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# Regional COVID-19 mortality in Brazil by age

***Emerson A. Baptista*[1,*], *Bernardo L. Queiroz*[2] and *Everton E. C. Lima*[3]**

## Abstract

In this study, we use ternary color-coding to visualize and compare the age structure of deaths from COVID-19 in Brazilian meso-regions using the tricolore package in R, in two different phases of the pandemic. The analysis of the age profile is important to better understand the dynamics of the pandemic, and how it has affected the population over age 25, according to age groups (25–59, 60–79 and >80 years) and subpopulations of the country. The analysis focuses on the first wave of the pandemic, until the end of 2020, and the more recent wave. Overall, the results suggest that when the two recent waves of the pandemic are compared, different spatial patterns in the distribution of deaths across the country by sex and by age emerge. While the distribution of deaths is found to be concentrated at older ages, we also observe in the more recent period some areas of the country with a concentration of deaths among younger adults. The analysis further indicates that even in areas with a younger population age structure, which could act as a protective factor against complications, the age pattern of mortality is very heterogeneous, and we do not find a clearly defined age and spatial pattern. Our results highlight the importance of looking at the distribution of COVID-19 mortality across small areas, and show that there are many different levels of the pandemic in Brazil at the same time, rather than just one.

**Keywords:** COVID-19; mortality; age structure; ternary color-coding; meso-regions; Brazil

[1]Center for Demographic, Urban and Environmental Studies (CEDUA), El Colegio de Mexico, Mexico City, Mexico

[2]Department of Demography, Universidade Federal de Minas Gerais (UFMG), Belo Horizonte, Brazil

[3]College of Philosophy and Human Sciences (IFCH), University of Campinas (UNICAMP), Campinas, Brazil

[*]Correspondence to: Emerson A. Baptista, ebaptista@colmex.mx

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## 1 Introduction

The COVID-19 pandemic has negatively impacted public health worldwide, affecting trends in life expectancy at birth and placing additional burdens on health care systems. Since the early stages of the pandemic, Brazil has been among the countries hit the hardest by COVID-19 (Castro et al., 2021; Lima et al., 2021a; The Lancet, 2020). Thus, the pandemic brought a public health crisis to a country that had already become politically and socioeconomically fragile in recent years. In addition, Brazil's central authorities decided not to follow WHO recommendations, and hence ignored advice to employ measures to prevent the spread of the disease that were implemented in most countries that successfully controlled the pandemic. This failure to follow public health advice may have exacerbated the negative effects of the pandemic (Castro et al., 2021). Until September 2021, Brazil was ranked third globally in the number of confirmed cases, behind only the United States and India; and was ranked second globally in the number of deaths, surpassed only by the United States (Dong et al., 2020). Although these data reflect the large population sizes of these countries, they also indicate how their governments (mis)managed efforts to contain the pandemic. Moreover, there have been important regional disparities in the progression of the pandemic in Brazil, which motivated us to investigate and evaluate the spatial distribution of COVID-19 mortality in the country; and, in particular, to examine the question of how the pandemic spread across regions in a less developed country with a young population age structure (Candido et al., 2020; Castro et al., 2021; Lima et al., 2021a; Souza et al., 2020).

Deaths from COVID-19 have a steep age gradient, which is very similar to the age gradient observed in the general mortality rates of a population (Goldstein and Lee, 2020). The mortality rates are much higher for the elderly than they are for middle-aged and younger age groups; and in most countries, the mortality rates are higher for males than for females. Therefore, the population age structure can also be a risk factor for higher mortality, as locations with an older population can expect to have a relatively high overall number of deaths (Dowd et al., 2020; Goldstein and Lee, 2020). However, COVID-19 also appears to be more dangerous for people with previous health problems, as empirical evidence shows that infected people with cardiovascular diseases, diabetes or obesity face an increased risk of complications and of death (Jordan et al., 2020; Nepomuceno et al., 2020; Shuchman, 2020). While these research findings are important for understanding the different aspects of the spread of the pandemic at the national level, sub-national variations should also be investigated to provide support for public health interventions. In the context of the COVID-19 pandemic in Brazil, conducting sub-national analyses in Brazil is important because of the political approach taken by the federal government during the crisis. The responsibility for dealing with the spread of the disease was delegated to the municipalities. Mayors became responsible for the lockdowns, and population mobility restrictions policies and vaccination campaigns were also regulated by local authorities (Ribeiro and Leist, 2020; Storopoli et al., 2020).

