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Research paper

Estimating under-recognized COVID-19 deaths, United States, march 2020-may 2021 using an excess mortality modelling approach ☆

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A B S T R A C T

Background: In the United States, Coronavirus Disease 2019 (COVID-19) deaths are captured through the National Notifiable Disease Surveillance System and death certificates reported to the National Vital Statistics System (NVSS). However, not all COVID-19 deaths are recognized and reported because of limitations in testing, exacerbation of chronic health conditions that are listed as the cause of death, or delays in reporting. Estimating deaths may provide a more comprehensive understanding of total COVID-19–attributable deaths.

Methods: We estimated COVID-19 unrecognized attributable deaths, from March 2020—April 2021, using all-cause deaths reported to NVSS by week and six age groups (0–17, 18–49, 50–64, 65–74, 75–84, and ≥85 years) for 50 states, New York City, and the District of Columbia using a linear time series regression model. Reported COVID-19 deaths were subtracted from all-cause deaths before applying the model. Weekly expected deaths, assuming no SARS-CoV-2 circulation and predicted all-cause deaths using SARS-CoV-2 weekly percent positive as a covariate were modelled by age group and including state as a random intercept. COVID-19–attributable unrecognized deaths were calculated for each state and age group by subtracting the expected all-cause deaths from the predicted deaths.

Findings: We estimated that 766,611 deaths attributable to COVID-19 occurred in the United States from March 8, 2020—May 29, 2021. Of these, 184,477 (24%) deaths were not documented on death certificates. Eighty-two percent of unrecognized deaths were among persons aged ≥65 years; the proportion of unrecognized deaths were 0•24–0•31 times lower among those 0–17 years relative to all other age groups. More COVID-19–attributable deaths were not captured during the early months of the pandemic (March–May 2020) and during increases in SARS-CoV-2 activity (July 2020, November 2020—February 2021).

Interpretation: Estimating COVID-19–attributable unrecognized deaths provides a better understanding of the COVID-19 mortality burden and may better quantify the severity of the COVID-19 pandemic.

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Research in Context

Evidence before this study The World Health Organization declared a global pandemic on March 11, 2020 in response to the emergence and spread of Coronavirus Disease 2019 (COVID-19). Early estimates of excess deaths from the COVID-19 pandemic have been published, however, these studies have been unable to attribute these excess deaths to the SARS-CoV-2 virus and may overestimate the impact of the pandemic on mortality. We conducted a PubMed literature search using the following search terms: "COVID-19", "deaths", "SARS-CoV-2", "mortality", "excess mortality", and "death estimates" to identify any publications related to estimating deaths during the COVID-19 pandemic. We identified studies completed in the United States, but found limitations to the methods of these studies and opportunities to improve the approach and produce more reliable estimates of COVID-19 attributable deaths. Previous studies used excess mortality, time series ecological models with historic death counts to estimate the deaths that would be expected to occur from all-causes regardless of SARS-CoV-2 circulation and the COVID-19 pandemic. These studies calculated the excess deaths by subtracting the estimated expected deaths from the total number of all-cause deaths reported during the study period without incorporating viral surveillance data. Death patterns during a pandemic or unexpected event may be different compared with time periods before the pandemic, thus historic death data may not adequately capture these changes in death patterns during the pandemic period. Further, a pandemic may bring about changes in health seeking behaviours in the population, inability to access care, disruptions in availability of medications or treatments, and limitations in hospital and emergency department capacity, all of which may not have been observed before the pandemic. Additionally, without accounting for at least the SARS-CoV-2 circulation, models may overestimate excess deaths because of the assumption that all deaths above those deaths that were estimated as being expected to occur regardless of COVID-19 are attributable to the COVID-19 pandemic.

Added value of this study Our study estimated COVID-19–attributable that were unrecognized on death certificates in the United States from March 8, 2020—May 29, 2021 accounting for SARS-CoV-2 circulation and using death data from only the pandemic period to estimate both expected deaths, assuming no SARS-CoV-2 circulation and predicted deaths, accounting for the circulation patterns of SARS-CoV-2. Previous studies estimating COVID-19 excess deaths during the pandemic utilized historic death data from prior seasons to measure expected deaths for hte pandemic period and capture the typical patterns of death that would be expected regardless of the COVID-19 pandemic. In contrast, our study used data from the beginning of the COVID-19 pandemic and developed a model that could estimate expected deaths only relying on current death counts, which might reduce the possibility of underestimating the expected pattern of deaths during the pandemic period. Additionally, prior studies estimating excess deaths during the COVID-19 pandemic did not account for the circulation of SARS-CoV-2, whereas our model incorporated SARS-CoV-2 viral surveillance data to account for virus circulation by state, age, and time. Accounting for SARS-CoV-2 circulation reduces the risk of overestimating COVID-19 attributable deaths.

Implications of all the available evidence Our estimates of COVID-19–attributable unrecognized deaths improve on previous excess death estimates and better describe the burden of the COVID-19 pandemic on mortality by including SARS-CoV-2 viral surveillance data and not relying historic death data to estimate expected all-cause deaths across time. The findings from this study improve our understanding about the burden of SARS-CoV-2 infections on mortality and better understand the severity of the COVID-19 pandemic. The model allows for age-group and state-specific estimates of COVID-19–attributable and unrecognized deaths. The study also emphasizes the continued need to support detect, prevent, and control COVID-19, especially as over time the world begins to transition out of the pandemic.

1. Background

Infections with Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2), the virus that causes Coronavirus Disease 2019 (COVID-19), are nationally notifiable in the United States [1,2]. States and territories report SARS-CoV-2 infections and deaths through the National Notifiable Disease Surveillance System (NNDSS) to the Centers for Disease Control and Prevention (CDC). Deaths from all causes in the United States are reported to the National Vital Statistics System (NVSS) within the National Center for Health Statistics (NCHS), CDC [3]. NVSS classifies deaths using the International Classification of Diseases, 10th Edition (ICD-10) codes and if COVID-19 is listed on the death certificate as either an underlying or contributing cause of death, the death is assigned the ICD-10 code for COVID-19 [4-7]. As of May 29, 2021, 589,526 aggregate COVID-19 deaths were reported on the CDC COVID-19 Data Tracker [8] and 582,135 COVID-19 deaths were reported to NVSS [9].

Counting deaths via either nationally notifiable disease reporting or vital statistics might underestimate the full burden of COVID-19 mortality, as was observed during the 2009 influenza A(H1N1) pandemic when globally reported deaths were approximately 11 times lower than the estimated mortality burden [10,11]. Some reasons that reported deaths may be underestimates include that persons who die from COVID-19 might not seek medical care, or might seek care when the virus is no longer detectable, or those who do seek care might not be tested for SARS-CoV-2 infection [12-14]. Additionally, test results might be unavailable or incorrect because of timing of specimen collection, inadequate quality or quantity of the specimen collected, or sensitivity of the assay [15]. Further, there are delays in death reporting to local public health officials and national surveillance systems [16]. For patients with COVID-19, death can occur several days or weeks after being tested and reported and the death might be incorrectly attributed to a cause other than COVID-19 because of the time between identification and death [17-20]. Also, SARS-CoV-2 infections may result in nonrespiratory complications or exacerbate chronic conditions, which can lead to death (e.g., sepsis, circulatory diseases, respiratory diseases, diabetes, or renal failure), and COVID-19 might be incorrectly omitted as a contributing cause of death on the death certificate [17,20-23]. Several years of monitoring influenza deaths have provided evidence that influenza is not always listed as a cause of death although it likely contributed to the death [24-26]. Furthermore, guidance for certifying COVID-19 deaths was issued in March 2020 and the ICD-10 code for COVID-19 was not available or widely used on death certificates until April 2020, and it is possible that death certifiers did not revise death certificates issued before that point to reflect the role of COVID-19 in the death [4-7].

