The Different Measures of Period Shocks on Mortality: The Case of COVID-19

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Abstract

The COVID-19 pandemic has caused a tremendous increase in mortality over recent years, manifesting disparately among nations. Understanding the pandemic's immediate impact on mortality was essential to make decisions to control the virus's spread. In the long term, it has implications for the success of public policies and pension systems. Period measures, such as the period life expectancy, although convenient to overstate the impact of temporary epidemic mortality, can be misleading if considered a lifespan measure. In this study, using data from the World Population Prospects (WPP) 2022 and the Human Mortality Database (HMD), we computed and compared alternative mortality measures to assess the pandemic's impact on the life trajectory of individuals exposed to it. In particular, we calculated estimates of cohort life expectancy at birth and the Truncated Cross-Sectional Average Length of Life (TCAL) for all countries in the world. Despite the reductions of more than 40 months in male life expectancy at birth between 2019 and 2021 in Peru, South Africa, and more than 28 months in the United States, cohort life expectancy estimates show that among the most affected cohorts, the decline was only close to four months for males born around the 50's in Peru. Regarding the TCAL, results show expressive reductions in 1-year relative changes after 2019 but not in the absolute estimates. By incorporating the past mortality experience of different cohorts exposed to the pandemic, our study allows a better understanding of the lifespan impact of COVID-19 and its effects on population structure and dynamics.

Keywords: period shock; COVID-19; life expectancy; cohort life expectancy; TCAL

INTRODUCTION

In addition to the socioeconomic (Padhan and Prabheesh, 2021) and health implications (del Rio et al., 2020), the COVID-19 pandemic precipitated a tremendous rise in mortality levels in the last few years, manifesting disparately among nations. The impact, usually measured as reductions in period life expectancy at birth, was significant enough to interrupt historical trends of mortality decline. Estimates show more than four years of declines in life expectancy at birth between 2019 and 2021 in Bolivia, Mexico, and the Russian Federation (United Nations, Department of Economics and Social Affairs, Population Division, 2022). Similar analyses show substantial life expectancy reductions in the United States between 2019 and 2021, but not among the Western European countries (Schöley et al., 2022).

Numerous factors, including age distribution, comorbidity profiles, and contextual circumstances, have engendered disparities in the pandemic's impact across diverse nations (Dowd et al., 2020; Nepomuceno et al., 2020). Moreover, the pandemic has affected individuals differently based on socioeconomic and demographic attributes. Research has demonstrated that seniors and middle-aged adults, mainly men, have experienced higher fatality rates (Levin et al., 2020; Ramírez-Soto et al., 2021).

Assessing the immediate impact of COVID-19 was essential during the initial stages of the pandemic to inform decisions aimed at controlling the virus's spread. Such applications included implementation of lockdowns, restrictions, vaccination campaigns, and the provision of medical resources. Additionally, understanding the pandemic's long-term implications, including its effects on population size and structure, is crucial for the formulation and efficacy of public policies and pension systems (Tilstra et al., 2024).

However, accurately estimating the pandemic's impact on mortality remains challenging. Death counts from COVID-19 are likely underestimated due to inconsistencies in the testing system, and delays in death registration (Riffe et al., 2021), leading to observed excess all-cause mortality across many regions (COVID-19 Excess Mortality Collaborators, 2022; Karlinsky and Kobak, 2021). Also, assessing long-term implications remains challenging with the current period measures used.

The period life expectancy at birth, obtained by summarizing the mortality experience in a year, was also commonly used to measure the impact of temporary epidemic mortality, including the COVID-19 pandemic (Goldstein and Lee, 2020). Although it is a convenient way of summarizing current conditions and allowing the understanding of temporary changes due to a particular period condition, the measure must be interpreted carefully. The "period" life expectancy relies on the concept of the synthetic cohort, which is a hypothetical cohort of people who would be subject at each age to the age-specific rates of one particular period and does not describe the actual life course of a cohort (Aburto et al., 2021). Unless vital rates are constant over time, no individual faces rates observed during one period (Guillot, 2003). Notably, in pandemics such as COVID-19, life expectancy at birth can be a misleading indicator if considered as a lifespan measure. This happens because it implicitly assumes the epidemic is experienced yearly over and over again as a person ages (Goldstein and Lee, 2020).

Other indicators should be used to obtain more accurate measures for the life course impact of a mortality shock. For instance, one could use cohort measures, which totally incorporate the mortality experience of cohorts alive until a particular year (Kolk et al., 2022). While the period life expectancy at birth ($e_0^P(t)$) uses the mortality experience at a given year as input, cohort measures, such as the cohort life expectancy at birth ($e_0^C(t)$), use the mortality experience from birth to the end of a specific cohort. In this sense, the cohort measure could be seen as more realistic or appropriate to identify life course changes. Nevertheless, it needs the complete mortality experience as input. For incomplete cohorts, for instance, those alive during the pandemic, the measure relies on assumptions for future mortality. This can be complex given the uncertainty regarding the long-term impacts of a mortality shock.

