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Non-Covid Excess Deaths, 2020-21: Collateral Damage of Policy Choices?

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ABSTRACT

From April 2020 through at least the end of 2021, Americans died from non-Covid causes at an average annual rate 97,000 in excess of previous trends. Hypertension and heart disease deaths combined were elevated 32,000. Diabetes or obesity, drug-induced causes, and alcohol-induced causes were each elevated 12,000 to 15,000 above previous (upward) trends. Drug deaths especially followed an alarming trend, only to significantly exceed it during the pandemic to reach 108,000 for calendar year 2021. Homicide and motor-vehicle fatalities combined were elevated almost 10,000. Various other causes combined to add 18,000. While Covid deaths overwhelmingly afflict senior citizens, absolute numbers of non-Covid excess deaths are similar for each of the 18-44, 45-64, and over-65 age groups, with essentially no aggregate excess deaths of children. Mortality from all causes during the pandemic was elevated 26 percent for working-age adults (18-64), as compared to 18 percent for the elderly. Other data on drug addictions, non-fatal shootings, weight gain, and cancer screenings point to a historic, yet largely unacknowledged, health emergency.

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A data appendix is available at <http://www.nber.org/data-appendix/w30104>

I. Introduction

The pandemic caused by the novel coronavirus SARS-CoV2 (COVID-19, which we will call Covid, for simplicity) prompted extraordinary, although often untested, steps by individuals and institutions in the United States and around the world, in an effort to limit, or at a minimum slow the spread, of the disease. Although confirmed Covid cases and deaths have been widely tracked on a daily basis, little aggregate information has been provided on non-Covid excess deaths that may have been a direct consequence of these efforts. There was little curiosity about testing whether public or private Covid-policies were aggravating previous health problems. Using death-certificate and other data, this paper reports significant and historic health harms experienced in the U.S. during the pandemic, apart from those directly caused by Covid.¹

A first indicator of abnormalities comes from the 46 percent of the adult population who had not yet reached age 45. While largely unharmed by Covid, their aggregate mortality rates increased 26 percent above previous trends. This is larger than the percentage jump in deaths for senior citizens, where the Covid toll was largely concentrated, but has received scant notice. Drugs, homicides, traffic fatalities, and alcohol-induced causes killed tens of thousands more young adults than they had in the past. Deaths from various circulatory diseases and diabetes were also elevated. Suicides did not increase, though alcohol-related deaths and overdoses might also be considered consequences of self-destructive behaviors. Deaths were not, on average, elevated among minors.

We then look at ages 45-64 and the over-65 age group. Their non-Covid mortality was also elevated, but with almost all elevated causes associated with chronic conditions such as circulatory disease, diabetes, obesity, or liver disease rather than homicide or traffic accident. A final section of the paper looks at other health indicators such as substance abuse, non-fatal

¹ One of the earlier papers exploring this phenomenon, and inspiring this deeper dive, was Arnott, Kalesnik and Wu (2021).

shootings, weight gain, and cancer screenings. All of this suggests that large and sustained changes in living habits designed to avoid a single virus had not only “economic” opportunity costs, but also cost a shockingly large number of young lives. At the monetary value of a statistical life used in government cost-benefit analysis, the non-Covid excess deaths amount to a loss of well over \$1 trillion.

II. Data and methods used

Monthly fatalities are measured using the on-line CDC-Wonder tools, sponsored by the Centers for Disease Control and Prevention (CDC), for tabulating every death certificate filed with a U.S. state or District of Columbia (essentially every death in the country). The death certificates are provided to CDC by the states on a rolling basis, with the timing and quality of initial submissions varying across states. CDC also takes time to process and code them, especially the 20 percent of certificates that CDC does not receive digitally. As a result, CDC sponsors two distinct tools: “Multiple Cause of Death, 1999-2020” and “Provisional Mortality Statistics, 2018 through Last Month.” The data accessed with the Provisional tool is still being processed and coded, especially for “external causes of death” such as drug overdose, homicide, or traffic accident, particularly for the most recent six months.² Given that we accessed the tools in late March and April 2022, the monthly series for external causes shown in this paper end in September 2021.³

Each death certificate “contains a single underlying cause of death, up to twenty additional multiple causes, and demographic data” such as age (Centers for Disease Control and Prevention 2022). The tools permit tabulation by any of the thousands of underlying causes, or by selected cause groups such as “Alcohol-induced causes”, “Drug-induced causes,” or

² The expression “external causes of death” may be unfamiliar to many readers. Natural causes of death occur internal to the body, whether disease or senescence. External causes are the complement of natural causes and come from sources external to the body, the most common being accidents, overdoses, suicides, and homicides. Less common would include drowning, poisonings (other than drugs), animal attacks, and so forth.