Statistical models have been used to describe COVID-19 deaths [27-40], using similar excess mortality methods that have been used to estimate influenza-associated deaths [24-26,41,42]. Prior models estimating COVID-19 deaths used historic cause-specific mortality data to estimate expected deaths over time with different approaches to account for seasonal trends in deaths. Expected deaths were those deaths from other causes that were presumed to happen during the analtyic time series assuming no SARS-CoV-2 circulation and excess deaths were calculated by subtracting the expected deaths from reported all-cause deaths [27-40,42]. These methods are not able to distinguish between deaths that may represent misclassified COVID-19 deaths, but that may have been missed or not recorded and those deaths that may have occurred as a result of avoidance of emergency care or other factors which may have changed over the course of pandemic (e.g., hospital overcrowding, increased drug overdoses, or other complications or exacerbations which may have resulted in death because of disruptions in treatment access). These methods are further limited because without accounting for virus circulation, the resulting excess death estimates include both the misclassified COVID-19 deaths and deaths related to other factors from the pandemic, such as the inability to get necessary medical care [26]. To better quantify and estimate the number of excess deaths that were not captured as COVID-19 deaths or unrecognized on death certificates, we developed a regression model, using 2020–2021 all-cause mortality data reported to NVSS and SARS-CoV-2 viral surveillance data for six age groups across 50 states, New York City, and the District of Columbia.

2. Methods

2.1. Mortality Data

Deaths are reported to NVSS using a standardized death certificate with information on the deceased's demographics, date of death, place of death, and the chain of events leading to death, from which a single underlying cause of death is selected, and, if applicable, multiple contributing causes are determined. To classify cause-specific deaths, ICD-10 codes are assigned to diseases and conditions reported on the death certificate based on standardized coding rules, the process can take weeks to months and these data are typically not available in real-time [43]. Although COVID-19 can exacerbate certain chronic health conditions or may result in acute complications, complete real-time counts for all cause-specific deaths were not available at the time of this analysis. Further, guidance for reporting COVID-19 deaths on death certificates was finalized in April 2020 and before this time, few death certificates included COVID-19 as a cause of death [5-7]. In contrast, all-cause death data are available more rapidly, in near real-time, and, only lag real-time by one to two weeks [44]. We utilized all-cause deaths categorized into epidemiologic week (week when the deaths occurred) by state and six age groups: 0–17 years, 18–49 years, 50–64 years, 65–74 years, 75–84 years, and ≥85 years to estimate unrecognized COVID-19 deaths. Information on all data sources are in eTable 1.

Although all-cause deaths capture any death that occurs regardless of cause and are available in near real-time, there are delays in the death reporting, which can vary by jurisdiction [45,46]. To account for delays in death reporting, we used two approaches to adjust all-cause death counts for weeks where death reporting was incomplete. The first approach weighted the reported all-cause death counts per week by the inverse of the estimated completeness at the time the model was implemented [44]. The second approach used a completeness percent calculated by comparing the death count in a given week from the pandemic period to the average death count in that same week from the previous five years [46]. All-cause deaths were adjusted for reporting delays when the weighted under-reporting percent was less than one. If the weighted under-reporting percent was missing, all-cause deaths were adjusted if the completeness percent was less than one. Additional details regarding adjustment for completeness are available in the Appendix Methods.

Deaths resulting from COVID-19 are reported through death certificates either using the ICD-10 assigned code or through free text on the form as either the underlying cause or a contributing cause of death. The number of COVID-19 deaths are reported each week by state and week or by age and state for the entire pandemic period [3]. However, if the number of COVID-19 deaths by state and week or by week and age group are fewer than ten, these data are suppressed to protect privacy of the deceased. Because there were few deaths in the 0-17 year age group and data suppression limited the ability to calculate the number of deaths by state, week, and age group, we requested and obtained restricted unsuppressed COVID-19 death data [47]. In addition, NVSS routinely releases COVID-19 deaths for each state, age group, and month; however, our model required COVID-19 deaths by state, age group and week. To calculate COVID-19 deaths by state, age group, and week, first the percent of COVID-19 deaths by age group within each state was calculated and then applied to the reported, unsuppressed COVID-19 deaths by state and week. Because we obtained unsuppressed COVID-19 death counts for the 0-17 year age group and state, we did not need to estimate these deaths . Total all-cause deaths by age group and state are in eTable 2. Before estimating COVID-19–attributable unrecognized deaths, unadjusted and unsuppressed COVID-19 deaths by age group, state, and week were subtracted from completeness-adjusted all-cause deaths.

2.2. SARS-CoV-2 Surveillance Data

Viral surveillance data were used as a proxy for SARS-CoV-2 circulation to estimate the predicted number of all-cause deaths, accounting for virus circulation. The percent positive of SARS-CoV-2 tests across states and age groups was calculated from viral surveillance data including: the Electronic Surveillance System for the Early Notification of Community-based Epidemics (ESSENCE) [48] commercial laboratories, which represents diverse geographic areas across the United States and report SARS-CoV-2 testing information, test results, and basic demographic data. Real-time reverse transcriptase polymerase chain reaction (rt-PCR) SARS-CoV-2 test and result data were obtained by state, age group, and week. These data were combined with SARS-CoV-2 testing results reported by public health laboratories through the Public Health Laboratory Interoperability Project (PHLIP) [49] and Public Health Laboratory Information System 2 (PHLIS2) by age group and state for each week. The SARS-CoV-2 percent positive was calculated by dividing the number of positive SARS-CoV-2 results by the total number of SARS-CoV-2 tests, defined as tests with a known result, by age group and state from both systems (eFigure 1).

The time from illness onset or a SARS-CoV-2 laboratory test to death can vary from several days to weeks. Reports on COVID-19 deaths have indicated that time to death ranged from 8–21 days [17-20,50]. To adjust for time to death, the SARS-CoV-2 percent positive was lagged by one and two weeks in the model. If the SARS-CoV-2 percent positive was missing, the percent positive was carried forward from the week prior (eTable 2).

2.3. Population Data

Vintage 2019 population data were obtained from the U.S. Census Bureau [51]. Population data were summed across age group and state (eTable 2).

2.4. Regression Model

To estimate COVID-19–attributable unrecognized deaths among all-cause deaths without COVID-19 listed as a death cause, we used an excess mortality model. To avoid double counting, any deaths where the death certificate listed COVID-19 as an underlying or contributing cause of death were subtracted and the remaining all-cause deaths were modelled (Figure 1). Removing COVID-19 deaths also reduced potential underestimation in the calcula-

