Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Variations of COVID-19 mortality are affected by economic disparities across countries

Lan Yao, Lotfi Aleya, Scott C. Howard, Yanhong Cao, Cong-Yi Wang, Sara W. Day, J. Carolyn Graff, Dianjun Sun, Weikuan Gu,⁎⁎

Health Outcomes and Policy Research, College of Graduate Health Sciences, University of Tennessee Health Science Center, Memphis, TN 38103, USA
Chrono-Environnement Laboratory, UMR CNRS 6249, Bourgogne Franche-Comté Université, F-25030 Besançon Cedex, France
College of Nursing, University of Tennessee Health Science Center, Memphis, TN 38105, USA
Center for Endemic Disease Control, Chinese Center for Disease Control and Prevention, Harbin Medical University, PR China
The Center for Biomedical Research, Department of Respiratory and Critical Care Medicine, NHPC Key Laboratory of Respiratory Diseases, Tongji Hospital, Tongji Medical College, Huazhong University of Science and Technology, Wuhan 430030, PR China
Department of Orthopedic Surgery and BME-Campbell Clinic, University of Tennessee Health Science Center, Memphis, TN 38163, USA
Research Service, Memphis VA Medical Center, 1030 Jefferson Avenue, Memphis, TN 38104, USA
Key Laboratory of Etiologic Epidemiology, Education Bureau of Heilongjiang Province & Ministry of Health (23618104), 157 Baojian Road, Harbin, Heilongjiang 150081, PR China

HIGHLIGHTS
- Whether and how much the economic inequality affects the COVID-19 is an important question.
- When cases of COVID-19 reach its maximum, it tests the capacity of healthcare system.
- Data on COVID-19 mortality rates, lag times at the turning points of 106 countries collected.
- Different income levels influence of income levels on the response to the pandemic.
- Among major factors that influence the death rate, economic levels play the biggest role.
- The inequality of economic efforts resource allocation to fight the COVID-19 and other pandemics.

GRAPHICAL ABSTRACT

Abstract

Editor: Jay Gan

Background: When the COVID-19 case number reaches a maximum in a country, its capacity and management of health system face greatest challenge.

Methods: We performed a cross-sectional study on data of turning points for cases and deaths for the first three waves of COVID-19 in countries with more than 5000 cumulative cases, as reported by Worldometers and WHO Coronavirus (COVID-19) Dashboard. We compared the case fatality rates (CFRs) and time lags (in unit of day) between the turning points of cases and deaths among countries in different development stages and potential influence factors.

As of May 10, 2021, 106 out of 222 countries or regions (56%) reported more than 5000 cases. Approximately half of them have experienced all the three waves of COVID-19 disease. The average mortality rate at the disease turning point

http://dx.doi.org/10.1016/j.scitotenv.2022.154770
Received 10 January 2022; Received in revised form 18 March 2022; Accepted 19 March 2022
Available online 25 March 2022

0048-9697/© 2022 Published by Elsevier B.V.
Policy

Turning points was 0.038 for the first wave, 0.020 for the second wave, and 0.023 for wave 3. In high-income countries, the mortality rates during the first wave are higher than that of the other income levels. However, the mortality rates during the second and third waves of COVID-19 were much lower than those of the first wave, with a significant reduction from 5.7% to 1.7% approximately 70%. At the same time, high-income countries exhibited a 2-fold increase in time lags during the second and the third waves compared to the first wave, suggesting that the periods between the cases and deaths turning point extended. High rates in the first wave in developed countries are associated to multiple factors including transportation, population density, and aging populations. In upper middle- and lower middle-income countries, the decreasing of mortality rates in the second and third waves were subtle or even reversed, with increased mortality during the following waves. In the upper and lower middle-income countries, the time lags were about 50% of the durations observed from high-income countries.

Interpretation: Economy and medical resources affect the efficiency of COVID-19 mitigation and the clinical outcomes of the patients. The situation is likely to become even worse in the light of these countries’ limited ability to combat COVID-19 and prevent severe outcomes or deaths as the new variant transmission becomes dominant.

1. Introduction

When the wave of COVID-19 reaches its peak, it tests a country’s comprehensive capacity. This covers not only the healthcare system, but also the other sectors, such as transportation, food and nutrition, citizen’s mobility, social security, medical resources, financial aid, government response capacity, education and the public response to catastrophic diseases. When taking them together, we proposed the hypothesis that income level is the most important indicator of a country’s comprehensive capability. For any given country, its capacity to manage the disease will be reflected by the mortality rate at the turning point of the disease and the time lag between hospital admission and death (the lag time). When the cases in a country overwhelms the capacity of its healthcare system, mortality will rise and the interval between onset of the disease and death will be short.

Worldometers (https://www.worldometers.info/coronavirus/) and the World Health Organization (WHO) Coronavirus (COVID-19) Dashboard (https://covid19.who.int/) (Wang et al., 2020b) reported daily cases and deaths in most countries. Each wave of the pandemic shows two intrinsic turning points of the cases and the mortality. The case turning point is defined as the day(s) in which the cases reach its peak or the day(s) when the cases begin to decline, while the mortality turning point is defined as the day(s) when the deaths start to decrease. The time lag between the case and mortality turning points represents the interval between the initial case report and death.