³ For every month of 2020, each of our series could be obtained from either tool. We used “Multiple Cause of Death, 1999-2020” and note that differences from the Provisional tool are nonzero but negligible. While tallies for specific external causes are not yet available after September 2021, excess deaths not yet attributed to natural causes have remained elevated through the first quarter of 2022.

“Homicide.” Beginning in 2020, the death certificates potentially include a code (U07.1) for Covid among the causes of death. The counts of death certificates including U07.1 are well known because they were extensively reported in the news as U.S. “Covid deaths.”

Table 1 shows the nine cause groups we analyze. In selecting cause groups, our purpose was to capture the groups that have been most important in the past and/or have been the subject of debate regarding the pandemic. We also looked at cancer deaths but in this paper include them with the residual because, perhaps not surprisingly, cancer deaths were not yet noticeably above normal as of the end of 2021.⁴ Respiratory deaths are selected because of the possibilities that Covid crowds out other respiratory deaths or, alternatively, Covid deaths are coded as J00-J98 rather than U07.1. Alcohol-induced causes are “the subset of alcohol-related deaths that are certain to be caused by drinking alcohol” (Spillane, et al. 2020). Some of the alcohol-induced deaths reflect acute conditions such as poisoning but most were aggravation of chronic conditions, especially diseases of the liver. Alcohol-induced causes do not include fatal drunk-driving accidents and other deaths where alcohol might have combined with other causes.

Table 1. Cause-of-death groups in CDC Wonder

Description	ICD-10 Codes
Alcohol-induced causes	E24.4, F10, G31.2, G62.1, G72.1, I42.6, K29.2, K70, K85.2, K86.0, R78.0, X45, X65, Y15
Drug-induced causes	Several designated by CDC
Diseases of the circulatory system	I00-I99
Diabetes and obesity	E00-E88 "Endocrine, nutritional, and metabolic diseases"
Homicide	U01-U02, X85–Y09, Y87.1
Motor Vehicle Traffic	Several designated by CDC
Respiratory	J00-J98
Covid-19	U07.1
All other causes	

⁴ One of the theories of pandemic-induced cancer deaths is that patients miss screening, which delays detection and treatment, but not necessarily causing death until two or more years after the pandemic.

Age and cause-group excess deaths are estimated by subtracting “predicted” deaths and unmeasured Covid deaths from CDC-reported deaths. Each month’s deaths are expressed at an annual rate by dividing by number of days in the month and multiplying by 365.25. The natural logs of predicted deaths are the fitted values from a monthly time series regression of the natural logs of actual deaths on (i) a quadratic in time interacted with age group and cause and (ii) month-of-year indicators for each cause.⁵ The estimation period is January 1999 through December 2019, for a total of 24 time series (eight non-Covid causes and three age groups).

Estimated trends were typically upward for drugs, alcohol, homicide, and diabetes/obesity for each age group. In other words, “excess deaths” from these causes refers to excesses beyond the increases that would occur along the previous trend, which were already leading public health problems. Tacitly, this presumes that further increases in these health emergencies are “normal,” as long as the trend is not accelerating. See also Section III.

With Covid deaths occurring at an average annual rate of more than 400,000 through the end of 2021, a small amount of mismeasurement could have a significant impact on non-Covid excess death estimates (Mulligan 2020), especially for circulatory, diabetes, and obesity deaths, as they are common comorbidities with Covid. If, say, five Covid deaths were unrecorded for every 100 that were recorded, the unrecorded would artificially elevate excess death rates by 20,000 per year, which is a similar order of magnitude of the difference between actual and trend circulatory or diabetes/obesity deaths. We implement two adjustments of those causes, intended to be conservative as to the estimated number of excess non-Covid deaths. The first adjustment is to count zero excess circulatory (I00-I99) and diabetes/obesity (E00-E88) deaths in March and April 2020 when Covid testing rates were low and before the federal government began issuing add-on payments to hospitals for their treatment of Covid patients.⁶ The second adjustment uses the fact that excess circulatory and diabetes/obesity deaths have month-to-month time series that is similar to the time series for official Covid deaths. Specifically, for each of the two cause groups interacted with the three age groups, we regress the gap between actual and trend on

⁵ See also this paper’s Appendix. Mulligan (2022) uses this method for predicting substance-abuse deaths separately by substance (alcohol, narcotics, and psychotropics). Ruhm’s (2021) paper earlier in the pandemic evaluates various methods for predicting deaths; Mulligan (2022) notes that his results are similar to Ruhm’s preferred specification.

