# All-cause Excess Mortality Cross-sectional Correlation Analysis at Global Scale During COVID-19, 2020-22

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***Abstract:*** The excess mortality during COVID-19 is significantly higher than the reported death due to COVID-19 infections. This study conducts a cross-sectional correlation analysis between excess mortality and reported COVID-19 death, aging rate, GHS (Global Health Security) index, and government response stringency index in the timeframe from January 2020 to September 2022. This study aims to explore the main contributors to excess mortality, hence to provide guidance on future diagnosis and control of the pandemic. A cross-sectional log-linear model is fitted with 79 observations to estimate the explanatory power of reported COVID-19 death, aging rate, GHS index and stringency index on excess mortality at a global scale. The correlation between excess mortality and reported COVID-19 death is also examined on a nation level by calculating the Spearman correlation coefficient on the time series of the two. The cross-sectional log-linear model has adjusted $R^2 = 0.77$, $F\ statistic = 61.09$. The estimate for log of reported COVID death is $1.02 \pm 0.06$; aging rate is $-0.04 \pm 0.02$; GHS index is $-0.03 \pm 0.01$; stringency index is not significant. On a nation level, Brazil and United States have high correlations between reported and excess death ($r = 0.81, r = 0.68$), the reported death takes up 85% and 86% respectively, of excess death. India and Japan, similarly, have high correlation coefficient ($r = 0.71, r = 0.63$), but with COVID-19 death accounting 9% and 47% of excess death. Germany and China have relatively small correlations between reported and excess death ($r = 0.71, r = 0.63$), but Germany has reported death taking up 89% of excess death, whereas in China the ratio is 4%. At a global scale, the reported COVID-19 death has the most explanatory power in excess mortality, which means that most of excess mortality is attributed to death from COVID-19 infections. Aging rate has a negative correlation between excess mortality, this is partly because of the preference of aged population to live in countries with better health care capacities. There is no significant explanatory power of stringency index on excess mortality, suggesting that the impact of government responses on COVID-19 vary by each nation. On a country level, the correlation between COVID-19 death and excess mortality can also vary, mostly due to the different levels of health care disruptions, efficiency and impact of government measures and other COVID-19 unrelated events such as wars and heat waves.

***Keywords:*** excess mortality, COVID-19, all-cause excess mortality, government response, population aging, health care disruption

## 1. Introduction

The impact of COVID-19 on the mortality of the general population is usually assessed by the number of deaths reported on public data sources such as the World Health Organization. However, the explanatory power of this metric can be limited due to various reasons, such as the testing availability of each country and the definitions of deaths due to COVID-19 [1]. In order to give a more accurate estimate of the true death toll of COVID-19, as well as other extreme events, excess mortality is one of the appropriate measures. Excess mortality is defined as the difference between the observed death from all causes and the estimated death based on historical trends. It captures both the deaths directly caused by COVID-19 infection and indirectly caused by the consequence of the pandemic [2].

Current studies on excess mortality of COVID-19 mostly focus on the estimation process and descriptive analyses of excess mortality, and most correlation analyses are done qualitatively and are done on the country basis. Thanks to the excess mortality data available from previous studies such as The Economist [3] and the World Mortality Dataset [1], this study conducts a cross-sectional correlation analysis between excess mortality and reported COVID-19 death, aging rate, GHS (Global Health Security) index, and government response stringency index in the timeframe from January 2020 to September 2022. The authors aim to explore the main contributors to excess mortality, hence to provide guidance on future diagnosis and control of the pandemic.

## 2. Method

### 2.1. Data Source

The excess mortality data and reported death is obtained from The Economists [3], which includes panel data of 247 countries on a weekly basis from January 2020 to September 2022. The projected death data is obtained from World Mortality Dataset [4], which contains panel data from 123 countries from January 2020 to September 2022, the time intervals differ from each country, but mostly on a monthly basis. For issues of interdependence between the calculations of excess mortality and projected death, it is tested that there is no statistically significant difference (p=0.28) between excess mortality data from The Economists and that of World Mortality Database, so it should not significantly impact on the results if both datasets are used in conjunction. The government response stringency index is obtained from Oxford COVID-19 Government Response Tracker (OxCGRT) [5], which contains the average stringency index from January 2020 to September 2022 of 102 countries. The Chinese yearly all-cause mortality data is obtained from 2010-2019 from Chinese National Bureau of Statistics [6]. The aging rates data is obtained from The World Bank [7], which consists of the 2021 aging rates of 266 countries. The GHS (Global Health Security) index is obtained from [8] Bloomberg School of Public Health, which contains the 2021 GHS index for 195 countries.