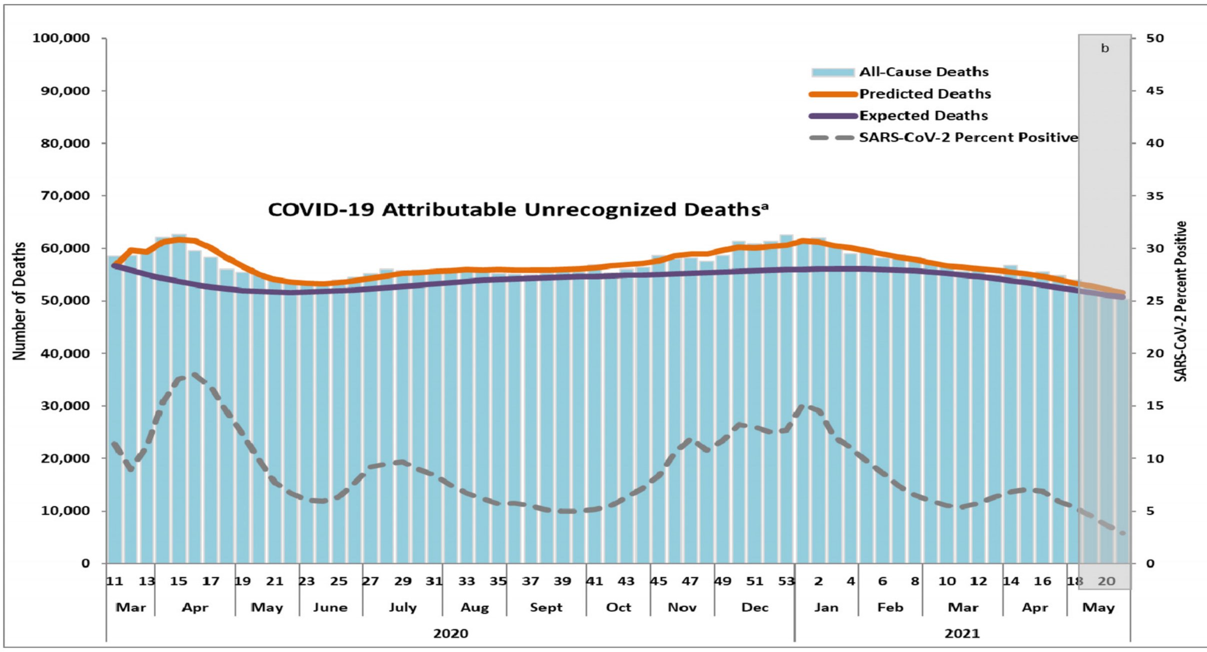

Figure 1. All-cause deaths after removing COVID-19 coded deaths, estimated expected deaths assuming SARS-CoV-2 circulation, predicted deaths accounting for circulation of SARS-CoV-2, and SARS-CoV-2 percent positive in United States by epidemiologic week for March 8, 2020—May 29, 2021 for all ages
a COVID-19–attributable unrecognized deaths were calculated as the difference between predicted deaths accounting for SARS-CoV-2 circulation and expected deaths assuming no circulation of the virus.
b Deaths reported in most recent weeks may still underestimate the total number of all-cause deaths after being corrected due to increases in deaths and delays in reporting during the pandemic.

tion of COVID-19–attributable unrecognized deaths because some reported COVID-19 deaths could be misclassified to another cause. We fit a random-intercept, over-dispersed quasi-Poisson log-linear model separately by six age groups between weekly corrected all-cause death counts minus COVID-19 deaths (E) and a 1-week and 2-week lag of state-specific viral surveillance data where $x_{s,w}$ is the percent positive for state s during week w in 2020 or 2021. Using 1-week and 2-week lagged (i.e. 8–21 days) SARS-CoV-2 percent positive as proxies for virus activity, we fit the model:

$$logE[z_{sw}] = \beta_0 + log(Pop_s) + \beta_1 x_{s,w-1}M(w) + \beta_2 x_{s,w-2}M(w) + g(w) + \theta_s$$

where $g(w)$ is a smooth temporal function modelled using natural cubic splines with 3 degrees of freedom for the 0-17 and 18-49 year age groups and 5 degrees of freedom for the other age groups, $M(w)$ is the month of year for week w, θ_s are random intercepts for states, and $x_{s,w}= 0$ or the absence of SARS-CoV-2 circulation (eFigure 6). θ_s follows a Normal distribution with mean of zero and a heterogeneous variance. The quasi-Poisson model does not assume that the over-dispersion is a function of the mean of reported deaths. We assumed a multiplicative relationship between the SARS-CoV-2 percent positive and all-cause deaths and used age group-specific population as the offset term to ensure that the estimated predicted deaths were not greater than the population. Natural cubic splines were used to model the pattern of all-cause deaths during the time series and to estimate expected deaths. A term for month was included to avoid overfitting the patterns of weekly all-case deaths.

The COVID-19–attributable unrecognized deaths $AD_{s,w}$ (Figure 1, eFigure 4) were defined as the difference between (1) predicted death counts assuming that SARS-CoV-2 circulation is the observed weekly SARS-CoV-2 percent positive and (2) expected death counts (e.g., deaths that would be expected occur each week regardless of SARS-CoV-2 circulation including those deaths due to injuries, accidents, or other causes unrelated to the pandemic) assuming no SARS-CoV-2 circulation (i.e., a zero SARS-CoV-2 percent positive and setting covariates $x_{s,w-2}$ and $x_{s,w-1}$ to zero):

$$AD_{sw} = e^{\beta_0 + g(w) + \theta_s}\left[e^{\beta_1 x_{s,w-1}M(w) + \beta_2 x_{s,w-2}M(w)} - 1\right].$$

When the difference between predicted and expected deaths was negative, the negative value was truncated to zero. Negative COVID-19 attributable deaths can occur when predicted deaths are lower than the expected deaths in a given week, indicating that there were no deaths in that week that were attributable to COVID-19 and tend to occur during periods of lower SARS-CoV-2 circulation. To estimate the uncertainty of the COVID-19–attributable unrecognized death estimates, we used Monte Carlo simulation with 5,000 iterations to obtain interval estimates for COVID-19–attributable unrecognized deaths $AD_{s,w}$. The 5,000 samples of all fixed-effect regression parameters were drawn from their asymptotic multivariate normal distribution. For each sample, we calculated $AD_{s,w}$ as above and defined the 95% uncertainty interval (UI) as the 2•5th and 97•5th quantiles of simulated $AD_{s,w}$. The estimated COVID-19–attributable unrecognized death count by state and age group is the mean estimated death after summing the iterations across the weeks. To calculate estimates by HHS Region, we summed iterations across week and states within a region and calculated the mean and the 95% uncertainty intervals from the distribution.

Analyses were completed in SAS Statistical Software Version 9•4 (SAS Institute, Inc., Cary, NC, USA) and the R project for statistical computing (version 4•0•3) [52]. This activity was reviewed by CDC and was conducted consistent with applicable federal law and CDC policy.[1] No funding was received for this study.

[1] See e.g., 45 C.F.R. part 46, 21 C.F.R. part 56; 42 U.S.C. §241(d); 5 U.S.C. §552a; 44 U.S.C. §3501 et seq.

Table 1
Estimated unrecognized COVID-19–attributable deaths and rates per 100,000 population from March 8, 2020–May 29, 2021