⁶ The CARES Act created a 20 percent add-on payment for Medicare reimbursements that involved Covid, whose administration began April 21 (American Hospital Association 2020, Centers for Medicare and Medicaid Services 2020). Zinberg (2020) also notes the undercounting of Covid deaths during March and April.

measured Covid deaths using the April 2020 through December 2021 time series. The age-by-cause estimate of unmeasured Covid is the product of measured Covid deaths and the corresponding regression coefficient.⁷ Also for the purpose of presenting conservative estimates, we do not estimate the number of official Covid deaths that were in fact due to other causes.

In addition to CDC Wonder, we also use the CMS weekly database of nursing home deaths that begins in June 2020 and distinguishes Covid deaths from other deaths. For supporting evidence, we also use the public use microdata files, but as of our writing they are only available through calendar year 2020. Our STATA code and supporting materials are hosted with this working paper at nber.org.

III. Excess deaths by age and cause

Table 2 shows the results by age. Because the table entries are expressed at annual rates in thousands, the pandemic totals would be roughly double the table entries if the pandemic and its effects on mortality ultimately prove to last twenty-four months.⁸ We find the adult age groups to have roughly similar numbers of excess deaths from non-Covid causes (first column), which is remarkable given that normally deaths are much more rare in the young age group (baseline column). Even including our estimate of 2,000 unmeasured Covid deaths ages 18-44, excess non-Covid deaths exceed Covid deaths for that group. Overall, the excess deaths aged 18-44 amount to a 26 percent increase in the age group's mortality. By comparison, the mortality rate for the elderly was elevated "only" 18 percent, primarily by Covid.

⁷ The estimated coefficients, and therefore our unmeasured Covid estimates, are somewhat closer to zero if April 2020 is excluded from the regression. No adjustment is made to the "other non-Covid causes" series, which has a mildly negative correlation with measured Covid deaths in the time series from April 2020 through the end of 2021.

⁸ Excess deaths for children (0-17) are approximately zero; our point estimate of the trend is about one thousand annual deaths *above* actual deaths.

Table 2. Excess deaths, by age of death*Average annual rate April 2020 - December 2021*

Age	Annual rate in 1000s			Baseline Level	All excess, % of baseline
	Excess, Non-Covid	Covid			
		Official	Unmeasured		
0-17	~0	~0	~0	35	~0
18-44	29	18	2	183	26%
45-64	33	96	9	545	25%
65+	35	319	31	2167	18%
Nursing home	NA	49	NA	NA	
Not nursing home	NA	270	NA	NA	
Total	97	433	41	2930	20%

Notes: Covid deaths are excluded from the first column. We use an expansive definition of unmeasured Covid for the purpose of conservatively assessing non-Covid causes.

To give a sense of the age and morbidity of the elderly Covid deaths, we distinguish nursing homes from the rest of the elderly population. Although nursing homes were infamous early in the pandemic for high rates of Covid infection and death, the majority of Covid deaths occurred after the summer of 2020 and did so among elderly who were not nursing-home residents.⁹ The residence status of these elderly suggests, but does not prove, that many Covid deaths may have occurred among elderly who were not as old and/or thought to be in better health than the average nursing home resident.

The age pattern of excess non-COVID deaths is revealing about the factors driving poor health during the pandemic, which might be categorized as supply versus demand. Health supply is one side of the coin; demand for health is the other. Covid might increase individuals' demand for health if, for example, taking extra care of chronic conditions enhances a patient's chances of surviving a Covid infection. On the other hand, the competing risks theory of health demand (Dow, Philipson and Sala-i-Martin 1999, Honoré and Lleras-Muney 2006) says that the introduction of a new mortality threat would reduce investments in health by reducing the expected lifetimes over which those investments would pay off. At the individual level, either of

⁹ Nursing home occupancy briefly fell a few percent in late 2020, perhaps due to concerns about Covid risk, but in 2021 return to historic levels.

these demand factors would show up primarily among the elderly, who have much greater risk from Covid. Supply factors, on the other hand, could affect even those who have little personal risk from Covid because many of them operate at a market level. In particular, as institutions close workplaces or change law enforcement practices, to name some examples, even the young may find that maintaining health becomes more expensive (or that unhealthy lifestyles are an easy escape from fear or boredom) even though Covid poses little direct threat to them.

