orders only in select counties or enacted for select counties on different dates; in these states, the most recent county-specific stay-at-home order date was used as the stay-at-home order date for the entire state.

Five states did not enact stay-at-home orders: Arkansas, Iowa, Nebraska, North Dakota, and South Dakota. In these states, we began by calculating doubling time over the entire time period, defined as from the date when 100 cumulative cases were reported until 30 April 2020. In addition, to allow for comparison with the other 45 states, we used 2 methods to approximate these time periods before and during stay-at-home orders.

With both methods, phase 1 began on the date by which 100 cumulative cases were reported in a state. With method 1, phase 1 extended for 21 days, the median duration of phase 1 among the 45 states that enacted a stay-at-home order. For method 2, phase 1 ended 14 days after implementation of the last state stay-at-home order (7 April in South Carolina). For both methods, phase 2 was defined as the remaining time period until 30 April 2020.

RESULTS

National Increases in COVID-19 Doubling Time

Nationally, the epidemic doubling time increased by 459.70% during phase 2 compared with phase1. The mean doubling time of COVID-19 in the United States during phase 1 was 2.68 days (95% CI, 2.30–3.24 days); this increased significantly during phase 2 to 15.00 days (12.89–17.94 days). Phase 1 spanned 31 days (from 4 March 2020, when 100 confirmed cases were reported in the United States, to 4 April 2020, 14 days after the United States reached a heightened stringency index on 21 March 2020), and phase 2 lasted 25 days (from 5 to 30 April 2020).

State-Level Increases in Doubling Time Among 45 States With Stay-at-Home Orders

Among the 45 states that implemented stay-at-home orders, during phase 1 the mean doubling time ranged from 2.50 days (New Jersey; 95% CI, 2.01–3.30 days) to 9.75 days (Alaska; 7.78–13.07 days) (Table 1 and Supplementary Figure 1), with the vast majority of states having doubling times between 2 and 6 days. The duration of time spent in phase 1 ranged from 9 days (Wyoming) to 33 days (Florida); the median duration of phase 1 was 21 days.

During phase 2, the mean doubling time ranged from 9.20 days (Minnesota; 95% CI, 7.70–11.44 days) to 70.43 days (Montana; 51.33–112.17 days) (Table 1 and Supplementary Figure 1). The duration of time spent in phase 2 ranged from 8 days (South Carolina) to 27 days (California), with a median duration of 17 days.

With the exception of Minnesota, all 45 states that implemented a stay-at-home order had a significantly longer epidemic doubling time in phase 2 than in phase 1. The absolute average increase was 15.43 days, and the increase ranged from 3.31 days (Minnesota) to 62.05 days (Montana). The relative average increase in doubling time was 335.53%, (95% CI, 277.0–394.0) and the percent increase ranged from 56.20% (Minnesota) to 883.61% (Louisiana) (Table 1 and Figure 1).

State-Level Increases in Doubling Time Among 5 States Without Stay-at-Home Orders

In the 5 states that did not implement a stay-at-home order, the mean doubling over the entire period from when the state reached 100 total cases until 30 April 2020 ranged from 6.03 days (Nebraska; 95% CI, 5.11–7.34 days) to 9.12 days (North Dakota; 7.31–12.10 days) (Table 2). The duration of this time period ranged from 30 days (North Dakota) to 41 days (Arkansas).

When we divided those 5 states without stay-at-home orders into phase 1 and phase 2 (Tables 3 and 4), both methods used to estimate those time periods showed relative increases in doubling time between phases, although the increases were smaller than observed among the other 45 states. Using our first definition, the relative increase in number of days it took for the number of new cases to double between Phase 1 to Phase 2 ranged from 30.34% (Nebraska) to 262.09% (South Dakota) and with the second definition it ranged from 11.21% (Nebraska) to 276.03% (South Dakota).

DISCUSSION

This analysis is among the first to describe the doubling time of COVID-19, a key metric of epidemic growth, in the United States during the first 4 months of the pandemic. We found increases in doubling time both nationally and at the state level when comparing phase 1 (before mitigation measures) to phase 2 (during mitigation measures). Increased doubling time indicates a slowing of the epidemic—more days are required for the cumulative number of cases to double.