Since the first report of COVID-19 in Wuhan City, the causative agent, SARS-CoV-2 has spread all over the world. The first wave of the disease occurred in early 2020, mainly in developed countries (Ghinaï et al., 2020). The rapid transmission of the disease is attributed to the frequent international travel (Yin et al., 2021). By the time of the second wave at the end of 2020, COVID-19 had influenced most countries in Africa (Salyer et al., 2021). By May 10, 2021, many countries had experienced all the three waves of COVID-19. Thus, multiple waves of COVID-19 have occurred in countries at different income levels. The data suggest that during the first wave of the COVID-19 pandemic, the SARS-CoV-2 virus transmitted more slowly in developing countries than in developed countries (Salyer et al., 2021; Ullah et al., 2021). However, the second wave of the COVID-19 pandemic was more severe on the African continent than the first wave (Salyer et al., 2021). The consequences in third wave in developed countries became worse.

Therefore, it is important to examine multiple variables over time, down to the local and national levels, for each wave of COVID-19 (Gu et al., 2021a). For example, the income levels of countries affected by the COVID-19 pandemic can be divided into high-, upper middle-, low middle-, and low-income groups. Countries differ in many ways, including demography, geography, culture, politics, language, social equity, and disease patterns, which may affect each country’s response to the COVID-19 pandemic, and whether they can be grouped into the same or different groups as a function of income level (Baena-Diez et al., 2020; Neill et al., 2021). Countries in similar or different income level may respond to COVID-19 differently during different waves of the pandemic. We aimed to investigate mortality and time lag, and the related factors, in countries from four income levels around the world to further understand how they differ in their fighting against each wave of the COVID-19 pandemic.

2. Methods

2.1. Data sources

On May 10, 2021, data were collected from Worldometers and the WHO Coronavirus (COVID-19) Dashboard. Inclusion criteria were 1) as of May 9, 2021, the confirmed cases were at least 5000; 2) the deaths on the cases turning point or the day with at least ten deaths; Exclusion criteria were 1) data without obvious turning point in either cases or mortality; 2) the deaths on the day of the turning point was less than ten; 3) the cases and mortality turning points were significantly different from one another; or 4) there were outliers, as determined by the authors. Standards about income levels were obtained from a list of countries using the World Bank’s Atlas method which relies on the gross national income (GDP) per capita in 2019 at nominal values as an indicator of income. Population statistics were collected from Worldometers (https://www.worldometers.info/world-population/population-by-country/).

2.1.1. Turning points of cases and deaths (in days)

We used the weighted number method to determine the turning point of a wave of COVID-19. Thus, we defined the cases turning point as the day with the largest average cases for the previous seven days (the 7-day average), while the mortality turning point is calculated from the largest 7-day average of deaths. The days between the cases and mortality turning points is defined as the time lag. The following criteria were used to determine a specific turning point: 1) three authors (Yao, Wang, Gu) made independent observations of the data and all agreed on the turning point; 2) a similar pattern was observed between the cases peak and deaths peak, and each cases turning point had a corresponding mortality turning point; 3) the cases and deaths on both sides of the turning point were at least 10% lower than the numbers on the day of the turning point. If two or more numbers of cases or deaths were equal at the turning point, the value obtained on the earliest date was selected as the turning point. If ambiguous peaks appeared, the study team would discuss and then make a decision to include or exclude.

2.1.2. Waves and sequence

We use a wave to describe a disease outbreak where the cases and deaths had turning points (peak days) and flanked on both sides by days when the cases or deaths were at least 10% fewer than they were on the peak day. Therefore, the counts of waves were equal to the numbers of turning points. In general, the mean interval between the symptom’s onset and COVID-19-related death was 13 days, varying from 6 to 30 days (Wang et al., 2020b).

We estimated a wave to be abnormal if the death turning point occurred earlier than the cases or the time lag between the cases and mortality turning points was longer than 30 days. Accordingly, time lag shorter than 5 days or longer than 20 days was detected as outliers.
2.2. Statistical analysis

Data of the cases and mortality turning points (in days) during the first three waves of COVID-19 in 106 countries were collected and stored in an Excel file. Descriptive analyses were performed to determine the time lag between the cases and deaths turning points and the case fatality rate (CFR), which is defined as the number of deaths on the day of the mortality turning point (the peak number of deaths) divided by the number of cases on the day of the cases turning point. For each country or region, mortality was determined as a function of the total cases per wave in a country or region, as follows:

\[
\text{Mortality} = \frac{\sum(D_0 \times C_0)}{T_0},
\]

where \(D_0\) is the number of deaths on the mortality turning point of a single wave in an individual country or region, \(C_0\) is the number of cases on the case turning point of the same wave in an individual country or region, and \(T_0\) is the total number of cases in all countries or regions during the same wave.