Table 3 shows the results by cause. Each entry is an excess above the sum of trend and our estimate of unreported Covid deaths. Excess deaths from circulatory diseases lead at 32,000 annually. Diseases associated with high blood pressure (hypertension) are especially important contributors to the circulatory total. Coronary heart disease (ICD codes I20-I25, especially heart attacks) was elevated a lesser percentage than circulatory diseases generally, although it was a major contributor to the additional deaths from circulatory diseases among ages 18-44. Deaths from coronary heart disease at home were elevated more than coronary heart disease deaths occurring away from home (these subcategories of circulatory disease are not shown in the table).

Table 3. Excess non-Covid deaths: top causes*Average annual rate April 2020 - December 2021, Ages 18+*

Underlying causes	Annual rate in 1000s		Excess, % of baseline	Elderly % of excess
	Excess	Baseline		
Circulatory diseases	32	892	4%	66%
Diabetes or obesity	15	153	10%	60%
Drug-induced causes	12	93	13%	0%
Alcohol-induced causes	12	41	28%	16%
Homicide	5	19	27%	2%
Traffic accident	4	37	11%	-16%
All others	18	1660	1%	22%
Total	97	2895	3%	36%
Potentially unmeasured Covid excluded from above	41			74%

Notes: External cause averages are only through September 2021. The baseline includes prior trends and seasonals (see also Table 4). The elderly % is negative if elderly deaths are below trend.

Another 15,000 excess deaths were attributed to diabetes (especially Type II) and obesity. Drug poisoning (especially illicit fentanyl) and alcohol-induced causes each contribute another 12,000 annual excess deaths each, beyond the alarming previous trends. Homicide and traffic accidents contribute another 9,000 excess deaths annually. All other causes contribute a total of 18,000 excess deaths.¹⁰ Total excess deaths are 97,000 annually beyond previous trends.

Although about three-fourths of Covid deaths were among the elderly, more than half of excess non-Covid deaths are among non-elderly adults. Table 3's final column how this especially true for the external causes of drugs, alcohol, homicide, and traffic accident. In fact, elderly deaths in traffic accidents were below prior trends during the pandemic, while they were above trend for non-elderly adults.

¹⁰ Because many of the "all others" are deaths in late 2021, we expect a significant number to ultimately be reallocated by CDC from our residual category to one of the categories circulatory through traffic accident.

Due to interest in the direct and indirect effects of the pandemic on public health, we prepared Tables 2 and 3 to show deaths relative to pre-pandemic trends. Table 4’s “Trend” column shows how, for some causes, the previous trends themselves were alarming.¹¹ Each year that passed was adding 18,000 to the annual number of deaths from diabetes, obesity, drugs, or alcohol. The previous trend for drugs alone is about 10,000. If that trend continues, roughly 200,000 will die from drug overdoses in the year 2030 alone. If it is considered “normal” for this trend to persist, these 200,000 deaths would – shockingly – be considered unexceptional and on-trend. Given these alarming pre-pandemic trends, we find it especially notable that non-Covid health outcomes were not more closely monitored to, among other things, determine whether public or private Covid policies were aggravating them.

Table 4. Non-Covid mortality changes decomposed into trend and excess

April 2020 - December 2021, Ages 18+

Underlying causes	Annual rate in 1000s		
	Trend	Excess	Sum
Circulatory diseases	-9	32	23
Diabetes or obesity	7	15	22
Drug-induced causes	10	12	22
Alcohol-induced causes	2	12	13
Homicide	0	5	5
Traffic accident	0	4	4
All other non-Covid	-7	18	11
Total	3	97	100