	Unrecognized Deaths	95% UI [a]	Percent of Unrecognized Deaths	Unrecognized death rate per 100,000 population	95% UI [a]
Age Group, years					
0–17	22	(0–139)	0•0%	0•0	(0•0–0•2)
18–49	7,681	(4,865–10,870)	4•2%	5•6	(3•5–7•9)
50–64	25,182	(21,489–28,903)	13•7%	40•0	(34•1–45•9)
65–74	34,993	(31,295–38,659)	19•0%	111•1	(99•4–122•8)
75–84	51,435	(47,542–55,458)	27•9%	322•1	(297•7–347•3)
≥85	65,163	(60,926–69,586)	35•3%	986•6	(922•4–1,053•5)
HHS Region					
1 (CT, MA, ME, NH, RI, VT)	7,324	(6,899–7,755)	4•0%	49•3	(46•5–52•2)
2 (NJ, NY, NYC)	16,137	(15,113–17,157)	8•8%	56•9	(53•3–60•5)
3 (DE, DC, MD, PA, VA, WV)	19,125	(17,935–20,307)	10•4%	62•0	(58•1–65•8)
4 (AL, FL, GA, KY, MS, NC, SC, TN)	44,062	(41,233–46,881)	23•9%	65•9	(61•6–70•1)
5 (IL, IN, MI, MN, OH, WI)	31,910	(29,883–33,913)	17•3%	60•7	(56•9–64•5)
6 (AR, LA, NM, OK, TX)	26,751	(24,972–28,534)	14•5%	62•6	(58•5–66•8)
7 (IA, KS, MO, NE)	10,354	(9,686–11,012)	5•6%	73•2	(68•5–77•9)
8 (CO, MT, ND, SD, UT, WY)	3,755	(3,516–3,993)	2•0%	30•6	(28•7–32•6)
9 (AZ, CA, HI, NV)	20,419	(19,172–21,675)	11•1%	39•8	(37•4–42•3)
10 (AK, ID, OR, WA)	4,641	(4,353–4,927)	2•5%	32•3	(30•3–34•3)
Time, month [b]					
March 2020	8,135	(7,686–8,607)	4•4%	2•5	(2•3–2•6)
April 2020	36,850	(34,584–39,125)	20•0%	11•2	(10•5–11•9)
May 2020	12,267	(11,467–13,065)	6•7%	3•7	(3•5–4•0)
June 2020	6,558	(6,120–6,988)	3•6%	2•0	(1•9–2•1)
July 2020	11,497	(10,684–12,294)	6•2%	3•5	(3•3–3•7)
August 2020	8,438	(7,792–9,087)	4•6%	2•6	(2•4–2•8)
September 2020	7,806	(7,197–8,427)	4•2%	2•4	(2•2–2•6)
October 2020	7,903	(7,336–8,465)	4•3%	2•4	(2•2–2•6)
November 2020	13,554	(12,523–14,575)	7•4%	4•1	(3•8–4•4)
December 2020	22,673	(20,795–24,576)	12•3%	6•9	(6•3–7•5)
January 2021	19,066	(17,647–20,516)	10•3%	5•8	(5•4–6•3)
February 2021	10,925	(10,108–11,749)	5•9%	3•3	(3•1–3•6)
March 2021	6,125	(5,682–6,570)	3•3%	1•9	(1•7–2•0)
April 2021	8,043	(7,491–8,601)	4•4%	2•5	(2•3–2•6)
May 2021	4,637	(4,299–4,966)	2•5%	1•4	(1•3–1•5)
Total	**184,477**	**(172,810–196,035)**		**56•2**	**(52•6–59•7)**

[a] UI: Uncertainty Interval
[b] Deaths reported in most recent weeks may still underestimate the total number of all-cause deaths after being corrected due to increases in deaths and delays in reporting during the pandemic.

3. Results

We estimated that 184,477 (95% UI: 172,810–196,035) additional COVID-19–attributable deaths were unrecognized through death certificates from March 8, 2020–May 29, 2021 (Table 1). When adding ICD-coded COVID-19 deaths reported through death certificates to unrecognized COVID-19–attributable deaths (Table 2), we estimated 766,611 (95% UI: 754,944–778,170 total COVID-19–attributable deaths through May 29, 2021. Overall, 24% of total estimated COVID-19–attributable deaths were not reported through death certificates (Table 2).

Among the unrecognized deaths, more than 151,592 (82%) occurred among individuals aged >65 years. More unrecognized deaths occurred early in the pandemic (Table 1, Figure 2, eTable 4, eTable 5), specifically during March, April, and May 2020 (n=57,251, 31%) and during peaks in SARS-CoV-2 circulation during July 2020 (n=11,496, 6%), November 2020 through February 2021 (n=66,218, 36%). Unrecognized COVID-19–attributable deaths varied by state with the highest death numbers and rates occurring in states with larger populations and widespread outbreaks (Figure 3, eTable 3, eFigure 7). The rates of unrecognized COVID-19–attributable deaths across HHS Regions ranged from 30•6/100,000 population (HHS Region 8: Colorado, Montana, North Dakota, South Dakota, Utah, Wyoming) to 73•2/100,000 (HHS Region 7: Iowa, Kansas, Missouri, Nebraska). The rates of unrecognized COVID-19–attributable deaths (Table 2) were highest among individuals aged ≥85 years (986•6/100,000 population, 95% UI: 922•4–1053•5), followed by individuals aged 75–84 years (322•1/100,000 population, 95% UI: 297•7–347•3).

Among the total COVID-19 deaths, accounting for those reported through death certificates and those we estimated, 7% of 332 deaths among children aged 0–17 years were not captured through death certificates (Table 2, eFigure 8). Most of the unrecognized deaths were among older adults who also had the most reported deaths. Approximately 27%, 24%, and 21% of total COVID-19–attributable deaths for adults aged ≥85 years, adults aged 75–84 years, and adults aged 65–74 years, respectively, were not captured through death certificates (Table 2, eFigure 8). The percent of unrecognized deaths by HHS Region ranged from 17–31%, with the lowest in Region 2 (New York, New York City, New Jersey); and the highest in Region 10 (Alaska, Idaho, Oregon, Washington). A higher percent of unrecognized COVID-19–attributable deaths were observed during March 2020 (68%), April 2020 (34%), and May 2021 (35%) (Table 2, eFigure 8), though data for more recent weeks may be incomplete and the estimates for these weeks may change.

4. Discussion

For the first 15 months of the COVID-19 pandemic (March 8, 2020–May 29, 2021), we estimated 766,611 total COVID-19–attributable deaths, including approximately 184,477 COVID-19–attributable deaths (24%) that were unrecognized through death certificates. Most of COVID-19 unrecognized deaths (82%) occurred

Table 2
COVID-19 ICD-coded deaths reported through death certificates and 95% uncertainty intervals, estimated unrecognized COVID-19–attributable deaths and 95% uncertainty intervals, total COVID-19–attributable deaths, and percent of total COVID-19 deaths unrecognized by age group, HHS Region, and Month