In the early stages of the epidemic in Brazil, the largest numbers of deaths were concentrated in places where the first Sars-CoV-2 infections were registered (Castro et al., 2021; Lima et al., 2021a; Souza et al., 2020). However, having more knowledge about the spatial pattern of mortality (Baptista and Queiroz, 2019a; Schmertmann and Gonzaga, 2018) and about the age structure of the population (Dowd et al., 2020; Kashnitsky and Aburto, 2020) over the course of the pandemic could have helped to mitigate regional differentials in mortality caused by this disease, and improved our understanding of the differences in the age structure of COVID-19 mortality (Barreto et al., 2020). In Brazil, as has been observed elsewhere, the risk of death from COVID-19 is largely related to the age structure, the general health conditions and the socioeconomic status of the population (Borges, 2017; Clark et al., 2020; França et al., 2017). We argue that in a country characterized by major regional and socioeconomic differences (Ribeiro and Leist, 2020), which occur regardless of geographic level (Baptista and Queiroz, 2019a; Queiroz et al., 2017; Schmertmann and Gonzaga, 2018), having detailed knowledge about the age patterns of localities is essential for understanding the mortality risks associated with COVID-19. Additionally, there is a hypothesis that the incidence of COVID-19 mortality among young people has been higher in Brazil than in other countries (Guilmoto, 2020), and this spatial analysis might shed some light on the validity of this claim.

In this study, we use ternary color-coding (Baptista et al., 2021; Kashnitsky and Schöley, 2018; Schöley, 2021) to visualize and compare the age structure of deaths from COVID-19 in Brazilian meso-regions in two different stages of the pandemic. This technique encodes the relative shares in three parts of a whole – in our case, in three age groups – and provides a visualization of the distribution of data marginalized over the geographical surface (Schöley, 2021). In addition, we calculate COVID-19 case fatality rates and mortality ratios to compare outcomes across regions and population age groups. The analysis of the age profile is important, as it can help us better understand the dynamics of the pandemic (Dudel et al., 2020; Guilmoto, 2020), and how they affect different age groups (25–59, 60–79 and >80 years), and different regions of the country. While the evidence indicates that COVID-19 mortality has been higher for older individuals in most countries (Goldstein and Lee, 2020; Jin et al., 2020; Kang, 2020), recent research has pointed to the possibility that mortality rates for younger people may be higher in less developed economies. In the case of Brazil, it could be added that large regional differences may also play an important role in the risk of COVID-19 mortality (Nepomuceno et al., 2020; Rezende et al., 2020).

# 2 Data and methods

## 2.1 Data source and level of analysis

We use data from the Brazilian Ministry of Health's database, DATASUS, which is publicly available online (https://opendatasus.saude.gov.br/dataset). The Ministry of Health, through the Health Surveillance Secretariat (SVS), has been developing surveillance for specific respiratory diseases in Brazil, including, since 2009, for Serious Acute Respiratory Syndrome (SARS) due to the Influenza A (H1N1) pandemic. SARS was incorporated into the surveillance network for influenza and other respiratory viruses, and, recently (2020), COVID-19 was also included in the network.

We collected the information on April 10, 2021, when Brazil had registered 351,334 deaths from and 13,445,006 cases of COVID-19. In addition, we made a break in the data in order to understand and compare the age structure of deaths from COVID-19 in the two waves observed in the country. In this study, the first wave started on February 24, 2020 (first case registered in the country), reached its peak between the months of May and July 2020, and ended on October 31, 2020. The second wave began on November 01, 2020, and ended on April 10, 2021.