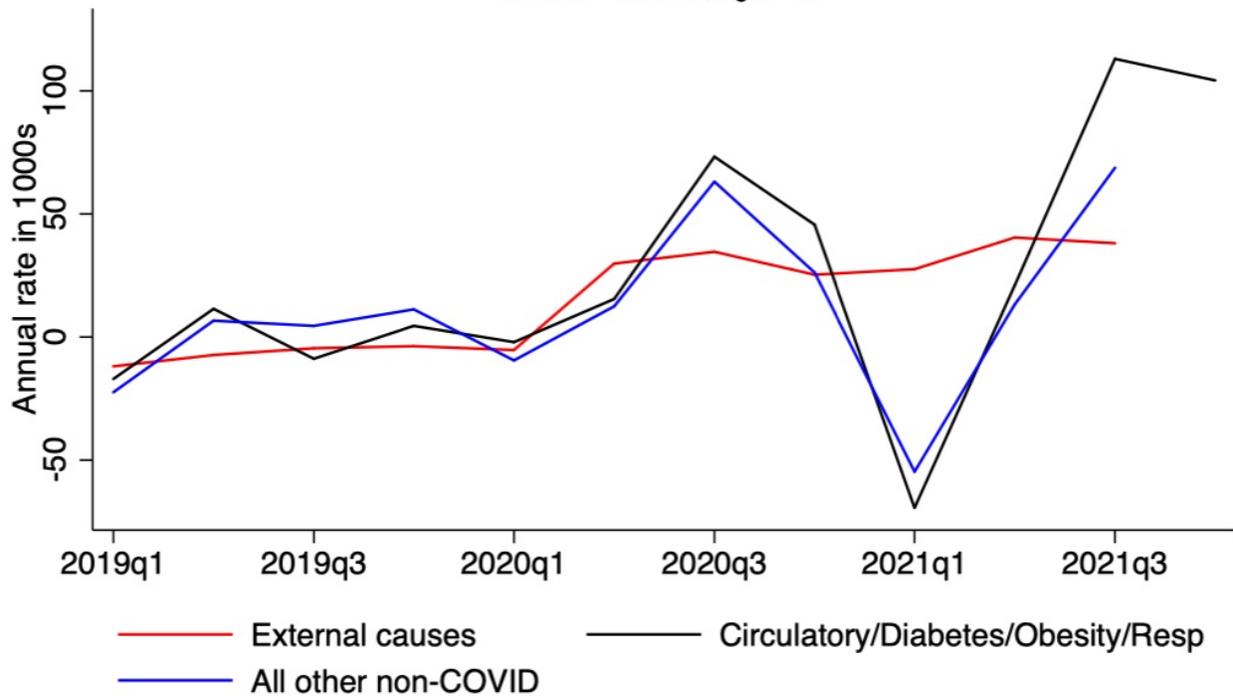
Notes: (1) The trend is the extrapolation of a quartic in time estimated Jan 1999 through Dec 2019. It is what would have been added to the annual rate on average between April 2020 and the end of 2021 if the previous trends had been followed, which is different from an annual trend rate because 21 months are covered. (2) Up to a seasonal adjustment, the sum of trend and excess is the average deaths during the pandemic minus average deaths pre-pandemic.

¹¹ Our appendix provides the details of how trends, seasonals, and excess deaths were calculated. The sum of trend and excess is approximately the change from the end of 2019 to the average month April 2020 – December 2021 (for external causes, average through September 2021), and would be exactly so if seasonal effects and December 2019 excess deaths were exactly zero. For example, Table 4 says that the annual rate of drug deaths increased about 22,000 (10,000+12,000) between December 2019 and the middle of the pandemic as we measure it (about December 2020), which is similar to the change over that period shown in the CDC’s moving sums (93,655-72,151 per <https://www.cdc.gov/nchs/nvss/vsrr/drug-overdose-data.htm>).

Figure 1 shows the results over time, aggregating the age groups and months into quarters. Causes are aggregated as either external (drugs, alcohol, homicide, and traffic accident), the other four causes we tracked individually, or all other non-Covid. Deaths from external causes jump immediately in 2020-Q2 and remain near or above that level for as long as we have data. From 2020-Q3 through the end of 2021, excess deaths from the four other causes are at least 23,000 at an annual rate, except for 2021-Q1 when excess deaths are negative.¹² The other series are noisy in part due to the challenge of getting an exact estimate for the strong seasonal for those types of deaths. Winters are hard on the elderly but uneven, with a very large difference between the death toll in bad flu seasons relative to mild flu seasons. It is unsurprising that, with lockdowns and social distancing, the winter months at the beginning of both 2021 and 2022 have been very mild flu seasons.