	Reported COVID-19 Deaths		Unrecognized COVID-19–attributable Deaths		Total COVID-19–attributable Deaths		Percentage of Total Deaths Unrecognized
	Deaths	Rate per 100,000 population	Deaths (95% UI) [a]	Rate per 100,000 population	Deaths (95% UI) [a]	Rate per 100,000 population	
Age Group, years							
0-17	310	0•4	22 (0–139)	0•0	332 (310–449)	0•5	6•6%
18-49	26,491	19•2	7,681 (4,865–10,870)	5•6	34,171 (31,355–37,360)	24•7	22•5%
50-64	91,102	144•8	25,182 (21,489–28,903)	40•0	116,284 (112,590–120,005)	184•8	21•7%
65-74	129,442	411•1	34,993 (31,295–38,659)	111•1	164,435 (160,737–168,101)	522•3	21•3%
75-84	160,183	1003•0	51,435 (47,542–55,458)	322•1	211,618 (207,725–215,641)	1,325•1	24•3%
≥85	174,608	2,643•6	65,163 (60,926–69,586)	986•6	239,771 (235,534–244,194)	3,630•2	27•2%
HHS Region							
1 (CT, MA, ME, NH, RI, VT)	26,669	179•6	7,324 (6,899–7,755)	49•3	33,993 (33,568–34,424)	229•0	21•5%
2 (NJ, NY, NYC)	78,821	278•2	16,137 (15,113–17,157)	56•9	94,958 (93,935–95,978)	335•1	17•0%
3 (DE, DC, MD, PA, VA, WV)	54,915	178•0	19,125 (17,935–20,307)	62•0	74,039 (72,849–75,222)	240•0	25•8%
4 (AL, FL, GA, KY, MS, NC, SC, TN)	111,069	166•0	44,062 (41,233–46,881)	65•9	155,131 (152,302–157,950)	231•9	28•4%
5 (IL, IN, MI, MN, OH, WI)	92,189	175•5	31,910 (29,883–33,913)	60•7	124,099 (122,072–126,102)	236•2	25•7%
6 (AR, LA, NM, OK, TX)	82,313	192•7	26,751 (24,972–28,534)	62•6	109,063 (107,285–110,846)	255•3	24•5%
7 (IA, KS, MO, NE)	24,735	174•9	10,354 (9,686–11,012)	73•2	35,089 (34,421–35,747)	248•2	29•5%
8 (CO, MT, ND, SD, UT, WY)	14,788	120•6	3,755 (3,516–3,993)	30•6	18,543 (18,305–18,782)	151•3	20•3%
9 (AZ, CA, HI, NV)	86,119	167•9	20,419 (19,172–21,675)	39•8	106,538 (105,291–107,794)	207•7	19•2%
10 (AK, ID, OR, WA)	10,517	73•3	4,641 (4,353–4,927)	32•3	15,158 (14,870–15,444)	105•6	30•6%
Time, month [b]							
March 2020	3,853	1•2	8,135 (7,686–8,607)	2•5	11,989 (11,539–12,460)	3•7	67•9%
April 2020	72,127	22•0	36,850 (34,584–39,125)	11•2	108,977 (106,711–111,252)	33•2	33•8%
May 2020	33,755	10•3	12,267 (11,467–13,065)	3•7	46,022 (45,222–46,820)	14•0	26•7%
June 2020	16,899	5•1	6,558 (6,120–6,988)	2•0	23,457 (23,019–23,887)	7•1	28•0%
July 2020	33,904	10•3	11,497 (10,684–12,294)	3•5	45,400 (44,588–46,197)	13•8	25•3%
August 2020	27,126	8•3	8,438 (7,792–9,087)	2•6	35,563 (34,917–36,213)	10•8	23•7%
September 2020	22,354	6•8	7,806 (7,197–8,427)	2•4	30,161 (29,552–30,782)	9•2	25•9%
October 2020	22,913	7•0	7,903 (7,336–8,465)	2•4	30,817 (30,249–31,378)	9•4	25•6%
November 2020	48,183	14•7	13,554 (12,523–14,575)	4•1	61,736 (60,705–62,758)	18•8	22•0%
December 2020	109,360	33•3	22,673 (20,795–24,576)	6•9	132,033 (130,155–133,936)	40•2	17•2%
January 2021	93,594	28•5	19,066 (17,647–20,516)	5•8	112,660 (111,241–114,109)	34•3	16•9%
February 2021	47,782	14•6	10,925 (10,108–11,749)	3•3	58,707 (57,890–59,531)	17•9	18•6%
March 2021	20,996	6•4	6,125 (5,682–6,570)	1•9	27,121 (26,678–27,566)	8•3	22•6%
April 2021	20,486	6•2	8,043 (7,491–8,601)	2•5	28,529 (27,977–29,086)	8•7	28•2%
May 2021	8,786	2•7	4,637 (4,299–4,966)	1•4	13,422 (13,085–13,752)	4•1	34•5%
Total	**582,135**	**177•4**	**184,477 (172,810–196,035)**	**56•2**	**766,611 (754,944–778,170)**	**233•6**	**24•1%**

[a] UI: Uncertainty Interval
[b] Deaths reported in most recent weeks may still underestimate the total number of all-cause deaths after being corrected due to increases in deaths and delays in reporting during the pandemic.

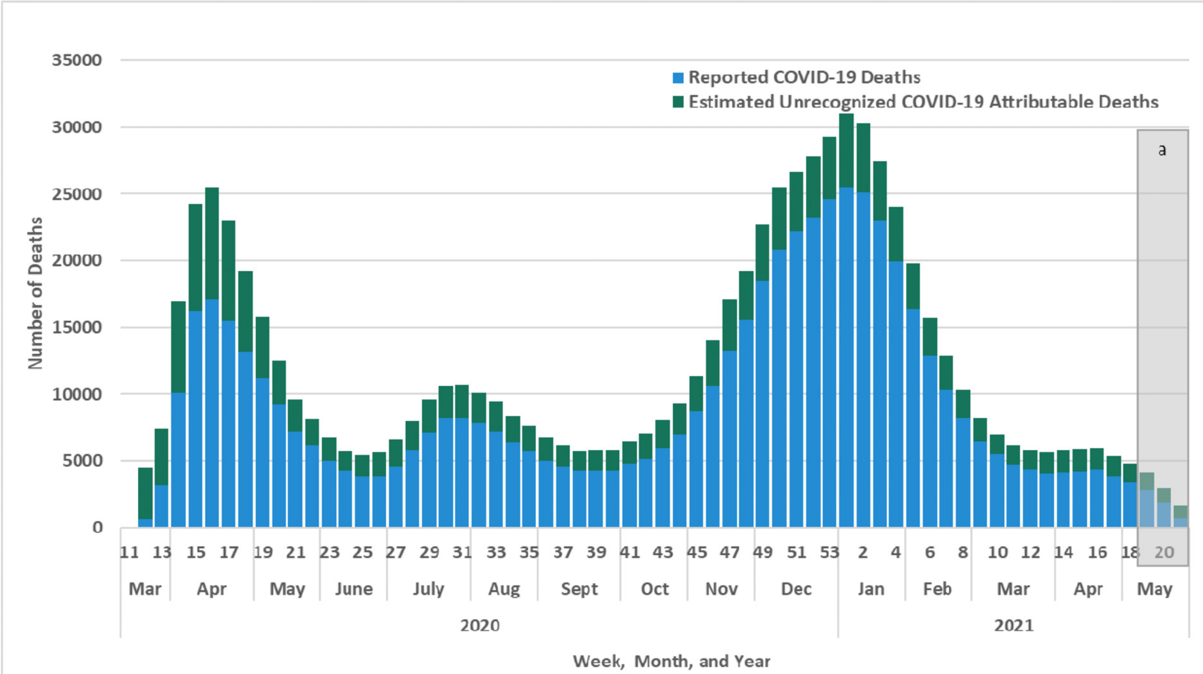

Figure 2. Death certificate reported and unrecognized COVID-19 deaths for all age groups by week from March 8, 2020—May 29, 2021 a Deaths reported in most recent weeks may still underestimate the total number of all-cause deaths after being corrected due to increases in deaths and delays in reporting during the pandemic.