Nationally, doubling time increased 459.70% from phase 1 to phase 2. During phase 1, the number of cases among susceptible persons doubled every 2.68 days, indicating rapid, sustained transmission. Notably, this prestringency doubling time in the United States is shorter than most early doubling time estimates

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Table 1. Coronavirus Disease 2019 Epidemic Doubling Time in 45 States With Stay-at-Home Orders

	Pre-Stay-at-Home Order		During Stay-at-Home Order		
State	Number of Days	Doubling Time, Harmonic Mean (95% CI), d	Number of Days	Doubling Time, Harmonic Mean (95% CI), d	Increase, %[a]
AK	13	9.75 (7.78–13.07)	16	41.64 (32.67–57.41)	327.08
AL	29	5.30 (4.19–7.20)	10	18.65 (14.75–25.38)	251.89
AZ	24	4.62 (3.51–6.75)	15	15.80 (13.72–18.63)	241.99
CA	24	3.56 (3.02–4.34)	27	13.09 (10.92–16.36)	267.70
CO	24	4.11 (3.21–5.74)	19	14.60 (11.67–19.51)	255.23
CT	17	3.12 (2.45–4.32)	22	12.01 (8.79–18.93)	284.94
DE	14	4.43 (3.57–5.84)	21	10.07 (8.26–12.90)	127.31
FL	33	4.15 (3.19–5.94)	12	29.83 (23.23–41.67)	618.80
GA	32	4.48 (3.54–6.09)	12	20.98 (16.24–29.63)	368.30
HI	10	5.12 (3.46–9.88)	20	41.36 (26.62–92.67)	707.81
ID	13	4.26 (2.91–7.92)	19	27.64 (18.96–51.00)	548.83
IL	18	3.00 (2.39–4.00)	25	11.20 (9.93–12.84)	273.33
IN	17	3.13 (2.51–4.16)	22	13.88 (12.21–16.07)	343.45
KS	20	5.27 (4.14–7.23)	16	9.91 (7.94–13.17)	88.05
KY	15	4.05 (3.25–5.38)	19	12.88 (9.93–18.31)	218.02
LA	21	2.99 (2.41–3.96)	23	29.41 (23.02–40.7)	883.61
MA	25	3.50 (2.91–4.37)	21	11.11 (9.21–14.00)	217.43
MD	25	3.92 (3.34–4.73)	16	13.35 (11.73–15.49)	240.56
ME	23	7.94 (6.09–11.41)	12	29.63 (22.22–44.46)	273.17
MI	20	2.73 (2.05–4.09)	22	21.48 (18.08–26.45)	686.81
MN	21	5.89 (4.69–7.93)	17	9.20 (7.70–11.44)	56.20
MO	29	4.93 (3.57–7.97)	9	24.59 (20.28–31.22)	398.78
MS	27	5.67 (4.53–7.59)	12	15.42 (13.17–18.60)	171.96
MT	15	8.38 (6.15–13.13)	16	70.43 (51.33–112.17)	740.45
NC	25	4.84 (3.91–6.34)	16	14.92 (13.29–17.00)	208.26
NH	14	4.64 (3.40–7.27)	17	12.38 (8.72–21.33)	166.81
NJ	19	2.50 (2.01–3.30)	25	15.05 (12.76–18.33)	502.00
NM	12	4.01 (2.84–6.84)	20	9.73 (7.36–14.37)	142.64
NV	24	5.54 (4.28–7.87)	13	19.60 (14.94–28.48)	253.79
NY	28	2.75 (2.18–3.72)	24	19.88 (16.19–25.74)	622.91
OH	18	3.44 (2.81–4.45)	23	12.01 (9.83–15.44)	249.13
OK	26	5.58 (4.11–8.67)	9	24.58 (18.62–36.12)	340.50
OR	15	4.65 (3.84–5.88)	23	20.02 (15.18–29.40)	330.54
PA	29	3.67 (3.05–4.6)	14	18.34 (15.26–22.96)	399.73
RI	18	4.02 (3.38–4.97)	16	9.45 (7.06–14.26)	135.07
SC	29	5.64 (4.36–8.00)	8	22.45 (18.32–28.97)	298.05
TN	27	4.60 (3.47–6.83)	14	15.88 (11.79–24.31)	245.22
TX	30	4.13 (3.25–5.68)	13	18.93 (15.65–23.97)	358.35
UT	24	5.41 (4.03–8.24)	14	17.50 (15.60–19.91)	223.48
VA	25	4.31 (3.65–5.26)	16	11.78 (10.70–13.11)	173.32
VT	14	6.15 (4.84–8.44)	20	43.14 (27.95–94.44)	601.46
WA	28	4.35 (3.37–6.13)	23	31.90 (24.82–44.65)	633.33
WI	21	4.56 (3.52–6.45)	21	16.83 (15.14–18.95)	269.08
WV	9	4.82 (3.72–6.84)	21	17.22 (12.45–27.87)	257.26
WY	11	8.73 (6.04–15.74)	18	17.14 (8.97–193.10)	96.33

Abbreviations: CI, confidence interval.