Other options includes cross-sectional measures, such as the Cross-Sectional Average Length of Life (CAL) (Brouard, 1986). CAL is an index that accounts for the real mortality conditions experienced by the various birth cohorts whose survivors are present in a population at a particular time t (Canudas-Romo and Guillot, 2015). This period measure uses as input the survival functions for all the cohorts present in that year and does not need assumptions on future mortality shocks. However, there are some limitations on the use of the CAL. To compute a single estimate, the measure requires at least 100 years of deaths and exposures. Also, to our knowledge, it has never been used in the context of a mortality shock. To allow the computation of CAL in settings of limited data, Canudas-Romo and Guillot (2015) proposed the Truncated CAL (TCAL). According to the authors, for cohorts born before the earliest year for which mortality data are available for the population with the shortest mortality series, one could use, as the missing cohort mortality conditions, the period age-specific death rates at the earliest available year t.

Some authors have tried to disentangle these other perspectives of COVID-19's impact on mortality. For instance, Kolk et al. (2022) analysed changes in period life expectancy between 2019 and 2020, along with changes in cohort life expectancy, and in the Years of Potential Life Lost (YPLL) in Sweden. Despite recent efforts, it is still unsure the impact of the pandemic in lifespans of individuals exposed to it, specially in low- and middle-income countries.

DATA AND METHODS

We used data from the World Population Prospects (WPP) 2022. In particular, we used observed age-specific death rates by single age groups for ages 0 to 100+ from 1950 to 2021 and forecasted death rates from 2022 to 2100 for all countries in the world. For illustrative purposes, in this paper we report results for a subset of countries across the globe that represent different mortality experiences during the pandemic, namely Australia, Japan, Italy, the United States, South Africa, and Peru. Results for all other countries are available at the [blind for peer-review] repository XXX.

From the Human Mortality Database (HMD), we complemented the WPP age-specific death rates for the years before 1950. Since the last age group is 100+, the oldest cohort in the first year of the pandemic was born in 1920; hence, we used HMD data from 1920 (or later, depending on each country data availability) onward. For the six countries analysed here, data start from 1920 for Italy, from 1921 for Australia, from 1933 for the United States, and from 1947 for Japan (while South Africa and Peru are not available in the HMD).

A robustness check was done to evaluate the comparability of the two data sources. For that, we selected the year 1950 and visually compared the absolute and relative differences in the death rates by age groups. The results can be seen in Annexes 1. The sources seem to be consistent until age 90 for both men and women. The inconsistencies found at ages >90 do not affect our estimates, as these cohorts are not present in 2020.

In the following, we describe the mortality measures that we use in this paper to estimate the impact of COVID-19 on mortality.

The Period Life Expectancy at Birth

One of the most widely used demographic measures to estimate the impact of COVID-19 on mortality is the period of life expectancy at birth. Let $\mu(x)$ denote the force of mortality in a population at age $x = 0, \ldots, 100+$. Period life expectancy at birth at time $t = 2015, \ldots, 2021$ is:

$$e_0^P(t) = \int_0^w l(x)dx = \int_0^w \exp\left(-\int_0^x \mu(a)da\right)dx \tag{1}$$

For this study, we approximated $\mu(x)$ using the observed age-specific death rates m_x^P obtained from the WPP 2022 between 2015 and 2021. Indeed, m_x^P is the maximum-likelihood estimator of $\mu(x)$ when the force of mortality is assumed to remain constant over each age class (see, e.g., Currie, 2016). We summarized period age-specific death rates into life tables using standard demographic methods (Preston et al., 2001), and estimates for the life expectancy at birth were obtained by sex. Following previous work that tried to measure the pandemic's impact (Schöley et al., 2022), we subtracted life expectancy at birth estimates of 2021 from estimates of 2019, the last year before the COVID-19 pandemic.

Given the observed association between COVID-19 fatality rates and age (Levin et al., 2020; Ramírez-Soto et al., 2021), we also analysed the contribution of different age groups to the change in life expectancy between 2019 and 2021. For that, we applied Arriaga (1984)'s age decomposition of differences in life expectancy comparing the change in the levels from 2019 to 2021 by sex.

The Cohort Life Expectancy at Birth

The period age-specific death rates (m_x^P) from 1920 to 2100 were also transformed into cohort age-specific death rates (m_x^C) by taking the diagonals over the years, following the life course of the different cohorts. We consider that after 2021, the cohorts would experience the forecasted mortality regimes provided by WPP 2022. Figure 1 presents how these estimates were obtained with the period data for the cohort born in 1950.