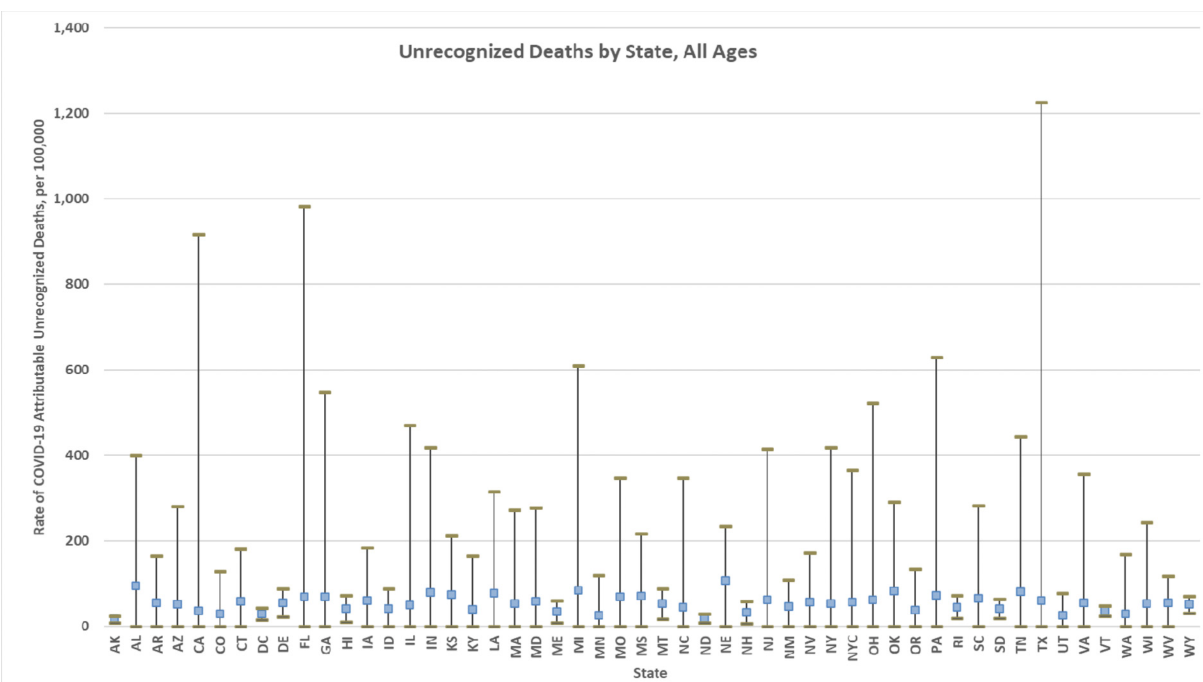

Figure 3. Unrecognized COVID-19–attributable death rates per 100,000 for all age groups by state from March 8, 2020—May 29, 2021

among individuals aged ≥65 years, the proportion of estimated deaths that were unrecognized among children was lower than the proportion of estimated deaths that were unrecognized among adults. Unrecognized deaths were more likely to occur during the early pandemic period (March—May 2020) and during periods of increased SARS-CoV-2 circulation (July 2020, November 2020—February 2021). These estimates may help to better capture the complete burden of COVID-19 on mortality and can be used to better understand the severity of COVID-19 and guide resources that may prevent additional deaths.

Previous studies used regression modelling approaches with all-cause deaths, estimated expected deaths using historic information, and calculated excess deaths as the difference between the expected deaths and total reported deaths [27-38,40,45,53]. Our COVID-19–attributable death estimates were higher than previously published U.S. death estimates from excess mortality models. Rossen et al., estimated 299,028 excess deaths during January 26–October 3, 2020 and attributed 198,081 (66%) to COVID-19 [32]. In our model, during March–September 2020, we estimated 301,568 total COVID-19 deaths, including 91,550 unrecognized COVID-19 deaths. These differences may be explained by disparate modelling approaches and different study time periods. To estimate excess COVID-19 deaths, Rossen modelled national all-cause deaths, then modelled national all-cause death after removing COVID-19 deaths, and subtracted the excess deaths from both models to obtain the number and percent of COVID-19 excess deaths [32]. The remaining excess deaths were attributed to other causes, potentially under estimating COVID-19 mortality. In contrast, we subtracted COVID-19 deaths from all-cause deaths before estimating state- and age-specific expected and predicted deaths accounting for SARS-CoV-2 circulation with viral surveillance data. The COVID-19 reported ICD-coded deaths were then added to the estimated unrecognized COVID-19 deaths to obtain total COVID-19–attributable deaths. Additionally, Rossen adjusted COVID-19 deaths for incomplete reporting. We, however, did not adjust COVID-19 deaths for potential under-reporting before subtracting from all-cause death counts which may underestimate the reported number of COVID-19 deaths, especially for more recent weeks.

In another study, Weinberger [37] calculated excess deaths during March–May 2020 by state and all-ages using data from 2015–2020. For this period, there were 95,235 COVID-19–coded deaths and Weinberger estimated 122,300 excess all-cause deaths including 27,065 deaths unattributed to COVID-19. Similarly, Rivera et al. estimated 21,179 more COVID-19 deaths than reported during March–May, 2020[31], and Woolf et al. estimated 30,755 unattributed COVID-19 excess deaths for March–April, 2020 [53]. In comparison, we estimated 57,252 unrecognized COVID-19–attributable deaths during the same time. Contrasting estimates may be explained by different models, incorporating age-specific analyses, different time periods and data sources, and methods to account for incomplete data. Combining age groups may mute the effect of age on COVID-19 death, particularly in older age groups. Our model used age-specific models to better catpure differences in death by age group. We also assumed that deaths during the pandemic period are different from historic deaths and only used all-cause deaths during the study period to estimate expected deaths rather than estimating expected deaths using historic death data. In addition, we also subtracted COVID-19 deaths prior to modelling to avoid double counting these deaths. Despite these differences, estimates were more similar to Weinberger and Woolf when more time was incorporated. Specifically, Weinberger estimated 108,834 excess COVID-19 deaths through November 2020, Woolf estimated 74,989 deaths unattributed to COVID from March–July. We estimated 75,306 (through July) and 113,007 (through November) COVID-19 unrecognized attributable deaths. The remaining differences could be related to methods used to account for reporting delays; Weinberger adjusted based on the time between the death report and death date. Woolf did not adjust for reporting delays. Our study adjusted comparing the reported death counts to historic death counts by week and state. These approaches result in different adjusted all-cause death counts used in models. Also potentially contributing to differences, we used more recently released death data, which included backfilled and more complete death counts for recent weeks.

In contrast to these studies, we estimated expected deaths from only all-cause deaths reported during the study period because we assumed that death counts during the pandemic period would differ from historic data. Mortality trends during a pandemic may be substantially different from past years because of overall increases in death related to the a new virus with no population immunity and potential decreases in specific causes of death. Therefore, estimating expected deaths using data from past seasons may not accurately reflect the underlying mortality from other causes during a pandemic. Additionally, unlike other studies, we subtracted known COVID-19 deaths reported through death certificates from all-cause deaths before applying our model to estimate unrecognized COVID-19 deaths among the remaining all-cause deaths. Additionally, we incorporated SARS-CoV-2 viral surveillance data into the model and estimated expected deaths in the absence of SARS-CoV-2 circulation and predicted deaths accounting for SARS-CoV-2 circulation.

Our approach to estimating the total COVID-19–attributable deaths is not without limitations. First, for some states and recent weeks, our methods to adjust for reporting delays based on historical death counts from the prior years may not sufficiently capture reporting delays during the pandemic given that the time between the occurrence of a death and reporting may be longer because of the increased numbers of deaths during the pandemic. If the adjustment did not fully correct the number of all-cause deaths at the time of the analysis, then our model may underestimate COVID-19 unrecognized unattributable deaths. Our model will be updated routinely using more recent all-cause death data. Death counts are continuously backfilled and updated for weeks after deaths have occurred, thus when more recent and complete data are analysed, the unrecognized death estimates will change. Second, our model may underestimate unrecognized COVID-19–attributable deaths given that the SARS-CoV-2 percent positive is based on individuals both with and without symptoms and may underestimate the virus positivity among persons with severe illness resulting in death. We were unable to account for the percent of individuals who are tested without experiencing symptoms as these data were not available. Third, the SARS-CoV-2 percent positive may be confounded by factors related to the pandemic. Specifically, the higher SARS-CoV-2 percent positive may be correlated and coincide with increases in deaths because of changes to health seeking behaviour, inability access to care, and hospital capacity during the pandemic. Fourth, we were not able to account for other factors that may affect death, such as the prevalence of chronic health conditions or state-level demographics including race or ethnicity. Fifth, not all of the data that we use to estimate COVID-19 unrecognized deaths are available by race/ethnicity or other socio-economic factors to allow us to explore the burden of COVID-19 death on groups that might be more affected by COVID-19 infections. Despite these limitations, we used a variation on traditional excess mortality models to estimate COVID-19–attributable unrecognized deaths in real-time and better describe total deaths because of COVID-19 in the U.S. population by time, age group, and geographic location. Further, estimates of COVID-19–attributable deaths are needed to capture a full picture of COVID-19 on mortality since many deaths are likely to be unrecognized through cause of death coding on death certificates. Deaths related to a COVID-19 illness may go unrecognized because of changes to health seeking behaviours in the population, limitations in testing, exacerbation of chronic health conditions that are instead listed as the cause of death, or delays in reporting.