The original data are available at the individual level (case by case) and by municipality. The main limitation in using municipal-level data in Brazil is that the numbers of cases and deaths in each municipality may be small, given the limited number of people exposed to the risk of developing the disease in any given area, which may, in turn, lead to many random fluctuations in the estimates. To avoid such problems, while also pursuing our goal of analyzing and understanding regional variations, we aggregated municipalities into 137 comparable small areas (Annex 1) using the IBGE definition of geographic meso-regions. These geographical areas are statistical constructions that are aggregated and defined by regional and socioeconomic similarities, and that have not changed their boundaries over time. In addition, they have been used elsewhere (Baptista and Queiroz, 2019a,b; Baptista et al., 2021; Lima and de Queiroz, 2014; Lima et al., 2021a). We also produced estimates using standardized rates to enable us to compare COVID-19 mortality levels, thereby eliminating the effects of the population age structure (Dowd et al., 2020).

## 2.2 Case fatality ratio and mortality levels

In this study, we analyze the regional disparities in COVID-19 mortality based on the spatial distribution of proportional deaths from this illness, disaggregated by age group and across 137 small areas of Brazil. We also compared the overall mortality levels, by age group and sex, in the two waves of the analysis to provide a descriptive view of the pandemic in Brazil over the course of the pandemic, and to contribute to the discussion on excess mortality (Lima et al., 2021b) and on the impact of COVID-19 on life expectancy (Castro et al., 2021).

One important measure of the dynamics of the pandemic is the severity of infection. In general, examining fatality rates can improve our understanding of the severity of the disease, help us identify the population at risk, and give us some idea of how the health care system is dealing with the pandemic. There are two main measures used to investigate the effects of a disease (Green et al., 2020; Kelly and Cowling, 2013; Spychalski et al., 2020). The first measure is the infection fatality ratio (IFR), which refers to the ratio of deaths among the entire infected population. In other words, the IFR can be defined as the number of COVID-19-associated deaths divided by the total number of infections. The second measure is the case fatality ratio (CFR), which is the ratio of deaths among confirmed cases (Dudel et al., 2020; Kelly and Cowling, 2013; Sánchez-Romero et al., 2021). However, a limitation of using the CFR to measure the risk of COVID-19 mortality is that the ratio is influenced by the number of people who receive the proper diagnosis. In other words, in countries with very few tests, we may observe higher CFRs because only people who have been admitted to hospitals or who have severe symptoms have been tested. In addition, we are counting deaths at a specific point in time, but some individuals with the disease might have a positive or a negative COVID-19 test outcome.

In contrast to the case fatality ratio (CFR), the IFR is not based only on the number of confirmed cases, and should therefore not be biased by potential shifts in testing policies, although it still has some limitations. One advantage of the IFR is that it incorporates asymptomatic and undiagnosed cases. However, the biggest problem that arises in determining these ratios is accurately establishing the numbers of cases (symptomatic and total) and deaths (Kelly and Cowling, 2013). As our current data do not provide enough information to enable us to estimate IFRs, we did not pursue analyses using this indicator. Unfortunately, Brazil's COVID-19 testing rates are among the lowest in the world, albeit with considerable regional heterogeneity. While a few previous studies have estimated IFRs in the country based on seroprevalence surveys, they did not cover the areas that are the focus of this paper (Marra and Quartin, 2021).

## 2.3 Ternary color-coding

We used the approach proposed by Kashnitsky and Schöley (2018), later detailed by Schöley (2021), to investigate the spatial variation in deaths from COVID-19 in Brazilian meso-regions. We map the deaths from COVID-19 by age group (25–59, 60–79 and >80 years) using ternary color-coding. This visualization technique maximizes the amount of information conveyed by colors. It works by expressing the relative shares among three parts – in our case, among three age groups – as the mixture of three primary colors (we define yellow as the primary color for the 25–59 age group, cyan as the primary color for the 60–79 age group and magenta as the primary color for the 80+ age group). In other words, ternary color-coding is designed to visualize proportions of a whole; that is, anything that splits into three non-negative parts that add up to a unified whole. This approach is perhaps its biggest limitation. A second problem can occur when the data are unbalanced; that is, if the observations are concentrated in one specific age group.