It should be noted that using the age-specific death rates by single age groups instead of by Lexis diagrams introduces a small bias in the derivation of cohort death rates (van Raalte et al., 2023). Further research could, for instance, use deaths and exposures by Lexis diagrams, which were however unavailable to us, or the average rate between the two periods [if published, cite Carl Schmertmann].

To compute the impact of COVID-19, a counterfactual scenario was used to obtain estimates of cohort life expectancies in the absence of the pandemic. Following the methodology used on the WPP 2022 (United Nations, Department of Economic and Social Affairs, Population Division, 2022), in which most mortality levels are assumed to return to pre-pandemic levels after 2024, we estimated a new set of age-specific mortality rates for 2020, 2021, 2022 and 2023. For that, we used monotone Hermite spline functions (Fritsch and Carlson, 1980) by age groups, sex and country, to interpolate the rates between 2019 and 2024, removing mortality disturbances due to the pandemic. [if time allows, use country-specific years of return to pre-pandemic levels following UN methodology rather than a common year (now 2024)]

A robustness check was done to evaluate the goodness of fit of the interpolation over the four years. For that, we selected the age of 60 and visually compared the WPP 2022 age-specific death rates estimates

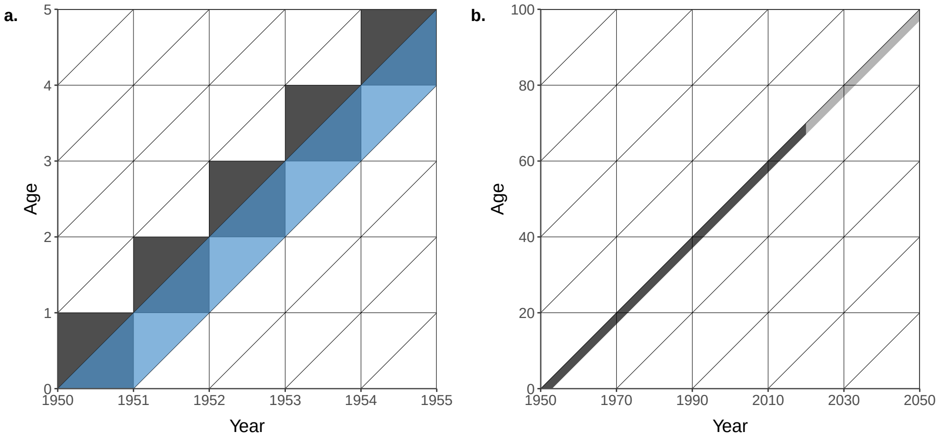

Figure 1: **a.** Lexis representation of the difference between the two data structures. Properly structured age–cohort data are represented in blue, and approximating cohorts by "taking the diagonals" of age–period data are represented in dark gray
b. Observed data in dark and forecasts in light gray

between 2020 and 2023, with the counterfactual scenario obtained with splines. The results can be seen in Annexes 2 for both male and females. Results for the other age groups are available in the online repository. We observe consistent results with the interpolation. The trends observed until 2019 are extrapolated with splines, and given the expected return of mortality levels around 2024, the interpolation smoothly falls back to the estimates over these years.

The cohort age-specific death rates of both WPP 2022 estimates and counterfactual scenario were then summarized into life tables, and estimates of cohort life expectancies at birth were obtained for all cohorts. In this case, the impact of the pandemic was obtained by subtracting from the cohort life expectancy obtained with WPP 2022 estimates, the cohort life expectancy obtained with the counterfactual scenario. The change here, when negative, indicates losses in life expectancy at birth for that cohort due to the unexpected deaths during COVID-19 years.

In this study, we opted not to utilize the forecasts provided by the World Population Prospects (WPP) 2019 as a counterfactual due to some methodological considerations. Firstly, the WPP 2019 forecasts are presented in 5-year intervals. In order to obtain single-year estimates, additional assumptions would be necessary, which introduces potential inaccuracies. Moreover, our supplementary material demonstrates the efficacy of the applied linear interpolation in approximating demographic trends. Finally, WPP 2022 incorporates adjustments for pre-pandemic years and re-calibrations reflecting changes in migration, fertility, and mortality patterns during the pandemic period, which significantly impacts mortality rates.

The Truncated Cross-Sectional Average Length of Life (TCAL)

Along with the period and cohort life expectancy at birth, we applied the Truncated Cross-Sectional Average Length of Life (TCAL) (Canudas-Romo and Guillot, 2015) to the period age-specific death rates. The TCAL is an extension of the Cross-Sectional Average Length of Life (CAL) (Brouard, 1986) that can be applied in settings of incomplete cohort mortality data. The CAL is a period index that takes into account the actual mortality conditions to which cohorts present in the population at time t have been subject.