The formula function of Excel was used to calculate the correlation coefficient \(r\) between these parameters. Significance levels were determined based on previously standardized rules. Countries were sorted into three groups based on high-, upper middle-, and lower middle-income levels and analyzed with respect to mortality and time lags; the low-income countries were omitted since data were unavailable to the researchers. Multiple analyses were conducted in the longitudinal order of the waves (i.e., counting the number of waves regardless of their timeline), waves based on time sequence (i.e., wave number was assigned according to their occurrence), and waves that were trimmed due to a small number of deaths or abnormalities in time lag. Multiple Linear models described the correlations among the variables. Student t-tests were conducted with #1 paired two-tailed distributions. Figures for mortality were visualized using the Chart function in Excel, including those of Australian Bureau of Statistics, GeoNames, Microsoft, Navinfo, and TomTom.

2.3. Role of the funding source

This study was conducted without a funding source.

3. Results

3.1. Mortality was significantly different at the turning points of each wave of COVID-19

As of May 10, 2021, 222 counties or regions reported cases of COVID-19. Among them, 106 (50%) countries or regions reported more than 5000 cases. Three of 106 countries did not exhibit any distinctive wave (Data in brief Table 1). Among the included 103 countries, 88 exhibited two waves, 36 exhibited three waves, but only 6 exhibited four waves. Accordingly, our analysis focused on the first three waves. The total cases for the first wave were 479,748 with 16,077 deaths, for the second wave 696,174 cases with 14,977 deaths, for the second wave 696,174 cases with 16,077 deaths, and for the fourth wave 59,098 cases with 1482 deaths. Due to the relatively small number of cases and deaths for the fourth wave, our further analysis was limited to the first three waves of COVID-19. The average mortality rates at the peak or turning point (death number/case number) for each wave were 0.038, 0.020, and 0.023 (Data in brief Table 1). After being normalized to the number of cases, the mortalities for time groups 1, 2, and 3 were 0.038, 0.019, and 0.018, with a reduction in the mortality rate at least 50% for waves 2 and 3 compared to the first wave. These analyses revealed that there were significant variations in mortality rates among countries in the first wave than those in the second and third waves. During the second and third waves, mortality among countries appeared nearly flat curve (Fig. 1).

Based on the non-weighted data, the correlation coefficient between waves 1 and 2 was 0.198 (p = 0.000) and −0.116 between waves 1 and 3 (p = 0.408) While the coefficient between waves 2 and 3 was 0.266 with a p-value of 0.408. Similarly, when the comparison was based on the pandemic onset, the correlation coefficient between waves 1 and 2 was 0.134 (p = 0.000), while that between waves 1 and 3 was −0.208 (p = 0.025). The correlation between wave 2 and 3 was 0.230 with a p-value of 0.517.

3.2. Mortality during the first three waves of COVID-19 varied across countries and income levels

The variations of mortality rates at the turning points were assessed in countries ranked by income levels. Two sets of mortality data were examined based on wave sequence and the other based on wave rate adjusted. The data based on wave sequence showed different patterns depending on the country’s income level. The high-income subgroup of countries exhibited a first wave mortality rate of 5.7%, which was considerably higher than that exhibited by the other subgroups (Fig. 2, panels A, C, and E). In contrast, the high-income group displayed a much lower mortality rate during the second and third waves (1.7%), approximately 70% reduction to the first wave. This group revealed insignificant difference of mortality rates between the second and third waves. The data based on average and weighted mortality showed a similar pattern. The time-adjusted data for the high-income group exhibited a pattern similar to that the data based on wave sequence (Fig. 2B).

The upper-middle income countries showed a different pattern for mortality, depending on the type of data analyzed (wave-sequence vs. time-adjusted). Analysis of the wave data revealed that first wave mortality for this subgroup was lower than the high-income countries (0.0575 vs 0.0347). The reduction of mortality between the second and third waves was 38% for this group, which was less than the reduction observed in the high-income subgroup. When the wave-sequence data from the upper middle-income countries was weighted by the cases, mortality was similar during the first three waves (Fig. 2C). In contrast, analysis of the time-adjusted data showed higher average mortality during the first wave than the second and third waves. When the time-adjusted data was further weighted by the cases, the first wave mortality was lower than that of the second and third waves (Fig. 2D).

The lower middle-income subgroup displayed an obvious trajectory of increased mortality in line with wave sequence. When the wave sequence data were analyzed, the first wave mortality calculated from average and case weighted numbers was lower than that calculated for the second and third waves (Fig. 2E). Analysis of the time-adjusted data showed higher average mortality during the first wave than the second and third waves. When the time-adjusted data was weighted by the cases, the mortality of the first wave was lower than that of the second and third waves (Fig. 2F).

When the data from each wave were analyzed separately, the income categories exhibited different patterns. During the first wave, the mortality exhibited by the high-income group was higher than that of the upper middle- and lower middle-income subgroups, regardless of the data type analyzed (Fig. 2, panels A-F). Most of the countries in this group exhibited a high first wave mortality, while the first wave mortality of the upper middle- and lower middle-groups were lower but similar to one another (Fig. 2, panels A1 and B1). During the second and third waves, the high-income group exhibited lower mortality than the upper middle- and lower middle-income subgroups, regardless of data type (Fig. 2, panels A-F). There were still variations among the countries in the high-income subgroup but the mortalities among countries in the upper middle- and lower middle-income subgroups were similar to one another (Fig. 2, panels C1–F1).