In this study, we find that COVID-19 deaths are concentrated at ages 40 and older; that is, that there is little variation with regard to the visual reference point, which is the threshold that marks perfectly balanced proportions (Baptista et al., 2021; Kashnitsky and Aburto, 2019; Schöley, 2021). In addition, we have also limited the lower bound age group, which starts at age 25 instead of at zero years old. Therefore, we have changed the age point of reference to the location of the average structure of COVID-19 mortality in Brazil, and have thereby visualized the direction and the magnitude of the deviations from that average.

# 3 Results

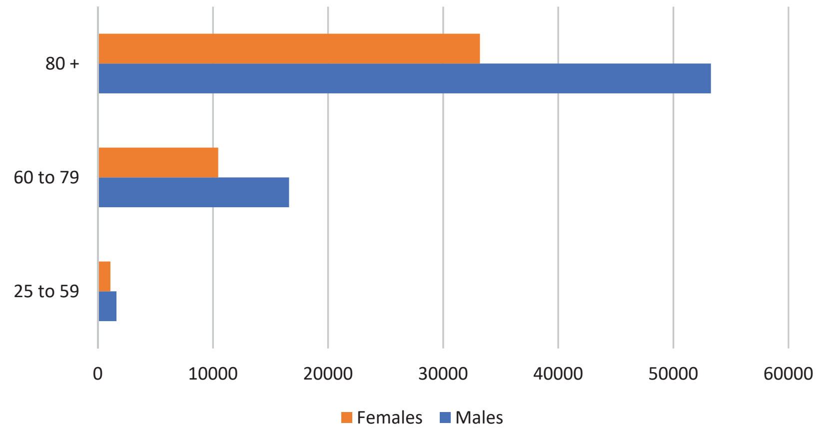
## 3.1 Preliminary analysis of COVID-19 mortality

Figure 1 shows the age-specific mortality rates for COVID-19. The goal here is to show the mortality differences by age and sex in Brazil. We opt to present this measure instead of the more traditional CFR, because, as we mentioned above, the latter is not an appropriate measure of COVID-19 mortality risk, since it is influenced by the number of people who receive the proper disease diagnosis. In the case of Brazil, we find that the age-specific mortality rates for males are higher than those for females in all age groups, in line with patterns observed in many other countries. However, for younger adults, the mortality risks in Brazil are shown to be greater than those observed in other countries.

Other studies have also investigated the impact of the pandemic using other measures. According to Lima et al. (2021b), Brazil had excess mortality of around 19% during the pandemic compared to previous years, but with large regional variation, with the less developed Northern part of the country experiencing much higher excess mortality than the more industrialized Southern and Southeastern parts of Brazil. In the same vein, Castro et al. (2021) estimated the impact of the pandemic on life expectancy at birth and at age 65 in Brazil. The results showed a reduction of about 1.3 years in life expectancy between 2019 and 2020, but with greater declines in the Northern than in the Southern states of the country.

Table 1 shows summary results for the country and its main regions. The distribution of COVID-19 deaths by age in Brazil follows a pattern similar to that observed in other countries. For males, we find that around 28% of deaths are of individuals aged 25 to 60, about 50% are of individuals aged 60 to 79 and 22% are of individuals aged 80 or older. For females, these values are 24%, 48% and 28%, respectively. In addition, there is some variation across regions of the country,

**Figure 1:**
**COVID-19 mortality rates per 100,000, by age group and sex, Brazil, 2021**




**Source:** Ministry of Health (2021).

which we will highlight later in the spatial analysis. One interesting result is that the distribution of deaths differs slightly by sex. For example, more of the female than the male deaths are concentrated at older ages, while slightly more men than women died at young adult ages.

