Research article

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What can lifespan variation reveal that life expectancy hides? Comparison of five high-income countries

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Abstract

Objectives: In most countries, life expectancy at birth (e0) has improved for many decades. Recently, however, progress has stalled in the UK and Canada, and reversed in the USA. Lifespan variation, a complementary measure of mortality, increased a few years before the reversal in the USA. To assess whether this measure offers additional meaningful insights, we examine what happened in four other high-income countries with differing life expectancy trends.

Design: We calculated life disparity (a specific measure of lifespan variation) in five countries – USA, UK, France, Japan and Canada – using sex- and age specific mortality rates from the Human Mortality Database from 1975 to 2017 for ages 0–100 years. We then examined trends in age-specific mortality to identify the age groups contributing to these changes.

Setting: USA, UK, France, Japan and Canada

Participants: aggregate population data of the above nations.

Main Outcome Measures: Life expectancy at birth, life disparity and age-specific mortality.

Results: The stalls and falls in life expectancy, for both males and females, seen in the UK, USA and Canada coincided with rising life disparity. These changes may be driven by worsening mortality in middle-age (such as at age 40). France and Japan, in contrast, continue on previous trajectories.

Conclusions: Life disparity is an additional summary measure of population health providing information beyond that signalled by life expectancy at birth alone.

Keywords

Health policy, non-clinical, public health

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Introduction

Life expectancy at birth (denoted e0) is an efficient summary of population health and how it changes over time. In the absence of extraordinary events – such as wars, environmental disasters and pandemics – e0 has trended steadily upwards in most populations in recent decades. Where it has fallen, other than transiently, it has often been associated with major crises, such as the AIDS pandemic, wars, famines or state collapse as in the ex-USSR.[1,2] While the eventual consequences of the COVID-19 pandemic remain unknown, the UK has experienced a fall in e0 of 0.9 and 1.2 years for females and males, respectively.[3] Given the long-term improvement in e0 prior to the pandemic in most high-income nations, any stalling in trends – i.e. prolonged increases slower than the long-term average – demand explanation. Identifying the cause of a falling e0 requires careful examination of mortality data by sex, age group and cause of death. This is especially important as improvements in some subgroups may, to some extent, compensate for declines or stalls in other subgroups. For example, in the 1980s, concern about the slowdown in what had, until then, been increasing life expectancy in countries of Central and Eastern Europe might have been greater if it had been widely recognised that continued mortality gains in infancy and childhood were obscuring worsening in adult mortality.[4] Thus, like any summary measure, e0 can conceal details with practical or policy importance, so there is a strong theoretical argument to look at other measures, in particular those capturing the distribution of mortality.

Lifespan variation is a term covering a class of complementary measures to e0 which measure the variability of age at death among individuals within a defined population.[5] Typically, as e0 increases, lifespan variation decreases; those countries with the highest e0 also have the lowest lifespan variation:[6] a phenomenon also observed in other primate species.[7] This is, in part, because the maximal attainable lifespan has changed little but death rates at younger ages have tended to fall. The measure of lifespan variation we use is life disparity, which measures the average gap between an individual's age at death and their remaining life expectancy at that age.[6] Some have argued that life disparity has a 'crucial' public health interpretation, not least because life disparity can differ between societies with similar life expectancies.[8,9]

One example is research by van Raalte et al., which showed that in the USA, where e0 increased by approximately 10% for men and 5% for women over 1980–2014, lifespan variation (measured as standard deviation) fluctuated then increased.[10] e0 in the USA then declined every year since 2015[11] driven by what have been termed 'deaths of despair',[12,13] from alcohol, other drugs and suicide.[13] Researchers concluded that had lifespan variation been monitored more closely, the mid-life mortality crisis in the USA could perhaps have been identified earlier.[10]

To see if lifespan variation might have been similarly useful in understanding the recent divergence of e0 trends in the UK, we extend the analysis of life disparity to four other high-income countries: the UK, where, like the USA, gains in e0 have trailed behind those in other industrialised countries[14]; Japan, which has seen sustained progress; and France and Canada, neighbours of the UK and USA, respectively, which lie in the middle. We ask whether e0 and life disparity in combination can (a) identify changes that could otherwise be missed and (b) detect changes in trends earlier.

Terminology

To ensure consistency and understanding of the terms used throughout this paper, Box 1 provides definitions from leading experts in the fields of demography and population health.

Box 1. Definitions of relevant terminology.