Let $p_c(x, t-x)$ denote the probability of surviving from age 0 to x according to the mortality conditions prevailing in the cohort born at time $t-x$, and $\mu(a,t)$ the force of mortality at age a and at time t. CAL at time $t = 2015, \ldots, 2021$ is:

$$CAL(t) = \int_0^w p_c(x, t-x)dx = \int_0^w \exp\left[-\int_0^x \mu(a, t-x+a)da\right]dx \tag{2}$$

In other words, CAL involves summing probabilities of surviving for different cohorts, instead of survival probabilities for one period, as in the case of the period life expectancy at birth (Guillot, 2003). Given the nature of the measure, to compute a single estimate, at least 100 years of deaths and exposures are needed. Since a substantial number of countries lack this complete cohort mortality data, Canudas-Romo and Guillot (2015) proposed the Truncated CAL (TCAL).

Let Y_1 be the earliest year for which mortality data are available. Cohorts born after Y_1 will have complete mortality information. For cohorts born before Y_1, without complete cohort mortality data, we use the period mortality experienced in the earliest year Y_1, and $\mu(a,t)$ the force of mortality at age a and at time t. TCAL at time $t = 2015, \ldots, 2021$ is:

$$TCAL(t, Y_1) = \int_0^w l^*(x, t, Y_1)dx \quad (3)$$

where:

$$l^*(x, t, Y_1) = \exp\left[-\int_0^z \mu^*(a, Y_1)da - \int_z^x \mu(a, t - x + a)da\right] \quad (4)$$

According to the authors, for cohorts born before the earliest year for which mortality data are available for the population with the shortest mortality series, one could use, as the missing cohort mortality conditions, the period age-specific death rates at t.

Using the period age-specific death rates, we computed the TCAL for the years between 2015 and 2021. The TCAL computation for each country followed the availability of the data. For South Africa and Peru, for instance, the survival functions of cohorts born before 1950 (earliest available data) were estimated considering the mortality experience in 1950, as suggested by Canudas-Romo and Guillot (2015). In other words, to compute TCAL for 2020, for example, in which cohort data was needed from 1920, we considered that the observed mortality experience was the same throughout the whole period from 1920 to 1950. Figure 2 presents the data used to compute TCAL for 2020 in dark gray. The missing cohort mortality data missing in light gray is approximated considering demographic stability before 1950.

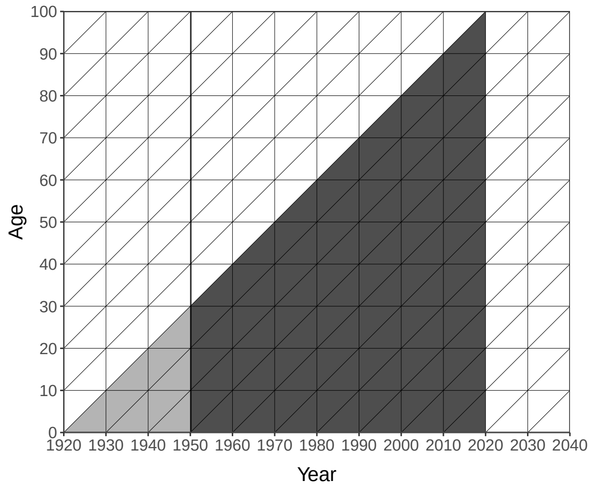

Figure 2: TCAL for 2020 using data available from 1950

RESULTS

Period Life Expectancy at birth

We assess the impact of COVID-19 by obtaining estimates from different measures, as detailed in the Data and Methods section. We report the period life expectancy at birth estimates in Figure 3. The consistent increase in period life expectancy observed between 2015 and 2019 was followed by different trajectories during the pandemic among the six outlined countries.

For Australia and Japan, increases in period life expectancy were also observed during the pandemic. Due to the stringent restrictions and high vaccination rates still in 2021, low COVID-19 mortality was observed in both countries between 2020 and 2021 (Adair et al., 2023; Munira et al., 2023). Also, due to behavioral changes induced by the pandemic and the reduced social and work activities, deaths from other causes may have declined over this period, contributing to lower mortality levels (Castro et al., 2023). Between 2019 and 2021, an increase of around 25 months was observed in male life expectancy at birth in Australia. The change for females in the country was around 10 months, changing from 81.1 to 83.2. In Japan, both male and female life expectancy at birth increased by around 8 months (from 85.1 in 2019 to 85.8 years in 2021).

In Italy, there was a noticeable impact observed in 2020, followed by a partial rebound in 2021. The difference in period life expectancy at birth between 2019 and 2021 was around 10 months for males (81.4 to 80.5) and 6 months for females (85.6 to 85.1). The United States encountered a significant decline in life expectancy during the first year of the pandemic, a trend that persisted into 2021 (Schöley et al., 2022). We estimated reductions of around 28 (76.6 to 74.3) and 18 months (81.7 to 80.2) in male and female life expectancy at birth, respectively, between 2019 and 2021.