Despite its limitations, in Table 1, we also show estimates of case fatality ratios by region of the country. The overall CFR in Brazil is 0.0280, ranging from 0.0345 in the Southeast to 0.0223 in the South. Recent data indicate that compared to all other countries in South America, Brazil has the highest CFR. Moreover, when we compare age-standardized measures for Brazil with those for 178 other countries in

**Table 1:**
**Summary statistics, COVID-19, Brazil and regions, 2021**

| Region | CFR | M/F deaths first wave | M/F deaths second wave | % deaths under 60 first wave | % deaths under 60 second wave |
|---|---|---|---|---|---|
| North | 0.0255 | 1.39 | 1.10 | 0.2227 | 0.2343 |
| Northeast | 0.0245 | 1.38 | 1.35 | 0.2619 | 0.2607 |
| Center-West | 0.0254 | 1.31 | 1.17 | 0.2893 | 0.2609 |
| Southeast | 0.0345 | 1.31 | 1.26 | 0.2901 | 0.2659 |
| South | 0.0223 | 1.43 | 1.37 | 0.2728 | 0.2512 |
| Brazil | 0.0280 | 1.36 | 1.25 | 0.2625 | 0.2545 |

**Source:** Ministry of Health (2021).

the world with available data, we find that the mortality levels in Brazil are greater than in 90% of these countries.

Additionally, we observe an interesting gender pattern of COVID-19 mortality in Brazil. During the first pandemic wave, the male-to-female ratio of deaths was 1.36. This means that there were 136 male deaths to every 100 female deaths. We also observe variations in this measure across regions. This ratio ranges from 1.43 in the South to 1.31 in the Center-West and Southeast. When we compare the first and the second waves, we see a decline in the gender differences in COVID-19 mortality for all regions of the country. For Brazil as a whole, the ratio went from 1.36 to 1.25 between the first and the second pandemic waves. Despite this reduction, males still had higher mortality levels than females, as shown in Figure 1. This gender differential in COVID-19 mortality has also been reported in other studies (Souza et al., 2020). Moreover, it can be argued that pre-existing gender gaps in mortality, such as those caused by the higher risks of external causes of death in males, were present even before the virus affected the population. In addition, in Brazil during the pandemic, males have accounted for almost 60% of deaths and 53% of hospitalizations related to COVID-19, and for over 70% of deaths and 40% of hospitalizations related to respiratory diseases besides COVID-19 (SARI) (Souza et al., 2020). In general, males in Brazil have higher mortality rates than females, and they have significantly higher rates of death from external causes. In the first stages of the pandemic, it was observed that mortality rates for younger adults declined due to changes in external causes of death (Santos et al., 2021). In other countries and regions, for example, the risk of dying was found to be higher for males than for females, but with a decline above age 80 (Ahrenfeldt et al., 2021). Aburto et al. (2021) also investigated the impact of the pandemic on life expectancy at birth and at age 60 for a series of countries. The study showed that the impact of the pandemic on life expectancy was greatest for males. This cause of death has been largely responsible for the elevated mortality risk among males during the pandemic, and explains a considerable share of the gender differentials in mortality in Brazil (Aburto et al., 2021). However, other empirical evidence indicates that that the restrictions imposed to limit the spread of COVID-19 have reduced external causes of death during the pandemic (Santos et al., 2021). Hence, it is possible that the new disease was responsible for causing another mortality gender gap.

## 3.2 Ternary color-coding results

Figure 2 (females) and Figure 3 (males) show the proportional distribution of COVID-19 deaths by age group and pandemic wave across Brazilian meso-regions. Before presenting the main findings, we show an example of how to interpret the ternary color-coding that uses females (Figure 2) for the first wave (left) as an example. Each point within the triangle represents a meso-region. The reading on the percentage of deaths from COVID-19 observed in each age group and meso-region occurs in a clockwise direction. Therefore, in this study, the percentage of deaths in the 25–59 age group can be read on the left side of the triangle; the percentage of deaths in the 60–79 age group can be read on the right side of the triangle; and the percentage of deaths in the 80+ age group can be read at the bottom of the triangle. Taking the visual reference point (point of intersection of the three lines within the triangle) as an example, which is the average structure of COVID-19 mortality in Brazil, the observed percentages are 24.5, 46.4 and 29.2 for ages 25–59, 60–79 and 80+, respectively. The colors represent the direction and the magnitude of the deviation from the average distribution of COVID-19 mortality in Brazil by age group. Yellow, cyan and magenta represent, respectively, a higher-than-average share of COVID-19 deaths in the 25–59, 60–79 and 80+ age groups. The saturation of the colors expresses the amplitude of the deviation, with perfect gray indicating a region that has an age distribution of mortality composition equal to the Brazilian average (Kashnitsky and Schöley, 2018).