### 2.2. Key Variables and Calculation

Excess mortality: The difference between the reported number of deaths in a given time interval in 2020–2022 and an estimate of the number of deaths for that period had the COVID-19 pandemic not occurred.

$$\text{Excess mortality} = \text{Reported death} - \text{Projected death} \quad (1)$$

Excess mortality rate: The percentage difference between the reported death and projected death in a given time interval.

$$\text{Excess mortality rate} = \frac{\text{Excess mortality}}{\text{Projected death}} * 100 \quad (2)$$

Cumulative excess mortality rate: The total percentage difference between the reported death and projected death up to a given time.

$$\text{Cumulative excess mortality rate} = \frac{\text{Total excess mortality}}{\text{Total projected death}} * 100 \tag{3}$$

Aging rate: The percentage of population of ages 65 and above.

Stringency index: A measure of the level of stringency of government responses based on 21 indicators of government response imposed by each country [5]. Stringency index ranges from 0-100, with 0 being the least stringent, 100 being the most stringent.

Global Health Security Index: A measure of assessment of countries' health capabilities and preparedness for pandemic across six categories and 37 indicators [8]. GHS index ranges from 0-100, with 0 being the least capable and 100 being the most capable.

## 2.3. Analysis Method

**Model for predicting expected death in 2020-2022 for China.** Due to the absence of China's projected death data from World Mortality Dataset, a linear time series model is built for China using the model of Karlinsky and Kobak [1]. Yearly mortality data from 2010-2019 is used to estimate the projected mortality for each year from 2020 to 2022, in order to compute cumulative excess mortality rate. The following regression model is fitted:

$$D_t = \beta_0 + \beta_1 t + \epsilon_t \tag{4}$$

Here, $D_t$ is the number of deaths observed in a year, $\beta_0$ is the intercept, $\beta_1$ is a linear slope across years, and $\epsilon_t \sim N(0, \sigma^2)$ is a Gaussian noise. Since this model is on yearly basis, it only captures yearly trend and does not account for seasonality within a year.

The estimate for $\beta_0$ is $-9306.06 \pm 574.22$, $\beta_1$ is $5.10 \pm 0.29$, and the adjusted $R^2 = 0.97, F = 320.5$.

**Cross-section regression model for excess mortality.** The cross-sectional data is computed by summing the excess mortality and reported COVID-19 death (from January 2020 to September 2022) for each country. A stepwise variable selection based on AIC (Akaike Information Criterion) is used to select the variables included in the model. Then the log-linear model is fitted using lm function in R base package. Since the OLS method is used to fit the model, the model is examined to ensure each assumption had been met. Specifically, the normality of log of excess mortality is tested by Shapiro test (p-value=0.24), heteroskedasticity by studentized Breusch-Pagan test (p-value=0.03), and multi-collinearity by VIF (Variance Inflation Factor) (VIF<2 for every independent variable). The OLS standard errors is replaced by HC (heteroskedasticity consistent) standard errors to account for heteroskedasticity. The goodness of fit is evaluated by conducting F test of overall significance, t tests for slope estimates, and adjusted $R^2$.

**Correlation between reported COVID-19 death and excess death for each country**. The correlation analysis is conducted between reported COVID-19 death and excess death for each country by doing Spearman's rank correlation test using the weekly time series data for each country.