In South Africa and Peru, period life expectancy witnessed a continuous decrease throughout 2020 and 2021. This result highlights the dramatic situation encountered by Latin American and African countries during the pandemic, with the delayed start in the vaccination campaigns. Peru presented the highest excess mortality per 100,000 inhabitants as of June 2021 (Karlinsky and Kobak, 2021). Between 2019 and 2021, we estimate a decrease of around 40 months in male (62.8 to 59.5) and around 49 months in female life expectancy at birth in South Africa (69.1 to 65). In Peru the results were similar, with decreases of around 45 months in life expectancy for both male and females (73.9 to 70.1 for males, and 78.5 to 74.8 for females).

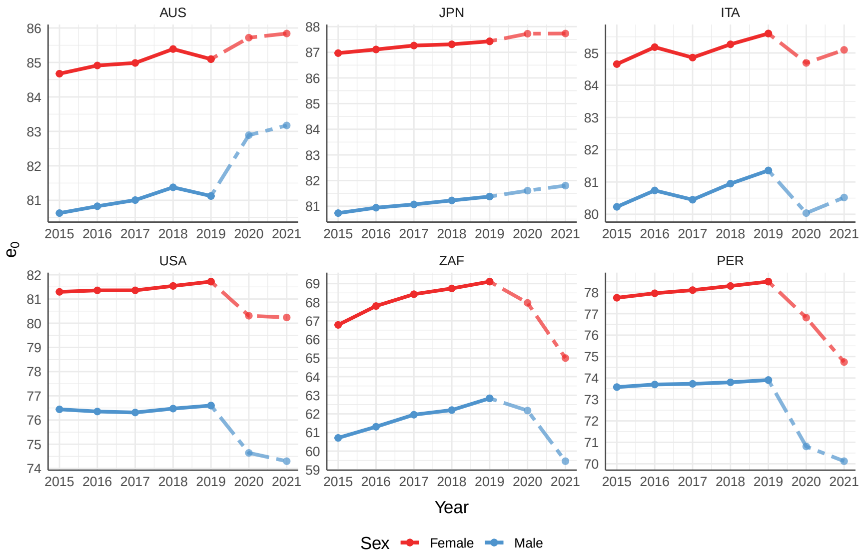

Figure 3: Trends in period life expectancy at birth, 2015-2021

Considering the age influence found in the fatality rates due to COVID-19, we analyzed the contribution of each age group to the differences in life expectancy at birth between 2019 and 2021. The results are shown in Figure 4. As expected from the increases in life expectancy over this period, positive contributions to the change in life expectancy of almost all age groups were observed in Australia and Japan. Relatively small negative contributions were also observed between ages 75 and 95. In terms of sex differences, male contributions were higher than female. Among the other countries, the contribution of most age groups, with exception of ages between 0 and 5 years old, were negative. The most expressive contribution was observed in Peru, among ages between 60 and 70 years old.

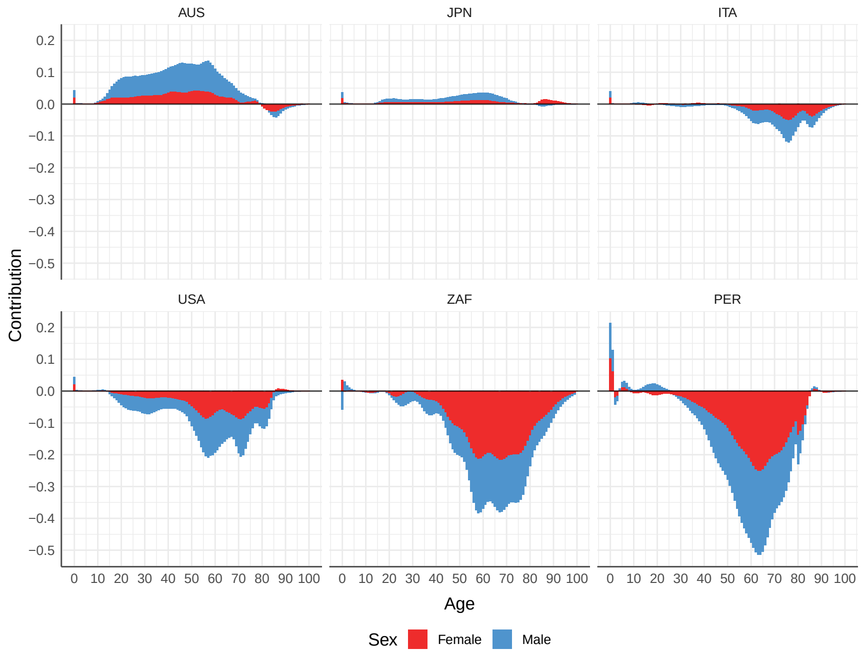

Figure 4: Age-Decomposition of differences in life expectancy at birth between 2019 and 2021

As discussed, although it is helpful to compare changes in mortality rates over the years or between populations, the period life expectancy at birth can be a misleading indicator in the context of a mortality shock. The previous results do not indicate that among Peru's male population alive during the pandemic years, there was an average loss of 45 months of life. Instead, they indicate losses in the average length of life of different hypothetical cohorts of individuals if they had experienced the mortality conditions observed in a pandemic year throughout their lives. It is doubtful that this would be the case for any cohort of individuals.