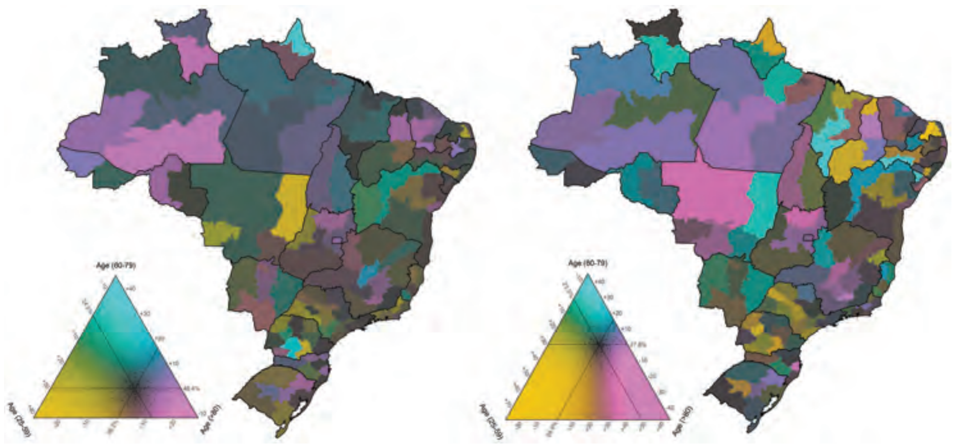
The overall results indicate that, for both sexes, the percentage of deaths in the 60–79 age group is higher in almost all meso-regions in both waves. When we compare males and females, we see that in the 25–59 and 60–79 age groups, there are more meso-regions in which the number of male deaths from COVID-19 is higher than the national average than in which the number of females deaths from COVID-19 is higher than the national average; while in the 80+ age group, the opposite pattern is observed.

Another important finding is that the gap has narrowed between the two waves studied. That is, whereas in the first wave, the number of deaths from COVID-19 among men in the 25–59 age group was higher in approximately 83% of the meso-regions; in the second wave, this share had declined to ~67%. In addition, it is not possible to observe a clear spatial pattern (or cluster) between the meso-regions for both sexes, although the results confirm that the ternary compositions are more spread out for men, especially in the first wave, since the data are more balanced. These overall results provide us with some clues that will be explored in more detail below.

A more specific analysis of the spatial variation by sex shows that there is no clear trend in deaths from COVID-19 for females (Figure 2). Roughly speaking, when we compare the two waves, we see that in the most developed region, the Southeast, the proportion of deaths from COVID-19 increased in the 60–79 age group; and, consequently, the proportion of deaths decreased in the 25–59 and 80+ age groups. In the Center-West region, mortality increased in the 60+ age groups and decreased in the younger age groups (25–59). On the other hand, when we look at the proportion of deaths from COVID-19 in the meso-regions in the North, Northeastern and Southern regions, we see no clearly defined patterns, as the spatial variation appears to be quite heterogeneous.