Figure 1. Excess non-Covid deaths

2019Q1 - 2021Q4, ages 18+



Note: External causes are drugs, alcohol, homicide, and traffic accident. Excess is actual minus trend, which is estimated by age and cause group with 1999-2019 data and includes seasonal factors. Estimated unrecorded COVID deaths are excluded. Source: CDC Wonder

¹² Other causes are less elevated in 2020-Q2 in part because we assume zero excess deaths from circulatory diseases, diabetes, and obesity in April 2020 in order to avoid counting unmeasured Covid deaths.

IV. Other Evidence of Health Status during the Pandemic

It would be surprising if health harms were limited only to those who died by the end of 2021. Additional drug and alcohol use during the pandemic has been indicated in household surveys (Patrick, et al. 2022) and alcohol sales data (Pollard, Tucker and Green 2020). Tobacco companies reported additional cigarette sales as “staying home in the pandemic gave people more chances to smoke and more cash to spend” (Geller and Cavale 2020). The Gun Violence Archives (GVA) reports 31 percent more nonfatal gun injuries in 2020 than in 2019, which is similar to the 28 percent increase we find in homicides over the same time period. GVA also finds a 44 percent increase among children aged 0-11 and 33 percent increase among adolescents aged 12-17 (Gun Violence Archive 2021).

Lin, et al (2021) find a 1.5 pound average weight gain per month spent in shelter-in-place.¹³ Bhutani, Dellen and Cooper (2021) report similar results, concluding that “Covid-19 lockdown periods disrupted weight management among many Americans and that associated health effects are likely to persist.” Chang et al (2021) conducted an international meta-analysis of weight gain among children and adolescents, finding that the “Covid-19 pandemic worsened the burden of childhood obesity.”

Massachusetts General Brigham hospital reported a 74 percent reduction in cancer screens in March, April, and May 2020 as compared to the prior year. Because cancer diagnoses fell 33 percent, this suggests that cancer would be diagnosed later, at more advanced stages, eventually resulting in additional morbidity and mortality. When cancer screening resumed in summer 2020 the University of Cincinnati Cancer Center reported almost quadruple the lung cancer diagnoses per screen.¹⁴

¹³ See also Khubchandani, et al. (2022).

¹⁴ National Cancer Institute (2021) is the source for the statistics in this paragraph.

V. Conclusions

Beginning with Grossman (1972), the human capital approach to health economics emphasizes the role of patient and family efforts in maintaining health. Health is very much a “home production” activity. It should be no surprise that a widespread disruption to patient circumstances would degrade health and even elevate mortality from chronic conditions (Mulligan 2020). Nevertheless, early in the pandemic some experts mocked this perspective as a “pet theory about the fatal dangers of quarantine” (Case and Deaton 2020). Little monitoring of longstanding health behaviors occurred.¹⁵

With the benefit of two years of death certificates, this paper documents mortality patterns in the U.S. From April 2020 through the end of 2021, Americans died from non-Covid causes at an average annual rate 97,000 in excess of previous trends for a cumulative total of 52 per 100,000 population through the end of 2021. Presumably excess mortality continues into calendar year 2022. As a magnitude for comparison, we note that, converted to dollars at a \$10,000,000 average value of a statistical life, the non-Covid excess deaths through the end of 2021 cost \$1.7 trillion.

Hypertension and heart disease deaths combined were elevated 32,000. Some of these appear to be heart attacks suffered at home without visiting a hospital. Diabetes or obesity, drug poisoning, and alcohol-induced causes were each elevated 12,000 to 15,000 above previous (upward) trends. Homicide and motor-vehicle fatalities combined were elevated almost 10,000. Absolute numbers of non-Covid excess deaths are about evenly split by age between 18-44, 45-64, and over-65, with essentially no aggregate excess deaths of children. Mortality from all causes during the pandemic was elevated 26% for young adults ages 18 to 44, as compared to 18% for the elderly. Other data on drug addictions, non-fatal shootings, weight gain, and cancer screenings point to a historic, yet largely unacknowledged, health emergency.

¹⁵ The *President’s Budget for Fiscal Year 2023* (Office of Management and Budget 2022) includes a paragraph on opioid treatment as compared to several pages about addressing climate change. The 2022 *Economic Report of President* (Council of Economic Advisers April 2022) examines life expectancy patterns only through 2019. Neither document mentions that previous health conditions were aggravated during the pandemic.