**Visualizations and computations**. All visualizations and computations are done in RStudio (R version 4.2.0.).

DOI: 10.54254/2754-1169/16/20230991

# 3. Results

## 3.1. Summary Statistics of the Excess Mortality Stratified by Six Continents

Table 1: Summary statistics of excess mortality of six continents (Antarctica not included), including total excess death in absolute term, average, median, standard deviation (s.d.), maximum and minimum of excess mortality rate. (credit: original)

| Continent | Total exess deaths | average Excess mortality rate(%) | Median Excess mortality rate(%) | s.d. of Excess mortality rate(%) | Max Excess mortality rate(%) | Min pExcess mortality rate(%) |
|---|---|---|---|---|---|---|
| Africa | 1569843.74 | 14.05 | 17.98 | 10.42 | 26.86 | -6.47 |
| Asia | 1819157.85 | 15.24 | 11.28 | 11.90 | 43.64 | -0.95 |
| North America | 2125654.56 | 12.95 | 14.00 | 11.42 | 32.70 | -7.56 |
| Oceania | 19430.36 | 3.01 | -1.01 | 9.26 | 16.03 | -5.43 |
| South America | 781263.58 | 23.45 | 18.63 | 17.07 | 52.65 | 1.23 |
| The European | 3369867.14 | 13.29 | 11.20 | 8.62 | 32.60 | -2.97 |
| TOTAL | 9685217.24 | 14.25 | 11.64 | 11.28 | 52.64 | -7.56 |

In 121 countries and regions, the total number of excess deaths was 9.68 million, with an average excess mortality rate of 14.25%. Europe had the highest number of excess deaths, at 3.36 million, while Oceania had the lowest, at 19,000. South America had the highest average excess mortality rate at 23.45%, while Oceania had the lowest excess mortality rate at 3.01%. The highest median excess mortality rate was found in South America at 18.63% and the lowest in Oceania at -1.01%. South America had the highest standard deviation of excess mortality (17.07%) and Europe had the lowest standard deviation (8.62%). The country with the highest excess mortality rate is Peru in South America (52.65%), while the country with the lowest excess mortality rate is Greenland in North America (-7.56%).

## 3.2. Regression Model of Excess Death at Global Scale

Table 2: Summary of the cross-sectional log-linear model of excess mortality, including the intercept and slope estimates and the HC standard errors shown in brackets, the number of observations, $R^2$ and adjusted $R^2$, residual standard error, F statistic and significance level of each estimate. (credit: original)

| | *Dependent variable:* |
|---|---|
| | Log(Excess death) |
| Intercept | $4.0144^{***}$ |
| | (1.3114) |
| Log(Reported COVID death) | $1.0183^{***}$ |
| | (0.0649) |
| Aging rate | $-0.0381^{*}$ |

DOI: 10.54254/2754-1169/16/20230991

Table 3: (continued).

| | | |
|---|---|---|
| | (0.0215) | |
| GHS index | -0.0277$^{***}$ | |
| | (0.0100) | |
| Stringency index | | -0.0348 |
| | (0.0215) | |
| Observations | | 79 |
| $R^2$ | | 0.7676 |
| Adjusted $R^2$ | | 0.755 |
| Residual Std. Error | 0.8909 (df = 74) | |
| F Statistic | 61.0887$^{***}$ (df = 4; 74) | |
| *Note:* | $^{*}$p<0.1; $^{**}$p<0.05; $^{***}$p<0.01 | |

The reported COVID death, aging rate, GHS index and Stringency index of each country are included to fit a log-linear model with HC standard errors for excess mortality. Figure 2 is the summary of the model. Note that there are only 79 observations (79 countries of data) available since only countries with all 4 variables data available are included. The model has adjusted $R^2 = 0.77,$ $F$ statistic $=$ $61.09$. The estimate for log of reported COVID death is $1.02 \pm 0.06$, and is significant at 1% level; the estimate for aging rate is $-0.04 \pm 0.02$, and is significant at 10% level; the estimate for GHS index is $-0.03 \pm 0.01$, and is significant at 5% level; the estimate for stringency index is $-0.03 \pm 0.02$, and is not significant.