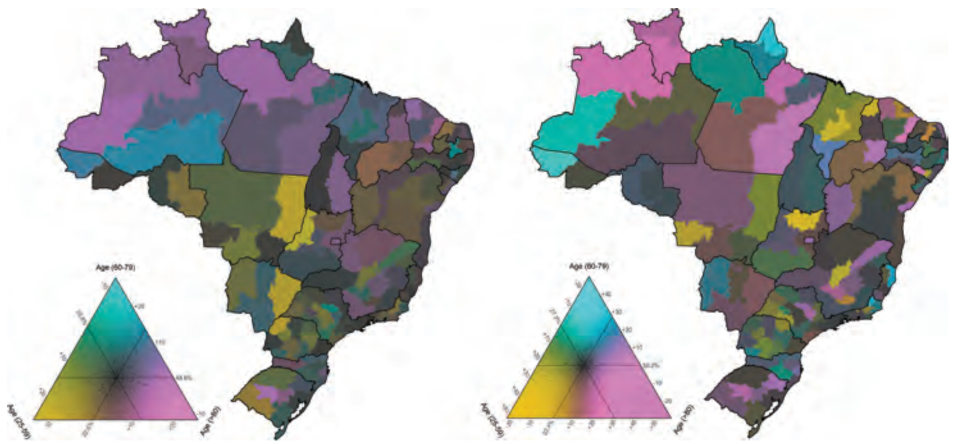
For males (Figure 3), we also observe no clear trend in deaths from COVID-19. In the Southern and Southeastern regions, the proportion of deaths from COVID-19 in the 60–79 age group increased, and the proportions of deaths in the 25–59 and 80+ age groups decreased. In the latter case, this may already be a reflection of vaccinations, which, in Brazil, followed age criteria, and occurred more quickly in

**Figure 2:**
**Spatial distribution of deaths from COVID-19 by age group in Brazilian meso-regions, females – first wave (left) and second wave (right)**



**Source:** Ministry of Health (2021).

**Figure 3:**
**Spatial distribution of deaths from COVID-19 by age group in Brazilian meso-regions, males – first wave (left) and second wave (right)**



**Source:** Ministry of Health (2021).

precisely these regions. In the other regions, the spatial variation observed is again quite heterogeneous.

## 4 Discussion

In Brazil, like in most other countries, COVID-19 outbreaks have varied greatly across regions and over time (Castro et al., 2021; Lima et al., 2021a). While the rhythms and stages of these outbreaks have depended on several factors, it is clear that COVID-19 mortality is strongly age-dependent (Castro et al., 2021; Dowd et al., 2020; Lima et al., 2021a; Nepomuceno et al., 2020). Additionally, the country is characterized by large socioeconomic and health inequalities, and, to a considerable extent, these differences are defined geographically (Castro et al., 2021; Lima et al., 2021a). Health inequalities are persistent in Brazil, due to factors such as differences in access to health care, the unequal provision of health care by the public and private sectors, and socioeconomic inequalities. The interaction between inequality and the COVID-19 pandemic is an important issue to be addressed. Hence, exploring the spatial pattern of COVID-19 mortality and infections across small regions of the country is of considerable relevance, as the results may shed light on how the COVID-19 pandemic has influenced pre-existing health inequalities in Brazil.

To explore the association between the pandemic and geographical inequalities in health, we used ternary color-coding to visualize and compare the age structure of deaths from COVID-19 in Brazilian meso-regions during two waves of the COVID-19 crisis. The analysis of the age structure is important for understanding the effects of the pandemic on the population as a whole (Dudel et al., 2020; Guilmoto, 2020), and by age group and region of the country – although there are, for example, differences in the underestimation of deaths and in their age structure due to the failure to correctly detect the cause of death. In addition, in all countries, COVID-19 mortality has been higher for older individuals (Goldstein and Lee, 2020; Jin et al., 2020; Kang, 2020), although recent research has pointed to the possibility that there have been high COVID-19 mortality rates at younger ages in less developed and middle-income countries. In the case of Brazil, large regional differences may also play an important role in mortality risks (Nepomuceno et al., 2020; Rezende et al., 2020). A combined analysis that takes into account the age and spatial patterns of COVID-19 deaths was previously lacking for Brazil. Our results go in the same direction as those of other studies on the effects of the pandemic. Castro et al. (2021) showed the differences in the impact of the pandemic on life expectancy at birth and at age 65 across states in Brazil, while Lima et al. (2021a) estimated the excess mortality across states in Brazil and other selected countries in Latin America. Both showed that the negative impacts were greater in the less developed states of the country; i.e., in the states located in the Northern and Northeastern regions.

