COVID-19 epidemic doubling time in the United States before and during stay-at-home restrictions

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ABSTRACT

Introduction: 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: Epidemic doubling time in the US was 2.68 days (95%CI:2.30–3.24) prior to widespread mitigation efforts, increasing by 460% to 15 days (95%CI:12.89-17.94) during the mitigation phase. Among states without stay-at-home orders, median increase in doubling time was 60% (95%CI: 9.2-223.3) while for states with stay-at-home orders, median increase was 269% (95%CI: 277.0-394.0).

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

KEYWORDS
COVID-19, Coronavirus, SARS-CoV-2, epidemic doubling time

SUMMARY

COVID-19 spread rapidly throughout the US in early 2020. Epidemic doubling time increased significantly during mitigation efforts compared to the period prior to stay-at-home orders, and states that implemented stay-at-home orders experienced significantly increased doubling time compared to states without.
INTRODUCTION

Over the last two decades, three novel coronaviruses have emerged: severe acute respiratory syndrome (SARS) in 2002 (1,2,3), Middle East respiratory syndrome (MERS) in 2012 (4), and a second, different respiratory syndrome (COVID-19), caused by SARS-CoV-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 (US) was reported in Washington on January 20, 2020 (7), and the first suspected occurrence of community spread was reported by the US Centers for Disease Control and Prevention (CDC) on February 26, 2020 (8), for a total of 15 reported cases in the country. By March 4, 2020 all states reported at least 100 cases (6) and by the end of April the US, with just over 4.2% of the global population, accounted for 32.8% of all reported infections (6).

Understanding the rapid transmission within the US is critical to informing interventions, but calculating the basic reproductive number, $R_0$, which describes transmission on an individual level, is relatively complex, and is 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). 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 US before and after state-specific stay-at-home orders were enacted in an effort to reduce transmission.
METHODS

Data sources

We utilized US COVID-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 (WHO), several countries’ CDCs, 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 (OxCGRT). The OxCGRT created the index from eight indicators that capture policy measures to restrict, contain, or eliminate opportunities for transmission (e.g., closure of non-essential businesses). OxCGRT notes 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

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 for both the national and state-level cases were then calculated.
Rather than calculating epidemic doubling time over the entire four-month period, we divided the timeframe into two distinct periods: pre-intervention and during the intervention (i.e. stay-at-home order). This allowed us to compare epidemic doubling time between these two periods.

On the national level, we defined the two time periods as:

1) Phase 1: Pre-heightened stringency. March 4, 2020, the date when 100 cumulative cases were reported nationwide, until April 4, 2020, 14 days after the states collectively reached a heightened stringency index of 67 out of 100;

2) Phase 2: During heightened stringency. April 5 until April 30, 2020.

On the state level, we defined the two time periods as:

1) Phase 1: Pre-stay-at-home order: the date by which 100 cumulative cases were reported in that state until 14 days after that state’s stay-at-home order was implemented;

2) Phase 2: During the stay-at-home order: the 15th day after the stay-at-home order until April 30, 2020

For both national 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 impact the number of new cases. Three states enacted stay-at-home orders only in select counties or enacted for select counties on different dates: Oklahoma, Utah, and Wyoming. 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 the date when 100 cumulative cases were reported until April 30. In addition, to allow for comparison to the other 45 states, we used two methods to approximate these pre- and during stay-at-home order time periods.

For each method, we defined Phase 1 as:

1) Method 1: The date by which 100 cumulative cases were reported in that state plus 21 days, which was the median duration of Phase 1 among the 45 states that enacted a stay-at-home order;

2) Method 2: The date by which 100 cumulative cases were reported in that state until 14 days after the last state stay-at-home order (April 7, South Carolina) was implemented.

For both methods, Phase 2 was defined as the remaining time period until April 30, 2020.
RESULTS

National increases in COVID-19 doubling time

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

State-level increases in doubling time among 45 states that implemented 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) to 9.75 days (Alaska, 95% CI: 7.78–13.07) (Table 1a and Supplementary Figure 2) with the vast majority of states having doubling times between 2 and 6 days. The duration of time each state spent in Phase 1 ranged from 9 days (Wyoming) to 33 days (Florida); the median Phase 1 time period lasted 21 days.

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

With the exception of Minnesota, all 45 states that implemented a stay-at-home order had a statistically significant longer epidemic doubling time in Phase 2 compared to Phase 1. The
The absolute average increase was 15.43 days, and the increase ranged from 3.31 (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 five states that did not implement stay-at-home orders

In the five states that did not implement a stay-at-home order, the mean doubling over the entire period time from each state’s 100 total cases until April 30, 2020 ranged from 6.03 (Nebraska, 95% CI: 5.11–7.34) to 9.12 days (North Dakota, 95% CI: 7.31–12.10) (Table 1b). The number of days during this time period ranged from 30 (North Dakota) to 41 days (Arkansas).

When we divided those five states into Phase 1 and Phase 2 (Tables 1c and 1d) both methods used to estimate those time periods showed relative increases in doubling time between Phase 1 and Phase 2, although those increases were smaller than those 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 US 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 pre-stringency doubling time in the US is shorter than most early doubling time estimates from Hubei Provence in China, which included 7.4 days (95% CI: 4.2-14) from December 10, 2019 – January 4, 2020 (5), and 6.4 days (95% CI: 5.8-7.1) from December 1, 2019 – December 31, 2019 (12). Our estimate for national doubling time before stay-at-home order is similar to that of China from January 20, 2020 – February 9, 2020 at less than 2 days (13), which may reflect rapid spread of infection in both countries during these time periods. Our estimates for post-stay-at-home orders cannot yet be compared with other nations, as there is limited literature for doubling time for COVID-19 in a post-intervention setting.