In conclusion, we estimated 766,611 total COVID-19 deaths occurred during March 8, 2020–May 29, 2021, the first 15 months of the pandemic. Of these, 184,477 (24%) were not captured through death certificates and not previously reported as COVID-19–attributable deaths. Our estimates suggest that more COVID-19–attributable deaths were unrecognized during the early pandemic period and during times with increased SARS-CoV-2 circulation. COVID-19–attributable deaths were less likely to be unrecognized among children and remained rare compared to the large number of COVID-19–attributable deaths that were unrecognized among adults. Given that our model indicates that nearly one-fourth of COVID-19–attributable deaths are not captured currently through death certificates, this model is useful for understanding the total burden of COVID-19 on mortality and to better describe the severity of the current pandemic.

Contributors

ADI, HHC, and CR conceived the study design and methods. ADI, NNP, KK compiled, managed, cleaned, and combined different data sources related to deaths, population, viral surveillance data used in model estimation. JR conducted reviews of literature to inform methods and approach to estimating COVID-19 attributable deaths. ADI and HHC designed statistical models to estimate COVID-19 attributable deaths. HHC wrote statistical code, ADI modified code to estimate COVID-19 deaths. ADI, NNP, HHC, and CR developed the all manuscript drafts, compiled feedback, and addressed all co-author comments. RT implemented statistical code and generated outputs for tables and figures. MS, AJH, AF along with all other authors provided feedback on design and methods and reviewed, contributed to, and approved final results and this publication.

Declaration of interests

There were no conflicts of interest reported by authors.

Data Sharing Statement

The data sources used in these analyses are publicly available and eTable 1 provides details and websites for the different data sources. Each of the individual datasets can be downloaded to build the analytic dataset with some modifications. Specific files used for analysis are not available because of strict data use agreements and guidelines regarding small cell sizes.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.lana.2021.100019.

References

[1] Centers for Disease Control and Prevention. 2020 Interim Case Definition, Approved August 5, 2020. https://wwwn.cdc.gov/nndss/conditions/coronavirus-disease-2019-covid-19/case-definition/2020/08/05/ (accessed Aug 21 2020).
[2] Centers for Disease Control and Prevention. 2020 Interim Case Definition, Approved April 5, 2020. https://wwwn.cdc.gov/nndss/conditions/coronavirus-disease-2019-covid-19/case-definition/2020/ (accessed Aug 21 2020.
[3] Centers for Disease Control and Prevention. National Vital Statistics System - Provisional Death Counts for Coronavirus Disease (COVID-19): Index of COVID-19 Surveillance and Ad-hoc Data Files. 1/7/2020 2020. https://www.cdc.gov/nchs/covid19/covid-19-mortality-data-files.htm (accessed 5/4/2020 2020).
[4] World Health Organization. International Guidelines for Certification and Classification (Coding) of COVID-19 as Cause of Death 4/20/2020 2020. https://www.who.int/docs/default-source/classification/icd/covid-19/guidelines-cause-of-death-covid-19-20200420-en.pdf?sfvrsn=35fdd864_2 (accessed 4/20/2020 2020).
[5] Centers for Disease Control and Prevention. National Vital Statistics System: Guidance for Certifying COVID-19 Deaths 2020. https://www.cdc.gov/nchs/data/nvss/coronavirus/Alert-1-Guidance-for-Certifying-COVID-19-Deaths.pdf (accessed 4/20/2020 2020).
[6] Centers for Disease Control and Prevention. National Vital Statistics System - COVID-19 ICD Code Update. 3/24/2020 2020. https://www.cdc.gov/nchs/data/nvss/coronavirus/Alert-2-New-ICD-code-introduced-for-COVID-19-deaths.pdf (accessed 4/20/2020.
[7] Centers for Disease Control and Prevention. National Center for Health Statistics - COVID-19 Death Data and Resources. National Vital Surveillance System: Guidance for Certifying Deaths Due to Coronavirus Disease 2019 (COVID–19), 2020.
[8] Centers for Disease Control and Prevention. COVID Data Tracker. 2020. https://covid.cdc.gov/covid-data-tracker/#datatracker-home (accessed 10/17/2020 2020).
[9] Centers for Disease Control and Prevention. National Center for Health Statistics - COVID-19 Death Data and Resources. 2020. https://www.cdc.gov/nchs/nvss/covid-19.htm (accessed 5/4/2020 2020).
[10] Dawood FS, Iuliano AD, Reed C, et al. Estimated global mortality associated with the first 12 months of 2009 pandemic influenza A H1N1 virus circulation: a modelling study. Lancet Infect Dis 2012;12(9):687–95.
[11] Simonsen L, Spreeuwenberg P, Lustig R, et al. Global mortality estimates for the 2009 Influenza Pandemic from the GLaMOR project: a modeling study. PLoS Med 2013;10(11):e1001558.
[12] Krantz SG, Rao A. Level of underreporting including underdiagnosis before the first peak of COVID-19 in various countries: Preliminary retrospective results based on wavelets and deterministic modeling. Infect Control Hosp Epidemiol 2020;41(7):857–9.
[13] Ma W, Huo X, Zhou M. The healthcare seeking rate of individuals with influenza like illness: a meta-analysis. Infect Dis (Lond) 2018;50(10):728–35.
[14] Woolhandler S, Himmelstein DU, Intersecting US. Epidemics: COVID-19 and Lack of Health Insurance. Ann Intern Med 2020;173(1):63–4.
[15] Arevalo-Rodriguez I, Buitrago-Garcia D, Simancas-Racines D, et al. False-negative results of initial RT-PCR assays for COVID-19: A systematic review. PLoS One 2020;15(12):e0242958.
[16] Centers for Disease Control and Prevention. National Vital Statistics System: Final Guidance and Provisional Death Counts. 4/2/2020 2020. https://www.cdc.gov/nchs/data/nvss/coronavirus/Alert-3-Final-COVID-19-Guidance-and-Provisional-Death-Counts.pdf (accessed 5/4/2020 2020).
[17] Cummings MJ, Baldwin MR, Abrams D, et al. Epidemiology, clinical course, and outcomes of critically ill adults with COVID-19 in New York City: a prospective cohort study. Lancet 2020;395(10239):1763–70.
[18] Korean Society of Infectious Diseases and Korea Centers for Disease Control and PreventionAnalysis on 54 Mortality Cases of Coronavirus Disease 2019 in the Republic of Korea from January 19 to March 10, 2020. J Korean Med Sci 2020;35(12):e132.
[19] Linton NM, Kobayashi T, Yang Y, et al. Incubation Period and Other Epidemiological Characteristics of 2019 Novel Coronavirus Infections with Right Truncation: A Statistical Analysis of Publicly Available Case Data. J Clin Med 2020;9(2).
[20] Palmieri L, Vanacore N, Donfrancesco C, et al. Clinical Characteristics of Hospitalized Individuals Dying With COVID-19 by Age Group in Italy. J Gerontol A Biol Sci Med Sci 2020;75(9):1796–800.
[21] Mendy A, Apewokin S, Wells AA, Morrow AL. Factors Associated with Hospitalization and Disease Severity in a Racially and Ethnically Diverse Population of COVID-19 Patients. medRxiv 2020.
[22] Richardson S, Hirsch JS, Narasimhan M, et al. Presenting Characteristics, Comorbidities, and Outcomes Among 5700 Patients Hospitalized With COVID-19 in the New York City Area. JAMA 2020;323(20):2052–9.
[23] Williamson EJ, Walker AJ, Bhaskaran K, et al. Factors associated with COVID-19-related death using OpenSAFELY. Nature 2020;584(7821):430–6.
[24] Thompson WW, Comanor L, Shay DK. Epidemiology of seasonal influenza: use of surveillance data and statistical models to estimate the burden of disease. J Infect Dis 2006;194(Suppl 2):S82–91.
[25] Thompson WW, Shay DK, Weintraub E, et al. Mortality associated with influenza and respiratory syncytial virus in the United States. JAMA 2003;289(2):179–86.
[26] Thompson WW, Weintraub E, Dhankhar P, et al. Estimates of US influenza-associated deaths made using four different methods. Influenza Other Respir Viruses 2009;3(1):37–49.
[27] Blangiardo M, Cameletti M, Pirani M, Corsetti G, Battaglini M, Baio G. Estimating weekly excess mortality at sub-national level in Italy during the COVID-19 pandemic. PLoS One 2020;15(10):e0240286.
[28] Fouillet A, Pontais I, Caserio-Schonemann C. Excess all-cause mortality during the first wave of the COVID-19 epidemic in France, March to May 2020. Euro Surveill 2020;25(34).
[29] Modig K, Ahlbom A, Ebeling M. Excess Mortality from Covid-19. Weekly Excess Death Rates by Age and Sex for Sweden and Its Most Affected Region. Eur J Public Health 2020.
[30] New York City Department of Health and Mental Hygiene (DOHMH) COVID-19 Response TeamPreliminary Estimate of Excess Mortality During the COVID-19 Outbreak - New York City, March 11-May 2, 2020. MMWR Morb Mortal Wkly Rep 2020;69(19):603–5.
[31] Rivera R, Rosenbaum JE, Quispe W. Excess mortality in the United States during the first three months of the COVID-19 pandemic. Epidemiol Infect 2020;148:e264.
[32] Rossen LM, Branum AM, Ahmad FB, Sutton P, Anderson RN. Excess Deaths Associated with COVID-19, by Age and Race and Ethnicity - United States, January 26-October 3, 2020. MMWR Morb Mortal Wkly Rep 2020;69(42):1522–7.
[33] Scortichini M, Schneider Dos Santos R, De' Donato F, et al. Excess mortality during the COVID-19 outbreak in Italy: a two-stage interrupted time-series analysis. Int J Epidemiol 2020.
[34] Sinnathamby MA, Whitaker H, Coughlan L, Lopez Bernal J, Ramsay M, Andrews N. All-cause excess mortality observed by age group and regions in the first wave of the COVID-19 pandemic in England. Euro Surveill 2020;25(28).
[35] Vestergaard LS, Nielsen J, Richter L, et al. Excess all-cause mortality during the COVID-19 pandemic in Europe - preliminary pooled estimates from the EuroMOMO network, March to April 2020. Euro Surveill 2020;25(26).
[36] Vieira A, Peixoto VR, Aguiar P, Abrantes A. Rapid Estimation of Excess Mortality during the COVID-19 Pandemic in Portugal -Beyond Reported Deaths. J Epidemiol Glob Health 2020;10(3):209–13.
[37] Weinberger DM, Chen J, Cohen T, et al. Estimation of Excess Deaths Associated With the COVID-19 Pandemic in the United States, March to May 2020. JAMA Intern Med 2020;180(10):1336–44.
[38] Weinberger D.M., Chen J., Cohen T., et al. Estimating the early death toll of COVID-19 in the United States. December 10, 2020 2020. https://