[a]All states experienced statistically significant increases in doubling time at the $P \leq .05$ level with the exception of Minnesota.

from Hubei Provence in China, which included 7.4 days (95% CI, 4.2–14 days) from 10 December 2019 to 4 January 2020 [5], and 6.4 days (5.8–7.1 days) from 1 to 31 December 2019 [12]. Our estimate for national doubling time before stay-at-home order is similar to that of China from 20 January to 9 February 2020, at <2 days [13], which may reflect rapid spread of infection in both countries during these time periods. Our estimates for after stay-at-home orders cannot yet be compared with other nations, because there is limited literature on doubling time for COVID-19 in a post-intervention setting.

Although doubling times increased in all states, the rate of increase was slower in states without than in those with

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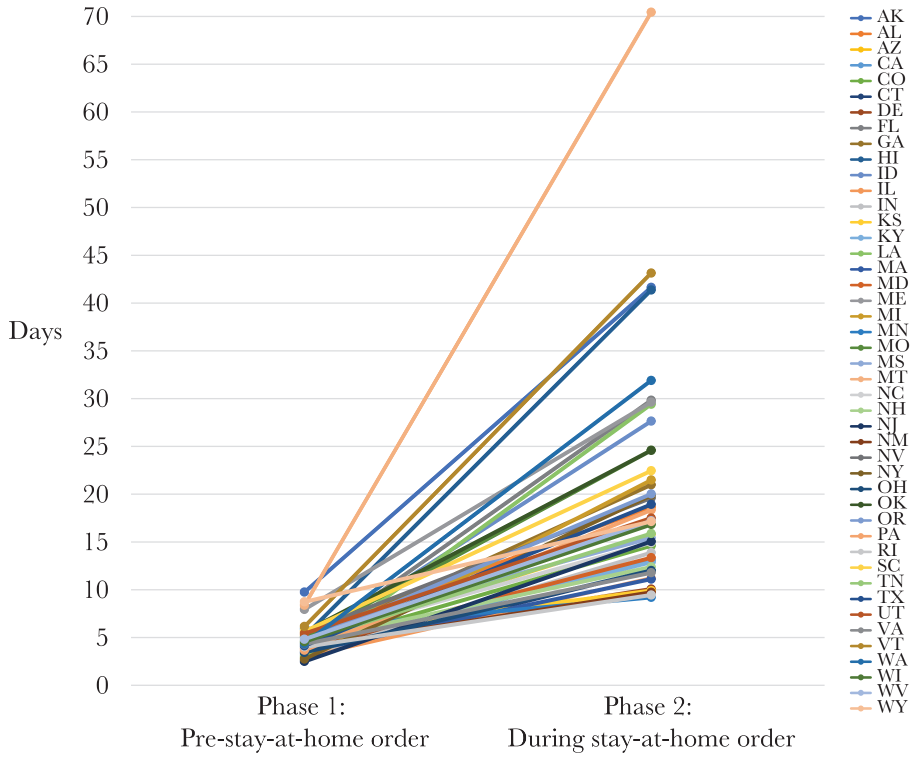

Figure 1. Coronavirus disease 2019 epidemic doubling time in 45 states with stay-at-home orders.

stay-at-home orders. The number of additional days it took for cases to double in phase 2 versus phase 1 was on average 12.27 days in the 45 states with and 6.0 days in the 5 states without stay-at-home orders. Among states without stay-at-home orders, the median increase in doubling time was 60.34% or 51.50% (depending on which definition we used for Phase 2) while for states with stay-at-home orders the median increase was 269.08%. Furthermore, 3 of the states without stay-at-home orders were among the bottom 4 states with the smallest percentage increase in doubling time, and 4 were in the bottom quintile nationally. These findings suggest that stay-at-home orders combined with varied levels of implementing practices of testing, tracing, and isolation recommended by the US Centers for Disease Control and Prevention, as well as travel restrictions, likely played a key role in significantly reducing the epidemic growth rate. These approaches have been demonstrated to be effective in outbreaks in general, and in the 2002 SARS pandemic specifically [14].