While doubling time increased in all states, the rate of increase was slower in states without stay-at-home orders compared to states with 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 stay-at-home orders and 6.0 days in the five 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, three of the states without stay-at-home orders were among the bottom four states with the smallest percentage increase in doubling time and four were in the bottom quintile nationally. These findings suggest that stay-at-home orders combined with varied levels of implementing CDC-recommended practices of testing, tracing, and isolation, 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 severe acute respiratory syndrome pandemic specifically (14).

This analysis is limited to available surveillance data, which under-report the true number of cases and likely reflects selection bias (15). Reporting is limited in part by each state’s supply of and capacity to deliver diagnostic testing. Not all symptomatic persons were able to be tested, and asymptomatic cases were unlikely to be tested. While incidence is underestimated due 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 non-randomized design of the study prevent any causal inference between restrictions imposed and epidemic trajectory. Furthermore, our analysis does not account for changes in testing capacity over time.

We estimate that the number of COVID-19 cases in the US doubled about every two days from March 4, 2020 until April 4, 2020, two weeks after the states collectively were at their highest stringency index, and that this 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 is effectively implemented. As states lift and then re-establish some restrictions, additional research is needed to evaluate the evolving epidemiology of COVID-19 in the US and the impact of interventions aimed at slowing its spread.
AUTHOR CONTRIBUTIONS

ML conceptualized the study and led the writing of the manuscript. JS co-led the writing of the manuscript and led the design of the data visualizations. RY and JS led the literature review; JT conducted the initial analysis and RY conducted the subsequent analysis. All co-authors contributed to the writing and analysis of the paper. All authors reviewed and commented on previous drafts of the manuscript.

CONFLICT OF INTEREST DISCLOSURES

The authors have declare that we have no conflicts of interest to disclose.

FUNDING/SUPPORT:

This study received no external funding.
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Table 1a. COVID-19 Epidemic Doubling Time in 45 states with stay-at-home orders

| State | Pre-Stay-at-Home Order | During Stay-at-Home Order |
|-------|-------------------------|---------------------------|
|       | Number of Days | Doubling Time (Harmonic Mean) | 95% Confidence Interval | Number of Days | Doubling Time (Harmonic Mean) | 95% Confidence Interval | Percent Increase |
| 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 | 13.88 (12.21, 16.07) | 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 |
| State | Ratio | Lower CI | Upper CI | Doubling Time | Lower CI | Upper CI |
|-------|-------|----------|----------|---------------|----------|----------|
| 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 |

* All states experienced statistically significant increases in doubling time at the p = <0.05 level with the exception of Minnesota
### Table 1b. COVID-19 epidemic doubling time in 5 states without stay-at-home orders

| State | Number of Days | Doubling Time (Harmonic Mean) | 95% Confidence Interval |
|-------|----------------|-------------------------------|-------------------------|
| 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)            |

Note that this time period for each state begins on the date when 100 total confirmed cases were reported until April 30, 2020.

### Table 1c. COVID-19 epidemic doubling time in 5 states without stay-at-home orders

| State | Number of Days | Doubling Time (Harmonic Mean) | 95% Confidence Interval | Percent Increase |
|-------|----------------|-------------------------------|-------------------------|------------------|
| AR    | 21             | 5.92                          | (4.68, 8.03)            | 126.35           |
| IA    | 21             | 5.22                          | (4.33, 6.56)            | 60.34            |
| ND    | 20             | 7.92                          | (6.07, 11.41)           | 56.06            |
| NE    | 21             | 5.57                          | (4.54, 7.19)            | 30.34            |
| SD    | 21             | 5.17                          | (4.39, 6.30)            | 262.09           |

*Only South Dakota had a statistically significant increase at the p < 0.05 level

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.

### Table 1d. COVID-19 epidemic doubling time in 5 states without stay-at-home orders

| State | Number of Days | Doubling Time (Harmonic Mean) | 95% Confidence Interval | Percent Increase |
|-------|----------------|-------------------------------|-------------------------|------------------|
| AR    | 32             | 7.42                          | (5.91, 9.95)            | 104.31           |
| IA    | 29             | 5.67                          | (4.83, 6.87)            | 51.50            |
| ND    | 21             | 8.19                          | (6.27, 11.84)           | 49.82            |
| NE    | 23             | 5.80                          | (4.73, 7.50)            | 11.21            |
| SD    | 22             | 5.34                          | (4.49, 6.58)            | 276.03           |

* All states experienced statistically significant increases at the p = 0.05 level except Iowa and Nebraska
Phase 1 is defined for each state as the date when 100 total confirmed cases were reported until 14 days after the last stay-at-home order was enacted in the US (April 7, 2020 in South Carolina). Phase 2 is defined as the fifteenth day until April 30, 2020.
Figure 1: COVID-19 epidemic doubling time in 45 states

Phase 1: Pre-stay-at-home order

Phase 2: During stay-at-home order