3.2.1. Time lags among countries for waves 1, 2, and 3

The data collected from 106 countries showed average time lag between the cases and mortality turning points were 4.388 days for wave 1, 12.55
Fig. 1. Robust mortality at the case turning point of the COVID-19 pandemic for 103 countries. Panels A, B, and C show mortality based on wave numbers without considering the time sequence. Panels D, E, and F show mortality of waves based on the timeline. Panels G and H show the distribution of mortalities based on wave number and timeline. In panels G and H, the blue, pink, and grey colors represent waves 1, 2, and 3, respectively. Panel I shows the directly calculated and weighted mortality of three waves without the use of corrected data. Panel J shows the directly calculated and weighted mortality of three waves using data from which the outliers had been removed. Panel K shows the mortality of the first three waves, calculated from data after correction based on timeline. Panel L shows the dates of peak mortality for the first three waves, after correcting for both outliers and timeline.
Fig. 2. Turning point mortalities during the first three waves of COVID-19 disease in countries with different income levels. Panels A, C, and E show the average mortalities for waves 1, 2, and 3 in countries of high-, upper middle- and low middle-income, respectively. Panels B, D, and F show the mortalities for waves 1, 2, and 3 in these countries after adjustment with timeline. Panels A1, C1, and E1 show the distribution of mortalities for waves 1, 2, and 3 in countries with different income levels. Panels B1, D1, and F1 show the distribution of mortalities for waves 1, 2, and 3 in these countries after timeline adjustment.
days for wave 2, and 11.277 days for wave 3 (Data in brief Table 3). The
trends in time lag were similar to one another whether or not we eliminated
time lags longer than 30 days (Fig. 3A) (Wang et al., 2020a, 2020b). Therefore,
the data from which these longer lags were removed were used for further
analysis. Overall, the high-income countries exhibited longer time lags
between the case and mortality turning points (Fig. 3B). During the first
wave, the time lag for the high-income countries was 7.6 days, compared
with 5.8 days for the upper-middle-income countries and 2.1 days for the
lower-middle-income countries. During the second and third waves, the
time lag for the high-income countries extended to 12 days, while that for
the upper middle- and lower-middle-income countries was about half the
length of high-income countries (approximately 6 days). There was a wide
variation in lag times among the high-income countries, which ranged
from $-14$ to 20 for wave 1, $-2$ to 29 for wave 2, and $-17$ to 28 for
wave 3 (Fig. 3C). Similar variation was observed among the upper
middle-income countries, where lag times ranged from $-12$ to 22 for
wave 1, $-13$ to 23 for wave 2, and $-12$ to 26 for wave 3 (Fig. 3D). In con-
trast, the lower middle-income countries exhibited relatively little variation,
with lag times ranging from $-14$ to 14 for wave 1, $-5$ to 17 for wave 2, and
$-3$ to 17 for wave 3 (Fig. 3E). There were countries in all 3 income catego-
ries that exhibited mortality turning points that were earlier than the case
turning point, resulting in negative values for lag time.

3.2.2. Relationship between mortality and lag time during COVID-19 waves 1, 2,
and 3 in different countries

Overall, we did not detect any correlation between mortality and the lag
time (Fig. 4A and Data in brief Table 3). However, when the data was sorted
into groups of countries by income level prior to analysis, different patterns
emerged (Fig. 4B). For countries in the high-income group, the lag time was
negatively correlated with mortality during the first wave, while this relation-
ship became positive for the third wave (Fig. 4, panels B, C, D, E). There was
no statistically significant correlation between mortality and lag time for the
countries in the upper-middle-income group during the first or second waves,
but there was a negative correlation during the third wave, which exhibited a correlation coefficient (r value) of $-0.263$
(Fig. 4B, panels F, G, H). For countries in the low-middle-income group,
there was a positive correlation of mortality and lag time during the first
wave (Fig. 4B) that became negative during the third wave (Fig. 4, panels
I, J, K). Thus, the groups of countries with high- and lower-middle-
incomes exhibited patterns differ from each other, while the upper
middle-income group fell between the two (Fig. 4B).

3.3. The cases per million population among countries of different income levels

We specifically examined the incidence rate per million people in differ-
ent countries during the peak period to show that the differences in mortal-
ity and the lengths of time from onset of COVID-19 symptoms to death
among these countries was not a result of developed countries having larger
populations and fewer people suffering from the disease. The incidence per
million of the first wave did not vary between countries with different in-
comes, while during the peak of the second and third waves, the incidence
per million in developed countries was higher than the cases less-developed
countries experienced (Fig. 5). As shown in Fig. 5A and B, calculated with
raw and corrected data, the cases per million in the countries of high in-
come in the third wave becomes much more than that of countries of
upper and mid low incomes. The distributions of cases among three
waves in countries with different income levels are different, with much
less cases in the low middle-income countries (Fig. 5D–H).