Cohort Life Expectancy at Birth

We estimated cohort life expectancies at birth for cohorts born after 1950 among all countries. Also, we estimated counterfactual cohort life expectancies at birth for the same cohorts, considering a scenario without the impact of COVID-19 on mortality. Finally, we subtracted from the counterfactual the estimated cohort life expectancies to obtain the changes due to the impact of the pandemic. The changes in cohort life expectancy at birth by birth cohort are presented in Figure 5.

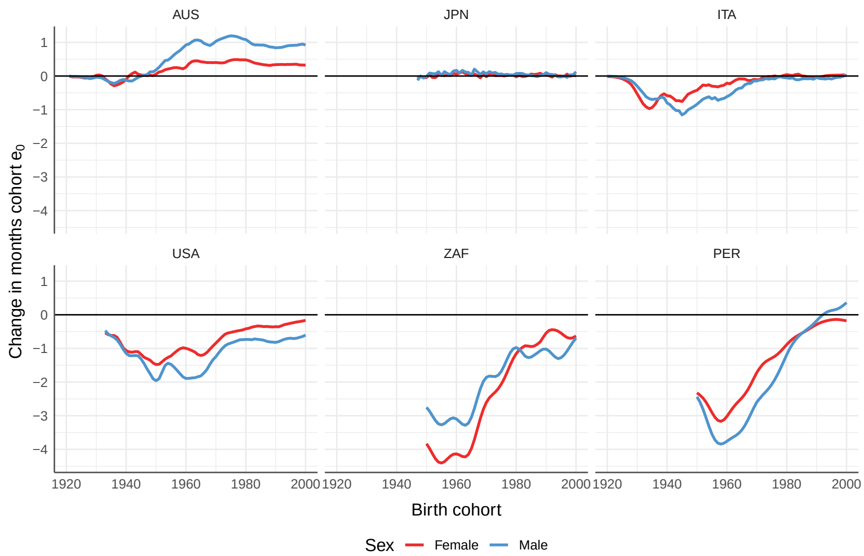

Figure 5: Change in cohort life expectancy at birth by birth cohort

From the results, it is possible to observe that, similarly to the period estimates and previous research, the male population was affected the most due to the pandemic, compared to the female population. It is also possible to observe differences among the cohorts. The results indicate that most changes in cohort life expectancy follow a U shape skewed to the left. This means cohorts born around 1920 presented more minor changes in cohort life expectancy due to the pandemic. Cohorts born between 1955 and 1975 (between 65 and 85 years old in 2020) seem to have been affected the most by increased deaths during the pandemic. This result highlights the interaction of cohort and age effects during the pandemic. This result also aligns with previous research that shows that middle- and old-aged adults have experienced the highest fatality rates due to COVID-19. The outcomes can be slightly different between countries. Nonetheless, among the most affected cohorts, the change in cohort life expectancy at birth was close to 4 months.

Truncated CAL

We estimated TCAL between 2015 and 2021, as shown in Figure 6. From the results, it is possible to observe that after the pandemic, there was a slight change in the pace of increase in TCAL. The results indicate, as stated by Guillot (2003), that CAL, by accounting for the entire mortality experience of cohorts before a time t, absorbs a mortality shock. The impact of the pandemic, in this case, can only be seen with the 1-year rate of change in the TCAL of the six countries. As shown in Figure 7, after 2019, especially in the United States, South Africa, and Peru, there was a significant change in the pace of change of the measure.