## 3.3. Correlation Between COVID-19 Death and Excess Death on Country Scale

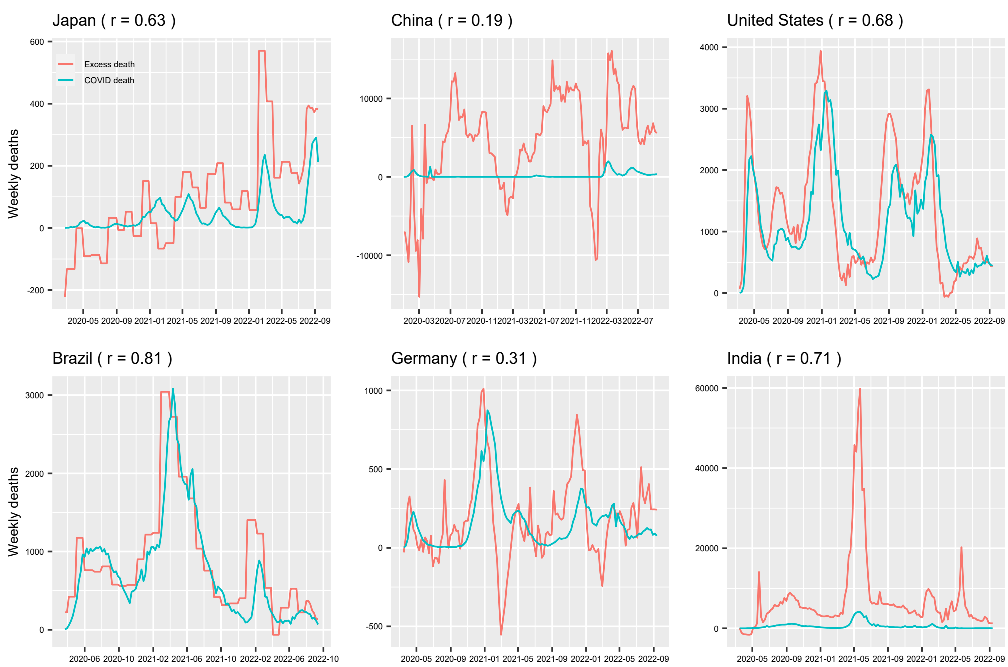


Figure 1: Excess mortality vs reported COVID-19 death weekly time series of six selected countries, with the Spearman correlation coefficient (r) between the two series, starting from week 1 in 2020. (credit: original)

DOI: 10.54254/2754-1169/16/20230991

The correlation between the reported COVID-19 death and excess death is high at global scale ($r = 0.6$). However, this is not the case for all countries, figure 3 shows the heterogenous patterns and trends in six representative countries.

Brazil and United States have high correlations between reported and excess death ($r = 0.81, r = 0.68$), as well as a small gap between them. The reported death takes up 85% and 86% respectively, of excess death. India and Japan, similarly, have high correlation coefficient ($r = 0.71, r = 0.63$), but larger gaps between reported and excess death, with COVID-19 death accounting 9% and 47% of excess death. Germany and China have relatively small correlations between reported and excess death ($r = 0.31, r = 0.19$), but Germany has reported death taking up 89% of excess death, whereas in China the ratio is 4%.

It is also notable that the gap between excess and reported death can sometimes be negative, this is mostly seen in China and Germany, during the first quarters of 2020, 2021 and 2022. Negative gap is also present in Japan during 2020 and the first half of 2021, and in first quarters of 2021 and 2022 in United States.

## 4. Discussion

### 4.1. Overview of the Excess Mortality Stratified by Six Continents

Between January 2020 and September 2022, the number of excess deaths was 9.68 million in 121 countries counted, and 6.53 million people died of COVID-19 infection during the period.The number of excess deaths is far exceeding the number of people who died of COVID-19 infection.

Oceania was the continent with the least excess deaths and the lowest excess mortality rate, with only 19 thousand more deaths than expected, among which Australia alone accounted for 18 thousand excess deaths, accounting for a large part of the excess deaths in Oceania.

With 3.37 million excess deaths, Europe has the highest number of excess deaths of any continent. Russia has the highest number of excess deaths among all the countries counted, with 1.29 million, which is the one of the reasons for the high number of excess deaths in Europe. This figure is far higher than that of Italy (230,000), which is the second highest in Europe.In addition, the standard deviation of excess mortality in Europe is the smallest, which means that the distribution of excess mortality in Europe is relatively concentrated.