Fig. 3. The similarities and differences in lag times for in countries at different income levels. Panel A shows the lag times of all countries examined during COVID-19 waves 1, 2, and 3 in different countries. The raw data includes the lag times of all countries, while the “only days <30” data was adjusted to include only lag times that were less than absolute 30 days. Panel B shows lag times for waves 1, 2, and 3 in countries with different income levels, using the “only days <30” dataset. Panel C shows the distribution of lag times for countries in the high-income group. Panel D shows the distribution of lag times for countries in the upper-middle-income group. Panel E shows the distribution of lag times for countries in the lower-middle-income group.
3.4. Other factors and among countries of different income levels

Many other factors have been linked to the scale of COVID-19 pandemics. Most of these analyses are based on the data of first wave (Gualda et al., 2021; Yao et al., 2021). In particular, transportation and population density have been linked to the COVID-19 pandemics in developed countries (Yin et al., 2021; Ma et al., 2021). There reports also simultaneously pointed out a fact that developed countries had higher rate of infection in the first wave of the pandemics. It is also known that the developed countries have larger portion of aging population than that of developing countries. Aging population in assumption affects the death rate of developed countries (Wang et al., 2020a), especially in the first wave of the disease (Data in brief Table 4). The correlation coefficient between the first wave mortality rate and population older than 65 was 0.419, while the correlation coefficients between the second and third wave mortality rate and population older than 65 were −0.230 and −0.280.

We also collected the data of ownership of passenger cars and analyzed its relation to the death ratio in three waves. The correlation coefficient between the first wave mortality rate and ownership of passenger cars was 0.354, while the correlation coefficients between the second and third wave mortality rate and ownership of passenger cars were −0.287 and −0.339. Within three income levels, the correlation coefficient between first wave death rate and income levels is 0.316. The coefficient between second and third wave death rates and income levels were −0.215 and −0.277. The correlation coefficient between disease lagging days and other factors did not show significantly different (Data in brief Table 5).

3.5. Recent data confirmed the patterns of third wave

The data for the third wave were less than the first two waves in our early collection. On Feb 20, 2022, we collected most recent data on the third wave and compared the mortality among countries and regions at different income levels. The results confirmed our early analysis that the
mortality in the up-middle and middle low-income levels higher than that of the high-income level. Fig. 6 shows that there is a clear difference among the patterns of death rates in different income levels (Fig. 6A). The average death rate in up middle and middle low levels are higher than that of the high-income level (Fig. 6B). This result indicates that our analysis correctly reflects the association between the death mortality and income levels in different waves.

4. Discussion

Country’s comprehensive ability to manage the COVID-19 pandemic varies widely (Gu et al., 2021a). Different countries vary in their overall national capacity due to differences in their income levels, which in turn affects their ability to respond to COVID-19. This difference in ability is reflected in different peaks of disease and death during the first three waves of COVID-19. High-income countries, usually developed countries, were the first group affected by the COVID-19 because of the frequent domestic and international mobility (Yao et al., 2021; Ma et al., 2021). The unprecedented infection of the SARS-CoV-2 virus, the over-loaded hospital and adverse outcomes caught every country off guard. Thus, during the first wave of the pandemic, although developed countries possessed better medical resources and comprehensive national capacity, their response to the COVID-19 was still inadequate. However, as the hazards of COVID-19 and the contagious power of SARS-CoV-2 were fully realized, developed countries showed themselves to have better capability to battle the second and third waves of COVID-19. For example, the relatively rapid population screening (Gu et al., 2021b) and development of vaccines against SARS-CoV-2 facilitated better control of COVID-19 after the three waves (Regev-Yochay et al., 2021).

In sharp contrast, countries with upper- and lower-middle incomes exhibited patterns in the battle against COVID-19 that were opposite to those of the high-income countries (Salyer et al., 2021). Their first wave of the COVID-19 pandemic came later than developed countries, but their first-wave rates of infection and death were still relatively large. More
importantly, their performance in fighting the second and third waves of the pandemic showed little improvement over that during the first wave. The explanation is that these countries may have exhausted all resources during the first round, while during the second and third waves, their comprehensive national capacity limited their ability to continue to supply more resources to control the pandemic. Their performance was also complicated by mutation of SARS-CoV-2, leading to the accumulation and spread of viral variants, some of which were more infectious, spread more quickly (Williams and Burgers, 2021), and caused more cases and deaths in countries that had experienced first wave (Bambrā et al., 2020; Yang and Qi, 2022; Rozenfeld et al., 2020).

These differences are shown in analyses of key indicators both, the mortality and time lag (Wang et al., 2020b). Mortality at the peak of each wave, as determined from the cases and deaths at the turning points, measures the overall capacity to mitigate COVID-19. The real test of a country’s ability to fight the COVID-19 pandemic was that when the patients reached the capacity, hospitals became overloaded. The test of this disease response is not merely the number of beds in the hospitals, but also the education level of the population, the dissemination of the disease, disease diagnosis, whether the patients can be admitted to the hospital in time, whether the diagnosis and treatment can be obtained in time to prevent avoidable deaths, and the effective rehabilitation for the patients (Bambrā et al., 2020; Yang and Qi, 2022; Rozenfeld et al., 2020; Carethers, 2021; Liao and De Maio, 2021). Therefore, a study like this can reflect the impact of a country’s income level on its ability to deal with a disaster on the scale of the COVID-19 pandemic.