Overall, our results suggest that the spatial pattern in the distribution of deaths across the country by sex differed in the two recent waves of the pandemic, and that the two waves differed in other interesting ways as well. While the distribution of deaths was concentrated at older ages, we also observed that in the more recent period, some areas of the country had high concentrations of deaths among younger adults. For example, we found that in the more developed areas of the Southeastern region, there was an increase in the proportion of deaths in the 60–79 age group, and a reduction for other ages.

The analysis also indicated that even in areas with a younger population age structure, the age pattern of mortality was very heterogeneous, and there was no clear spatial pattern. The regions with a young age structure were mainly characterized by worse health conditions overall and less access to proper health care, which might have influenced the distribution of mortality by age group and the recent evolution of the pandemic. Previous studies have shown that Brazil has smaller numbers of hospital beds and ICUs than more developed economies (Noronha et al., 2020). Furthermore, overall access to health care is uneven in Brazil, with poorer individuals living in less developed areas having worse access to proper medical care than their counterparts in the more developed regions of Brazil. The previous health conditions of the population also play an important role, and are related to the observed results. Baptista et al. (2021) pointed out that, until 2019, areas in the Northern and Northeastern regions of Brazil still had a high prevalence of infectious diseases, although a rapid increase in mortality from chronic and degenerative diseases, such as cardiovascular diseases, has also been observed.

The separate analysis of the two waves showed that Brazil did not see a reduction in pandemic conditions over the period studied. The main difference was, however, that whereas in 2020 a temporal spread was observed across the country, with some regions being hit before others; in the more recent wave, the progression of the pandemic was similar all over the country (Castro et al., 2021; Lima et al., 2021a). This scenario, combined with the weakening of measures for dealing with the pandemic, as well as the slowing of the vaccination process, are conditions that need to be considered when seeking to change the future course of the pandemic and its effects on the population. In a country characterized by high levels of regional and socioeconomic heterogeneity, general mortality risks have been much higher in certain areas due to a lack of good health care infrastructure (Noronha et al., 2020), and because large shares of the population need emergency assistance from the government, and significant numbers of elderly people with comorbidities are not practicing social isolation. The populations in these areas face a greater risk of the collapse of the health care system, which could, in turn, lead to a considerable increase in the number of deaths from COVID-19, and to an increase in the number of deaths from all causes across different age ranges due to the indirect effects of the pandemic.

Our analyses are also subject to limitations. The first limitation, which is more general, is the insufficient quality of the COVID-19 data in the country due to the lack of adequate testing and reporting (Lima et al., 2021a). For these reasons, the data may be seriously underestimated, which directly affects estimates of the mortality levels and life expectancy of the population. The second limitation is that we needed to set an “arbitrary" time frame to carry out the study, even though we are aware that COVID-19 cases and deaths are still ongoing. However, the results of the analysis contribute to our understanding of the heterogeneity of the impacts of the COVID-19 pandemic in Brazil, which was also shown using excess mortality at the state level (Lima et al., 2021a). Finally, this study did not take into account other major risk factors associated with COVID-19 deaths, such as non-communicable diseases (e.g., cardiovascular disease and cancer), obesity, smoking, diabetes and socioeconomic status (Selvan, 2020; Wolff et al., 2021). Nevertheless, we argue that investigating the geographic variation in deaths from COVID-19 across Brazilian meso-regions by age and sex is an important contribution to identifying priority areas for intervention.

## Availability of data and materials

This data is publicly available at https://opendatasus.saude.gov.br.

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## ORCID

*Emerson A. Baptista* https://orcid.org/0000-0001-7582-2736
*Bernardo L. Queiroz* https://orcid.org/0000-0002-2890-1025
*Everton E. C. Lima* https://orcid.org/0000-0001-6275-9854

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## Annex 1