Among the countries counted, Bolivia, Kuwait and Peru had the highest excess mortality rates, with 52, 44 and 43 percent respectively. Among them, Bolivia and Peru are both South American countries, and their excess mortality rates raise the average excess mortality rate in South America, which is one of the reasons why South America has the highest average excess mortality rate.

### 4.2. Regression Model of Excess Death at Global Scale

The log of Reported COVID-19 death, aging rate, GHS index, and stringency index are included as input variables to the model, based on data availability. The adjusted $R^2$ is 0.77 (p-value=0), meaning that 77% of variations in log of excess mortality can be explained by the input variables, which shows that the model is useful in explaining excess mortality at global scale.

The estimate for log of reported COVID-19 death is $1.02 \pm 0.06$, which means that a 1% increase in reported COVID-19 death is expected to increase excess mortality by 1.02%, holding other variables constant.

The estimate for aging rate is $-0.04 \pm 0.02$, which means that a 1% increase in aging rate is expected to decrease excess mortality by 0.04%, holding other variables constant. Although small in magnitude, this result may be counterintuitive, since aging is a predominant risk factor of COVID-19 [9], and it may be reasonable to expect a positive relationship between aging rate and excess mortality.

DOI: 10.54254/2754-1169/16/20230991

However, it is also discovered that aging is positively correlated with GHS index (r=0.63), suggesting that aged population tend to live in countries with better health care capacities. This may help to explain the negative correlation between aging rate and excess mortality, since better health care capacities will lower excess mortality. However, there is still a possibility that aging rate may be endogenous, given its negative estimate and high significance level (10%) even after controlling for GHS index.

The estimate for GHS index is $-0.03 \pm 0.01$, which means that a 1 unit increase in GHS index is expected to decrease excess mortality by 0.03%, holding other variables constant. This is again, small in magnitude, however makes intuitive sense: the better health care capacities and the more preparedness to COVID-19, the lower the excess mortality.

The estimate for stringency index is not statistically significant. This is because excess mortality in most countries can been affected, either positively or negatively, by the government prevention strategies, therefore the correlation between stringency index and excess mortality is ambivalent. Some countries with low stringency index, such as Greenland (34) and Faeroe Islands (30), both have negative excess mortality rates, whereas Nicaragua, whose stringency index (11) is the lowest among the 102 countries, has an excess mortality rate in the 94% percentile. Similarly, countries with relatively high stringency index such as China (72), Malaysia (59) and Australia (52), have kept their excess mortality rate at low levels, whereas Peru has both a high stringency index (65) and a high excess mortality rate (42.7%) among the 102 countries. Small stringency index and low excess morality rate often occurs in island countries whose geographic location is separated from continents, therefore are likely to be insulated from COVID-19. Countries benefited the most from government responses are those with high stringency indices and small excess mortality rates such as China and Australia. On the contrary, Peru's high stringency index and excess mortality rate can be explained by its weak health system and inefficient government measures [10]. In general, the impact of the stringency of government responses on excess mortality appears to be country specific.

### 4.3. Correlation Between COVID-19 Death and Excess Death on Country Scale

On a global scale, the reported COVID-19 deaths alone can explain 68% of variations in excess mortality, and therefore is the variable with the most explanatory power amongst all included variables (aging rate, GHS index and stringency index). This suggests that COVID-19 death is, in most regions, the main contributor to the excess death. However, when examined on a country scale, heterogeneity appears in patterns of the co-movements between the two.

Conceptually, excess mortality consists of the following components: 1. Death directly caused by COVID infections. 2. Death caused by medical system collapse or the scarcity of health care resources due to COVID-19 pandemic. 3. Death indirectly caused by government's regulation such as medical inconvenience, severe side effects of vaccinations and strikes on mental health. 4. All other deaths from extreme events such as wars and natural disasters [1] For factors 2 and 3, their effect cannot be separated easily since the most predominant reason for disruptions is intentional service delivery modifications [11](mostly imposed by the government), which implies they are interrelated to each other.