Among high-income countries, the mortality they experienced during the second and third waves was reduced to 30% of that during the first wave (Wang et al., 2020b), despite there being more than twice the number of cases during the second and the third waves than during the first wave. In contrast, for countries with upper-middle and lower-middle income levels, the mortality they experienced during the second and third waves was either reduced a small amount relative to that of the first wave or was not reduced at all. At the same time, the number of cases they experienced during the second and third waves either remained similar to those they experienced during the first wave or increased by 30–50%. The time lag reflects how long a patient stayed in the hospital before dying. The short lag time experienced by high-income countries during the first wave suggests that they prepared for the COVID-19 pandemic but lacked experience in treatment. However, when the second and third waves arrived, they were much better prepared and experienced in treating patients, which is reflected in the near doubling of the lag times they experienced during the second and third waves, relative to those of the first wave. In contrast, the lag times experienced during the second and third waves by upper-middle and lower-middle income countries were approximately equal to those experienced by high-income countries during the first wave. These data suggest the shortage of medical resources for upper-middle- and lower-middle-income countries. This reduction or lack of medical resources illustrates the limitations of the overall national capacity (Miyan et al., 2022).

With the worldwide spread of SARS-CoV-2 variants and the vigorous promotion of COVID-19 vaccination in developed countries, the most severe test of fighting the COVID-19 pandemic has been transferred to the developing countries. Our results suggest that, going forward, COVID-19 will cause higher death rates in developing countries. The reason is simple: although the COVID-19 pandemic has been raging for more than eighteen months, there is still no approved treatment. The vaccination rates in developing countries lag far behind that in developed countries. At present, the developing countries are failing in the competition between vaccination and the transmission of COVID-19, which is likely to have unfavorable consequences for these countries in the near future. If vaccination rates decrease in the developed countries and the vaccine supply increases as the result of more productive manufacture, more vaccine doses will be shared with the developing countries.

Due to the limited availability of data, this study did not include the low-income counties. However, as the COVID-19 pandemic continues to spread to every corner of the world, it is likely to disproportionately affect the low-income countries. Based on the findings from this study, we predict that the situation will worsen when the pandemic reaches the same cases per million and mortality in the low-income countries as observed in the countries with upper-middle and lower-middle incomes, when their capabilities to fight the pandemic are at the lowest levels (Carethers, 2021; Liao and De Maio, 2021).

This study does have some limitations. The cases and deaths at the peak or turning point were arbitrarily chosen and may not reflect the real situation in every country. The data on the Worldometers and WHO websites may not necessarily complete, as these data are derived from self-reports. Due to conditions in different countries, the reported data may not represent their real data. In addition, we only used data from countries that had experienced more than 5000 cases to date. This is because when the case number is small, the number of deaths at the death turning point may be as few as 1 or 2. Also, because the onsets of COVID-19 in different countries or regions differ, this temporal lag leads to the issue as to how to identify the first, second, and third waves of the pandemic. This study used two methods solve the issues. The first was to count the number of waves of each country regardless of their timelines. The second was to determine the wave sequence and accompanying peak incidence based on time, i.e., to infer the interval e for each country or region should be regarded as a specific wave. In addition, because in some cases the turning points were not obvious and the mortality turning point happened earlier than the case turning point, the time lag in these cases were either too long (greater than 30 days) or negative. Our approaches in determining the waves and peaks of the COVID-19 pandemic go a long way toward explaining the problems that have arisen in various countries in the fight against the pandemic. For example, the peak death rate for a given country can be higher than the peak rate of hospital admissions, which may result in initial deficiencies during that country’s early response to the novel pathogen.
We realize that many other factors may influence the mortality and times lag of COVID-19. We did not measure the length or total number of cases and deaths for each wave, as we focus on examining how the various countries dealt with the challenge when the disease reached its maximum levels. Multiple other factors affect the spread of SARs-CoV-2 and the management of COVID-19. Other important factors for the “perfect storm” of the COVID-19 pandemic include population density and transportation (transmission) (Yin et al., 2021), GDP and preparedness of the medical systems (management), social systems and democratic levels, and even environmental factors such as forest area and climate (Lasaulce et al., 2021).

Despite these limitations, the current analysis shows the huge differences in the resistance of countries with different income levels to the COVID-19 pandemic. Other factors are unlikely to offset this difference. We have observed the gap between the resistance of developed and developing countries to the second and third rounds of the COVID-19 pandemic. When considering the second and third waves, the cases per millions population has been relatively smaller for the developing countries than that of the developed countries. If the patterns in the predicted fourth and fifth waves increases significantly, for example, due to the influence of the Delta variant of SARs-CoV-2 (or of another variant), it is expected that the pandemic containment capabilities of these countries might decrease. At this point, only vaccines could alleviate such a difficult consequence in the developing countries. However, since the vaccines were produced and used dominantly by the developed countries, the long-term supply and usage of vaccines in most of the developing countries are extremely low. This situation is unlikely to be changed unless actions are taken by all countries.

5. Conclusion

In summary, our analysis showed that in high-income countries the mortality rates during the second and third waves of the COVID-19 pandemic were lower than those during the first wave. Upper and lower middle-income countries experienced higher rates of mortality during the second and third waves. Similarly, in high-income countries the time lags between the cases and mortality turning points became longer during the second and third waves while there was no such lagging in upper and lower-middle income countries. These data suggest that the COVID-19 pandemic will continue to worsen in the developing countries, such that low-income countries will remain vulnerable if the COVID-19 pandemic is not under control.