The age pattern of excess non-COVID deaths reveals something about the types of factors driving poor health during the pandemic. With the young experiencing so many excess deaths, even though their average personal risk from Covid is minimal, many of the pandemic's effects on health seem to be working through market channels. Institutional efforts to limit infections, such as closing workplaces or changing law enforcement practices, may have made it more expensive to maintain health or made unhealthy lifestyles less expensive. Some have referred to the resulting deaths as deaths of despair or deaths of boredom.

Due to interest in the direct and indirect effects of the pandemic on public health, we express many of our findings in terms of deaths relative to pre-pandemic trends. For two or three cause groups, the previous trends themselves were already alarming, only to be surpassed during the pandemic. Given the pre-pandemic health situation, we find it especially notable that non-Covid health outcomes were not more closely monitored to, among other things, determine whether public or private Covid policies were aggravating them. Critics will likely suggest that the public policy choices did not lead to the large number of non-Covid excess deaths, that these excess deaths were a consequence of personal choices, driven by fear or boredom. We do not disagree that this may be a key driver of excess non-Covid deaths. But, we would point out that this is no excuse for ignoring this soaring death toll, or pushing an examination of these deaths to the back burner.

Summing our estimates across causes and age groups, we estimate 171,000 excess non-Covid deaths through the end of 2021 plus 72,000 unmeasured Covid deaths. *The Economist* has assembled national-level mortality data from around the world and obtains a similar U.S. estimate, which is 199,000 (including any unmeasured Covid) or about 60 persons per 100,000 population (Global Change Data Lab 2022). For the European Union as a whole, the estimate is near-identical at 64 non-Covid excess deaths per 100K. In contrast, the estimate for Sweden is -33, meaning that non-Covid causes of death were somewhat low during the pandemic.¹⁶ We suspect that some of the international differences are due to the standard used to designate a death as Covid, but perhaps also Sweden's result is related to minimizing the disruption of its citizen's normal lifestyles.

¹⁶ Of the 27 EU countries, 5 others have negative estimates: Slovenia (-3), Denmark (-15), France (-39), Ireland (-43), and Luxembourg (-96).

VI. Appendix: Decomposition into Trend and Excess

Using the data from January 2001 to December 2019, we estimated

$$\ln y_{a,c,t} = f(t; \phi_{a,c}) + m_t \mu_c + \varepsilon_{a,c,t} \quad (1)$$

where a denotes age group, c denotes broad cause of death group, and t is calendar time in months. $f(t; \phi_{a,c})$ is a quartic polynomial with a separate coefficient vector ϕ for each age by cause group. m_t is a vector of month-of-year indicators and μ_c the corresponding vector of cause-specific seasonal coefficients. $y > 0$ is deaths expressed at an annual rate by dividing by number of days in the month and multiplying by 365.25.

Excess deaths are

$$x_{a,c,t} = (1 - e^{-\varepsilon_{a,c,t}}) y_{a,c,t} \quad (2)$$

which can be positive or negative, according to the sign of the regression residual ε . As derived from the model (1), excess deaths occur only when deaths are high enough to exceed the previous trend and seasonal.¹⁷ We define the trend as:

$$T_{a,c,t} = [e^{f(t; \phi_{a,c}) - f(0; \phi_{a,c})} - 1] [y_{a,c,0} - x_{a,c,0}] \quad (3)$$

which can be positive or negative, according to whether the regression time polynomial, which is based only on pre-pandemic data, increases or decreases after the pandemic begins. Time zero is December 2019.

At intervals of 12 months, 24 months, 36 months, etc., the actual change is the sum of the trend and the excess change. For other intervals, seasonal adjustments (based on μ_c) are required:

$$y_{a,c,t} = x_{a,c,t} + [T_{a,c,t} + y_{a,c,0} - x_{a,c,0}] e^{(m_t - m_0) \mu_c} \quad (4)$$

where the year-over-years special case ($m_t = m_0$) is:

$$y_{a,c,t} - y_{a,c,0} = T_{a,c,t} + x_{a,c,t} - x_{a,c,0} \quad (5)$$

¹⁷ More rarely, the trend is negative and excess deaths occur when actual deaths fail to fall as much as the previous trend and seasonal.

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