weinbergerlab.github.io/excess_pi_covid/#national_all-cause_excess (accessed January 4, 2021 2021).
[39] Weinberger DM, Cohen T, Crawford FW, et al. Estimating the early death toll of COVID-19 in the United States. bioRxiv 2020.
[40] Woolf SH, Chapman DA, Sabo RT, Weinberger DM, Hill L, Taylor DDH. Excess Deaths From COVID-19 and Other Causes, March-July 2020. JAMA 2020;324(15):1562–4.
[41] Alling DW, Blackwelder WC, Stuart-Harris CH. A study of excess mortality during influenza epidemics in the United States, 1968-1976. Am J Epidemiol 1981;113(1):30–43.
[42] Serfling RE, Sherman IL, Houseworth WJ. Excess pneumonia-influenza mortality by age and sex in three major influenza A2 epidemics, United States, 1957-58, 1960 and 1963. Am J Epidemiol 1967;86(2):433–41.
[43] Murphy SL, X J, Kochanek KD, Arias E, Tejada-Vera B. National Vital Statistics Report on Deaths: Final Data for 2018. National Center for Health Statistics, CDC; 2021.
[44] Centers for Disease Control and Prevention. National Center for Health Statistics: Excess Deaths Associated with COVID-19. 12/30/2020 2020. https://www.cdc.gov/nchs/nvss/vsrr/covid19/excess_deaths.htm (accessed 5/4/2020 2020).
[45] Centers for Disease Control and Prevention. Timeliness of death certificate data for mortality surveillance and provisional estimatesVital statistics rapid release special report no. 001. US Department of Health and Human Services, Centers for Disease Control and Prevention National Center for Health Statistics, National Vital Statistics System; 2016.
[46] Centers for Disease Control and Prevention. Technical Notes: Provisional Death Counts for Coronavirus Disease (COVID-19). 12/22/2020 2020. https://www.cdc.gov/nchs/nvss/vsrr/covid19/tech_notes.htm (accessed 5/4/2020 2020).
[47] Centers for Disease Control and Prevention. FluView Interactive - Pneumonia and Influenza Mortality Surveillance from the National Center for Health Statistics Mortality Surveillance System. 2021. https://gis.cdc.gov/grasp/fluview/mortality.html2021).
[48] National Syndromic Surveillance Program. Syndromic Data Critical to COVID-19 Response. https://www.cdc.gov/nssp/index.html (accessed 5/4/2020 2020).
[49] Centers for Disease Control and PreventionEstimates of deaths associated with seasonal influenza — United States, 1976-2007. MMWR Morb Mortal Wkly Rep 2010;59(33):1057–62.
[50] Centers for Disease Control and Prevention. COVID-10 Pandemic Planning Scenarios. 2020. https://www.cdc.gov/coronavirus/2019-ncov/hcp/planning-scenarios.html#:~:text=COVID%2D19%20Pandemic%20Planning,%2C%20or%20other%20interventions. (accessed 9/17/2020 2020).
[51] U.S. Census Bureau. State Population by Characteristics: 2010-2019. 6/22/2020 2020. https://www.census.gov/data/tables/time-series/demo/popest/2010s-state-detail.html (accessed 8/10/2020.
[52] RCoreTeam. R Foundation for Statistical Computing.
[53] Woolf SH, Chapman DA, Sabo RT, Weinberger DM, Hill L. Excess Deaths From COVID-19 and Other Causes, March-April 2020. JAMA 2020;324(5):510–13.