Research in context

Evidence before this study. We performed a general literature review to look for studies of mortality rates and lag times for COVID-19. None of the studies we discovered focused on the data regarding turning points and the different income levels of the countries examined. Furthermore, there are presently no reports on mortality rates at the turning points for the different waves of COVID-19.

Added value of this study. When cases of COVID-19 in a country reach the maximum number, the necessary response test the capacity of the country’s healthcare system(s) and economic power to manage it. We used COVID-19 mortality rates, lag times at the turning points of the three waves of the disease to date, and the income levels of 106 countries to provide the first report that provides evidence for their capacity for management of the COVID-19 pandemic.

Implications of the available evidence. This comprehensive analysis of the case numbers, rates of mortality, and lag times for the first three waves of the COVID-19 pandemic in countries with different income levels provides a better understanding of the influence of income levels on the response to the pandemic. Understanding the heterogeneity of worldwide capacities has further informed the inequality of economic efforts and the need for equity in resource allocation to stop the CoVID-19 pandemic. The analysis of this data may serve as a warning of the severe outcome in low-income countries in the absence of intervention of the more affluent countries.

CRediT authorship contribution statement

LY and WG collected and analyzed data and drafted the manuscript. LY, JCG, and WG participated the data collection and confirmation. LY, WG, and LA participated data analysis and manuscript draft. YHC CYW, SCH, DS, and WG interpreted the results and edited the manuscript. WG and DS designed the project. All authors interpreted the data and edited the manuscript.

Declaration of competing interest

We declare no competing interests.

Acknowledgments

The authors alone are responsible for the views expressed in this article, which do not necessarily represent the decisions, policy, or views of any institution or organization represented by the authors. We thank Dr. Kyle Johnson Moore at office of Vice Chancellor for Research for kindly editing this manuscript.

Funding

This work was partially supported by funding from University of Tennessee Health Science Center (RO73290109) to WG in Memphis, TN, USA, and grant 90DDUC0058 to CG from the U.S. Department of Health and Human Services, Administration for Community Living.

Supplementary table in the Data in Brief

The supplementary tables will be available on-line.

Data sharing

All COVID-19 case, death, and dates collected are either presented in the article and appendix or available on-line at https://www.worldometers.info/coronavirus.

References

Baena-Diez, J.M., Barroso, M., Cordove-Coelho, S.I., Diaz, J.L., Gran, M., 2020. Impact of COVID-19 outbreak by income: hitting hardest the most deprived. J. Public Health (Oxf) 42 (4), 698–703 Nov 23.
Bambra, C., Riorian, R., Ford, J., Matthews, F., 2020. The COVID-19 pandemic and health inequalities. Novl Epidemiol. Community Health 74 (11), 964–968. https://doi.org/10.1136/jech-2020-214401 Epub 2020 Jan 13. PMID: 32535550; PMCID: PMC7298201.
Carethens, J.M., 2021. Insights into disparities observed with COVID-19. J. Intern. Med. 289 (4), 463–473. https://doi.org/10.1111/joim.13199 Epub 2020 Dec 6 PMID: 33164230.
Ghizani, I., McPherson, T.D., Hunter, J.C., Kirkling, H.L., Christiansen, D., Joshi, K., Rubin, R., Morales-Estrada, S., Black, S.R., Pacilli, M., Frischione, M.J., Chugh, R.K., Walblay, K.A., Ahmed, N.S., Stoecker, W.C., Hasan, N.F., Burdall, D.P., Reese, H.E., Wallace, M., Wang, C., Moeller, D., Korpics, J., Novovard, S.A., Benowitz, I., Jacobs, M.W., Darnai, V.S., Patel, M.T., Kauerauf, J., Charles, E.M., Etkin, N.O., Chu, V., Midgley, C.M., Roßle, M.A., Gerber, S.L., Lu, X., Lindstrom, S., Verani, J.R., Layden, J.E., 2020. Illinois COVID-19 Investigation Team. First known person-to-person transmission of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) in the USA. Lancet 395 (10230), 1137–1144. https://doi.org/10.1016/S0140-6736(20)30607-3 Apr 4.
Gu, T., Wang, L., Xie, N., Meng, X., Li, Z., Postlethwaite, A., Aleya, L., Howard, S.C., Gu, W., Wang, Y., 2021. Toward a country-based prediction model of COVID-19 infections and deaths between disease apex and end: evidence from countries with contained numbers of COVID-19. Front. Med. (Lausanne) 10 (8), 585115. https://doi.org/10.3389/fmed.2021.585115 Jun.
Gu, T., Yao, L., Meng, X., Graff, J.C., Thomason, D., Li, J., Dong, W., Jiao, Y., Aleya, L., Maida, M., Wang, C.Y., Zanger, B., Genini, S., Ray, K., Goldman, E., Ji, J., Alexandrov, A.V., Sun, D., Gu, W., Wang, Y., 2021. A cost-effective plan for global testing - an infection rate stratified, algorithm guided, multiple-level, continuously pooled testing strategy. Sci. Total Environ. 15 (765), 144251 Apr.
Guadala, E., Krousel, A., Palacios-Galvez, M., Morales-Marente, E., Rodriguez-Pascual, L., Garcia-Narrow, L.B., 2021. Social distancing and COVID-19: factors associated with compliance with social distancing norms in Spain. Front. Psychol. 14 (12), 727225 Sep.
Lasaulce, S., Zhang, C., Varma, V., Morísucci, I.C., 2021. Analysis of the tradeoff between health and economic impacts of the Covid-19 epidemic. Front. Public Health 5 (9), 620770 Mar.
Liao, T.F., De Maio, F., 2021. Association of social and economic inequality with coronavirus disease 2019 incidence and mortality across US counties. Jan 4 JAMA Netw. Open 4 (1), e2034578. https://doi.org/10.1001/jamanetworkopen.2020.34578
Erratum in: JAMA Netw. Open. 2021 May 3;4(5):e2114136. PMID: 33471120; PMCID: PMC7818127.