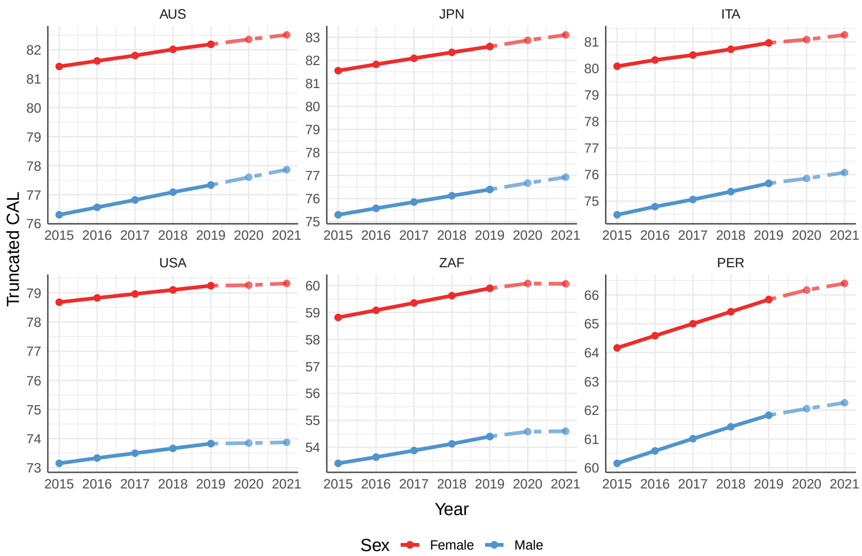

Figure 6: Truncated CAL, 2015-2021

The difference in the magnitude of the results between the cohort life expectancy, TCAL, and the period life expectancy is expressive and highlights the importance of accounting for other measures when exploring the impacts of the pandemic on mortality.

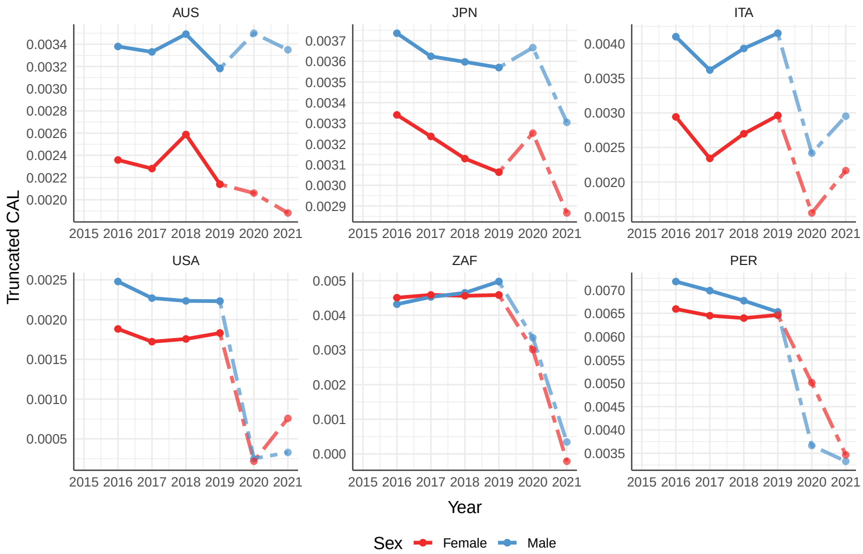

Figure 7: 1-year rate of change in Truncated CAL, 2015-2021

CONCLUSIONS

Measuring the short- and long-term impact of a mortality shock, such as the COVID-19 pandemic, is essential, but challenging. Despite the data issues and difficulty in removing the interaction with other causes of death, different measures can summarize the influence of a pandemic on mortality. For instance, to intermediate immediate actions to control the virus spread, several estimates of changes in excess mortality, period life expectancy, and years of life lost were obtained. Although they are convenient ways of summarizing current conditions and allowing the understanding of temporary changes due to a particular period condition, these measures don't offer assessments on the long-term implications of the pandemic on mortality.

Given the strong association between fatality rates and age, it is expected that the effects of the pandemic will be perceived differently by each birth cohort. [maybe also stress more about the age influence here, using results on the decomposition of changes in the period life expectancy] Therefore, it is essential to consider together with standard period measures such as the period life expectancy and excess mortality measures that capture the real lifespan impact of the pandemic on mortality.

This study uses data from the World Population Prospects (WPP) 2022 and the Human Mortality Database (HMD). We compute estimates of cohort life expectancy at birth and the Truncated Cross-Sectional Average Length of Life (TCAL) for all countries available in the WPP dataset. We highlight the results obtained for Australia, Japan, Italy, the United States, South Africa, and Peru. Results for other countries can be obtained in the supplementary material.

Despite the reductions of more than 40 months in male life expectancy at birth between 2019 and 2021 in Peru, South Africa, and more than 28 months in the United States, we estimate that the most expressive change in cohort life expectancy, when subtracting from a contrafactual scenario in the absence of the pandemic, was close to four months for males born around the 50's in Peru. Additionally, results obtained with TCAL show expressive reductions in 1-year relative changes after 2019 but not in the absolute estimates for all countries.

This result highlights the necessity of interpreting period measures carefully in the context of a mortality shock and contributes to the discussion of the mortality impact of the pandemic by including other measures, such as the cohort life expectancy at birth and the TCAL.

It is important to note that all measures have limitations. For this work, our approach relied on future assumptions for the mortality levels and the use of a contrafactual scenario, which is a hypothetical situation where the pandemic did not occur, removing excess deaths from the expected mortality in the years of COVID-19.

It is uncertain what the long-term impacts of the pandemic on mortality will be. Although the results indicate that the effects of the pandemic were not expressive in terms of months lost over the life course of individuals exposed to it, it is essential to be aware that COVID-19 had several impacts in other spheres, such as in physical and mental health, economics, besides the massive loss of life, especially in developing countries.