For most countries, deaths directly resulted from COVID-19 infections (factor 1) account for most variations in excess death, such as Brazil and United States, where the gap between excess and reported deaths is small, and the correlation coefficient is high. However, for factors 2-4, there is no homogenous pattern for all countries. On global average, health care disruptions (factor 2) are reported in almost half of the public health services [11], implying that these disruptions may be the second significant contributor to excess death. One exception is Germany, which did particularly well in health care services during the pandemic, it is ranked first in 'Healthcare readiness' amongst 250 countries in the regional safety assessment conducted by Deep Knowledge Group [12]. This is also reflected in the small gap between its excess and reported death, and sometimes even negative.

Government measures (factor 3) can either positively or negatively impact on excess death. Positive effect can be reduced social contact, and hence lower mortality resulted from other infectious diseases [1] due to lockdowns and social-distancing. Negative effect is mostly attributed to the above-mentioned health service disruptions, but impact on mental health cannot be neglected [13]. Countries benefited from government measures include (not limited to) Australia, New Zealand and China, which have reported lower all-cause mortality rates after the pandemic [14]. For China, this is evident in the negative gap between excess and reported death during the first quarters of 2020 and 2022, when government interventions were the most stringent. Similarly, negative gap in Brazil is coincided with decrease in cardiovascular diseases, respiratory diseases and other external causes [15]. Countries negatively impacted by government interventions, particularly on mental health, include Japan and United States. Suicide rate increased in Japan during the pandemic, and opioid deaths have increased in some US states [13].

Natural disasters and extreme events (factor 4) such as Russia Ukraine War and heat waves across the globe are also responsible for excess mortality, especially the latter one, whose effect on mortality is expected to increase in the coming half century [16]. It is also notable that the large gap between excess mortality and COVID death in China may be attributed to aging effects. China has the largest elderly population in the world and the process of aging is accelerating in recent years [17], excess deaths in China may well be attributed to elderly death when the care given does not meet the acceleration rate of aging.

### 4.4. Comparison with Similar Studies

Two other analyses of excess mortality conducted on global scale are studied[1,13]. These studies reported the excess mortality of 103 and 74 countries in 2020 and 2021, and ours included 79 countries in the timeframe 2020-2022. The linear model developed by Karlinsky and Kobak [1] for estimation of projected in death is particularly useful for the estimation of China's death ($R^2 = 0.99$). Both studies mention several factors contributing to excess mortality including age, health service availability and other cause-specific deaths, most interpretations are similar to those of this study. In addition, Karlinsky and Kobak reports a strong positive correlation between excess death and reported COVID deaths, although this is true at the global scale, it is found that there is weak positive correlation or even negative correlations in some countries. Furthermore, both studies do not explicitly account for the possible effect of government measures on excess mortality, whereas this study includes the stringency index data from Oxford University to study its correlation with excess mortality.

## 5. Conclusions

ßIn summary, the reported COVID-19 death has the most explanatory power in excess mortality at a global scale, which means that most of excess mortality is attributed to death from COVID-19 infections. Aging rate has a negative correlation between excess mortality, this is partly because of the preference of aged population to live in countries with better health care capacities. There is no significant explanatory power of stringency index on excess mortality, suggesting that the impact of government responses on COVID-19 vary by each nation. On a country level, the correlation between COVID-19 death and excess mortality can also vary, mostly due to the different levels of health care disruptions, efficiency and impact of government measures and other COVID-19 unrelated events such as wars and heat waves.

This study has a number of limitations. First is the constraints from data, the model only included 79 countries, there are still some countries not included due to unavailability of weekly updated time-series data or other input data. Second, other possible causes or covariates of excess mortality may not be quantifiable or hard to obtain data, such as the amount of decrease in access to local health services due to lockdowns, or cause-specific mortality data. Third, the model for China's weekly projected death may be robust since one average value of the year is assigned for all weeks in that year and did not account for seasonality within a year (due to data constraints). Future analyses are recommended to account for cause-specific excess mortality and health service disruptions if those data become available [13]. It is also expected that future studies to conclude a more accurate correlation between aging and excess mortality. Lastly, analyses in the impact of vaccination, including vaccination coverage and side effects of vaccinations, on excess mortality, are also recommended.

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