Ma, L., Yu, Z., Jiao, Y., Lin, L., Zhong, W., Day, S.W., Postlethwaite, A., Chen, H., Li, Q., Yin, H., Wang, G., 2021. Capacity of transportation and spread of COVID-19: an ironical fact for developed countries. Environ. Sci. Pollut. Res. Int. 28 (28), 37498–37505 Jul.

Miyah, Y., Benjelloun, M., Lairini, S., Lahrichi, A., 2022. COVID-19 impact on public health, environment, human psychology, global socioeconomic, and education. Sci. World J. 11 (2022), 5578284 Jan.

Neill, R., Hasan, M.Z., Das, P., Venugopal, V., Jain, N., Arora, D., Gupta, S., 2021. Evidence of integrated health service delivery during COVID-19 in low and lower-middle-income countries: protocol for a scoping review. BMJ Open 11 (5), e042872 May 3.

Regev-Yochay, G., Amit, S., Bergwerk, M., Lipsitch, M., Lesher, E., Kahn, R., Lustig, Y., Cohen, C., Doolman, R., Ziv, A., Novikov, I., Rubin, C., Gimpelovich, I., Huppert, A., Rahav, G., Aek, A., Kreiss, Y., 2021. Decreased infectivity following BNT162b2 vaccination: a prospective cohort study in Israel. Lancet Reg. Health Eur. 7, 100150 Aug.

Rozenfeld, Y., Beam, J., Maier, H., Haggerson, W., Boudreau, K., Carlson, J., Medows, R., 2020. A model of disparities: risk factors associated with COVID-19 infection. Int. J. Equity Health 19 (1), 126. https://doi.org/10.1186/s12939-020-01242-z PMID: 32727486; PMCID: PMC7387879.

Salyer, S.J., Maeda, J., Sembuche, S., Kebede, Y., Tshangela, A., Mousiff, M., Ihekweazu, C., Mayet, N., Abate, E., Ouma, A.O., Nkengasong, J., 2021. The first and second waves of the COVID-19 pandemic in Africa: a cross-sectional study. Lancet 397 (10281), 1265–1275. https://doi.org/10.1016/S0140-6736(21)00622-2 Apr 3.

Ullah, R., Saleman Rana, M., Qadir, M., Uman, M., Ahmed, N., 2021. Coronavirus pandemic: a major public health crisis for the developed and developing world. J. Infect. Dev. Ctries. 15 (3), 366–369 Mar 31.

Wang, X.Q., Song, G., Yang, Z., Chen, R.J., Zheng, Y.L., Hu, H.Y., Su, X., Chen, P.J., 2020. Association between ageing population, median age, life expectancy and mortality in coronavirus disease (COVID-19). Aging (Albany NY) 12 (24), 24570–24578 Nov 24.

Wang, L., Li, J., Guo, S., Xie, N., Yao, L., Cao, Y., Day, S.W., Howard, S.C., Graff, J.C., Gu, T., Ji, J., Gu, W., Sun, D., 2020 Jul. Real-time estimation and prediction of mortality caused by COVID-19 with patient information based algorithm. Sci. Total Environ. 20 (727), 138394.

Williams, T.C., Burgers, W.A., 2021. SARS-CoV-2 evolution and vaccines: cause for concern? Lancet Resp. Med. 9 (4), 332–335 Apr.

Yang, K., Qi, H., 2022. Research on health disparities related to the COVID-19 pandemic: a bibliometric analysis. Int. J. Environ. Res. Public Health 19 (3), 1220. https://doi.org/10.3390/ijerph19031220 PMID: 35162524; PMCID: PMC8835299.

Yao, L., Li, M., Wan, J.Y., Howard, S.C., Bailey, J.E., Graff, J.C., 2021. Democracy and case fatality rate of COVID-19 at early stage of pandemic: a multicountry study. Environ. Sci. Pollut. Res. Int. 7, 1–11 Sep.

Yin, H., Sun, T., Yao, L., Jiao, Y., Ma, L., Lin, L., Graff, J.C., Aleya, L., Postlethwaite, A., Gu, W., Chen, H., 2021. Association between population density and infection rate suggests the importance of social distancing and travel restriction in reducing the COVID-19 pandemic. Environ. Sci. Pollut. Res. Int. 1–7 Jan 13.