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SUPPORTING INFORMATION

Annex 1

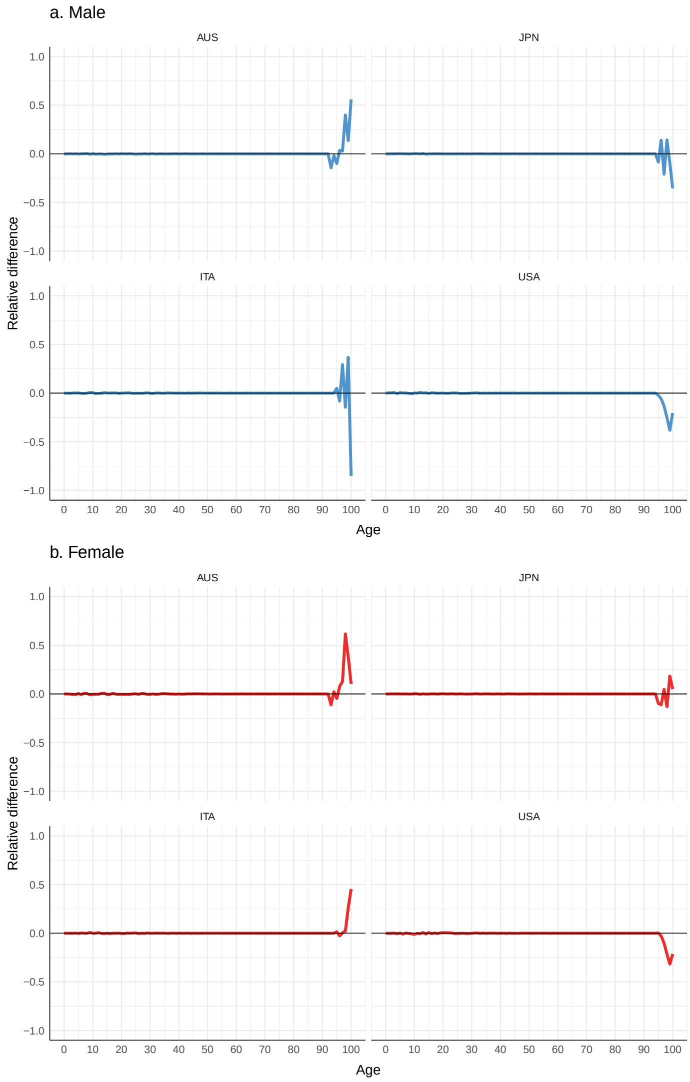

Figure 8: Relative age-specific mortality rates difference between HMD and WPP 2022 in 1950 ith reference to WPP 2022

Annex 2

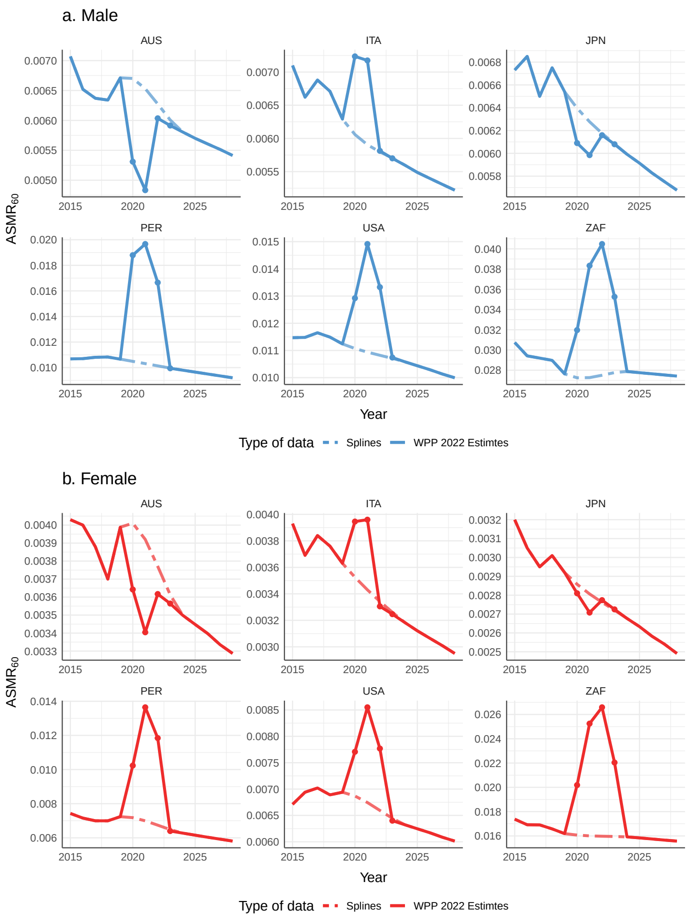

Figure 9: Linear Interpolation at age 60, Males and Females, 2015-2025