This analysis is limited to available surveillance data, which underreport the true number of cases and likely reflect selection bias [15]. Reporting is limited in part by each state's supply of and capacity to deliver diagnostic tests. Not all symptomatic persons were able to be tested, and asymptomatic persons were unlikely to be tested. Although the incidence is underestimated owing to these limitations, there is some consistency in the limitations, allowing for a reasonable approximation of doubling time. However, missing data, sources of bias, unmeasured confounding, and the nonrandomized design of the study prevent any causal inference between restrictions imposed and the trajectory of the epidemic. Furthermore, our analysis does not account for changes in testing capacity over time.

We estimate that the number of COVID-19 cases in the United States doubled about every 2 days from 4 March until 4 April 2020, which was 2 weeks after the states collectively were at their highest stringency index, and that this doubling time increased to 15 days after the higher stringency level was reached. Further increasing this length of time by slowing transmission—with the goal of stopping it—will rely on the extent to which urgently-needed additional testing, tracing, and isolation are effectively implemented. As states lift and then reestablish some restrictions, additional research is needed to evaluate the

Table 2. Coronavirus Disease 2019 epidemic doubling time in 5 states without stay-at-home orders

State	Number of Days[a]	Doubling Time, Harmonic Mean (95% CI), d
AR	41	8.14 (6.58–10.67)
IA	38	6.24 (5.36–7.47)
ND	30	9.12 (7.31–12.10)
NE	32	6.03 (5.11–7.34)
SD	31	6.74 (5.50–8.71)

Abbreviation: CI, confidence interval.

[a]Time period for each state begins on the date when 100 total confirmed cases were reported in that state until April 30, 2020.

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Table 3. Coronavirus Disease 2019 epidemic doubling time in 5 states without stay-at-home orders[a]

	Phase 1		Phase 2		
State	Number of Days	Doubling Time, Harmonic Mean (95% CI), d	Number of Days	Doubling Time, Harmonic Mean (95% CI), d	Increase, %[b]
AR	21	5.92 (4.68–8.03)	19	13.40 (9.85–20.94)	126.35
IA	21	5.22 (4.33–6.56)	16	8.37 (6.80–10.89)	60.34
ND	20	7.92 (6.07–11.41)	9	12.36 (10.00–16.15)	56.06
NE	21	5.57 (4.54–7.19)	10	7.26 (5.41–11.04)	30.34
SD	21	5.17 (4.39–6.30)	9	18.72 (14.47–26.51)	262.09

Abbreviation: CI, confidence interval.

[a]Phase 1 is defined for each state as the date when 100 total confirmed cases were reported until 21 days, which was the median length of Phase 1 across the 45 states that enacted a stay-at-home order. Phase 2 is defined as 22 days after 100 confirmed cases were reported until April 30, 2020.

[b]Only South Dakota had a statistically significant increase at the $P < 0.05$ level.

Table 4. Coronavirus Disease 2019 epidemic doubling time in 5 states without stay-at-home orders[a]

	Phase 1		Phase 2		
State	Number of Days	Doubling Time, Harmonic Mean (95% CI), d	Number of Days	Doubling Time, Harmonic Mean (95% CI), d	Increase, %[b]
AR	32	7.42 (5.91–9.95)	8	15.16 (8.76–56.38)	104.31
IA	29	5.67 (4.83–6.87)	8	8.59 (6.37–13.19)	51.50
ND	21	8.19 (6.27–11.84)	8	12.27 (9.66–16.82)	49.82
NE	23	5.80 (4.73–7.50)	8	6.45 (4.89–9.48)	11.21
SD	22	5.34 (4.49–6.58)	8	20.08 (15.32–29.13)	276.03

Abbreviation: CI, confidence interval.

[a]With method 2, phase 1 begins on the date by which 100 total confirmed cases were reported for the state and ends on 21 April 2020 (14 days after the last stay-at-home order was enacted in the United States, 7 April 2020 in South Carolina). Phase 2 is from 22 April 2020, the 15th day, until 30 April 2020.

[b]All states experienced statistically significant increases at the $P = .05$ level except Iowa and Nebraska.

evolving epidemiology of COVID-19 in the United States and the impact of interventions aimed at slowing its spread.

Supplementary Data

Supplementary materials are available at *The Journal of Infectious Diseases* online. Consisting of data provided by the authors to benefit the reader, the posted materials are not copyedited and are the sole responsibility of the authors, so questions or comments should be addressed to the corresponding author.

Notes

Author contributions. M. N. L. conceptualized the study and led the writing of the manuscript. J. S. co-led the writing of the manuscript and led the design of the data visualizations. J. S. and R. R. Y. led the literature review. J. T. conducted the initial analysis, and R. R. Y. conducted the subsequent analysis. All authors contributed to the writing and analysis of the manuscript and reviewed and commented on earlier drafts.

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