Term	Definition	Source
Age-standardised mortality rate (ASMR)	A mortality rate that can be calculated based on age-specific mortality rates for two or more populations, based on applying these populations' separate age-specific mortality rates to a common ('reference' or 'standard') population age-structure. A number of different standard age structures exist; the European Standard Population is one of the most commonly used.	Eurostat, 2013[15]
Life expectancy	A population-based statistical measure of the average number of years a person has before death. Life expectancies can be calculated for any age and give the further number of years a person can, on average, expect to live given the age they have attained. Life expectancy of a population at a certain point in time reflects the average number of years and individual would live if they faced during their entire life the current ASMRs, thus it gives the expected average length of life based on the current mortality pattern. Because age-specific mortality rates change over time, life expectancy does not accurately predict the actual number of years an individual will live.	Office for National Statistics (ONS), 2020[16] Smits and Monden, 2009[17]
Life expectancy at birth (e0)	Life expectancy at birth can be denoted as e0, life expectancy at 5 years old as e5, and so on. e0 is often simply referred to as life expectancy and is the most common metric of survival. It is the hypothetical average age at deaths given age-specific death rates in a given year.	Van Raalte AA et al., 2018[10]
Lifespan variation (LV)	Lifespan variation is a class of measures which calculate the amount of heterogeneity in age at death across all individuals in a population. LV can be measured by using an index of variation or inequality.	Seamen et al., 2019[5] Van Raalte AA et al., 2018[10]
Life disparity (LD)	Life disparity is one measure of lifespan variation, representing the average remaining life expectancy at the age when death occurs. It is a measure of life years lost due to death.	Vaupel JW et al., 2011[6]
Threshold age	Calculated from life tables, the 'cut-off' age where averting deaths before that age reduces LD, and averting deaths after it increases LD.	Zhang and Vaupel, 2009[18]

Methods

Data source

We extracted sex- and age-specific mortality rates from the Human Mortality Database (HMD) from 1947 until the latest available year (2017 or later) for the USA, Japan, UK, France and Canada, ages 0–100. HMD smoothes mortality rates at older ages (80+).[a] We present data from 1975 to the latest available year, unless otherwise stated. Ethical approval was not required.

Analytical approach

First, we report e0. Second, we measure lifespan variation using life disparity, replicating the method developed by Vaupel et al.[6] Box 2 provides an overview of this methodology, for which the full code and analyses undertaken can be found on Github.[b] Finally, we present trends in age-specific mortality to identify which age groups contributed to these changes.

Life disparity calculations. Life disparity (denoted $e^{\dagger}$) is defined as 'the average remaining life expectancy at the ages when death occurs'. It is calculated by summing age-specific contributions for all ages up to a maximum lifespan age (ω) which in our calculations is set to 100 years of age. These age-specific contributions are defined as the product of e_x and f_x, where e_x is defined as the remaining life expectancy at age x and f_x the life table distribution of deaths up to age x.[6] See the supplementary appendix in Vaupel et al. (2011) for a more complete definition. The values shown in the bottom row of Figure 1a and b are these age-specific contributions, $e_x f_x$, with selected values of age, x, on the horizontal axis. The values shown in the bottom row of Figure 2 are life disparity ($e^{\dagger}$), which is the sum of these age-specific contributions up to age ω. All calculations are based on period life tables.

Results

Figure 1a and b show the contribution of deaths at different ages to overall life disparity using the example of the USA and Japan, respectively, for 1947, 1975 and 2017. In each, the top panels show improvements in period survival by age over time, with age on the x axis and the proportion of people surviving to a given age on the y axis. Over time, as people live longer, the curve shifts to the right due to 'compression of mortality' or the 'rectangularisation' of the survival curve: mortality decreases are steeper at younger than older ages.[19,20]

The lower panels show the age-specific contributions to life disparity by deaths at different ages. Deaths in infancy and early childhood are on the left and those in adulthood on the right. In 1947, both by infant mortality and deaths throughout working and retirement ages were making an important contribution to life disparity, but the dramatic fall in deaths in children and, in Japan, people in their 20s, means that, by 2017, life disparity is largely due to variations in age of deaths at older ages. In 1975 and 2017, total life disparity was higher in the USA than in Japan, mostly due to the greater contribution from deaths at ages up to the mid-1970s in the USA. Put another way, in 1947, a higher proportion of deaths in Japan were in younger ages but by 1975, this had reversed.

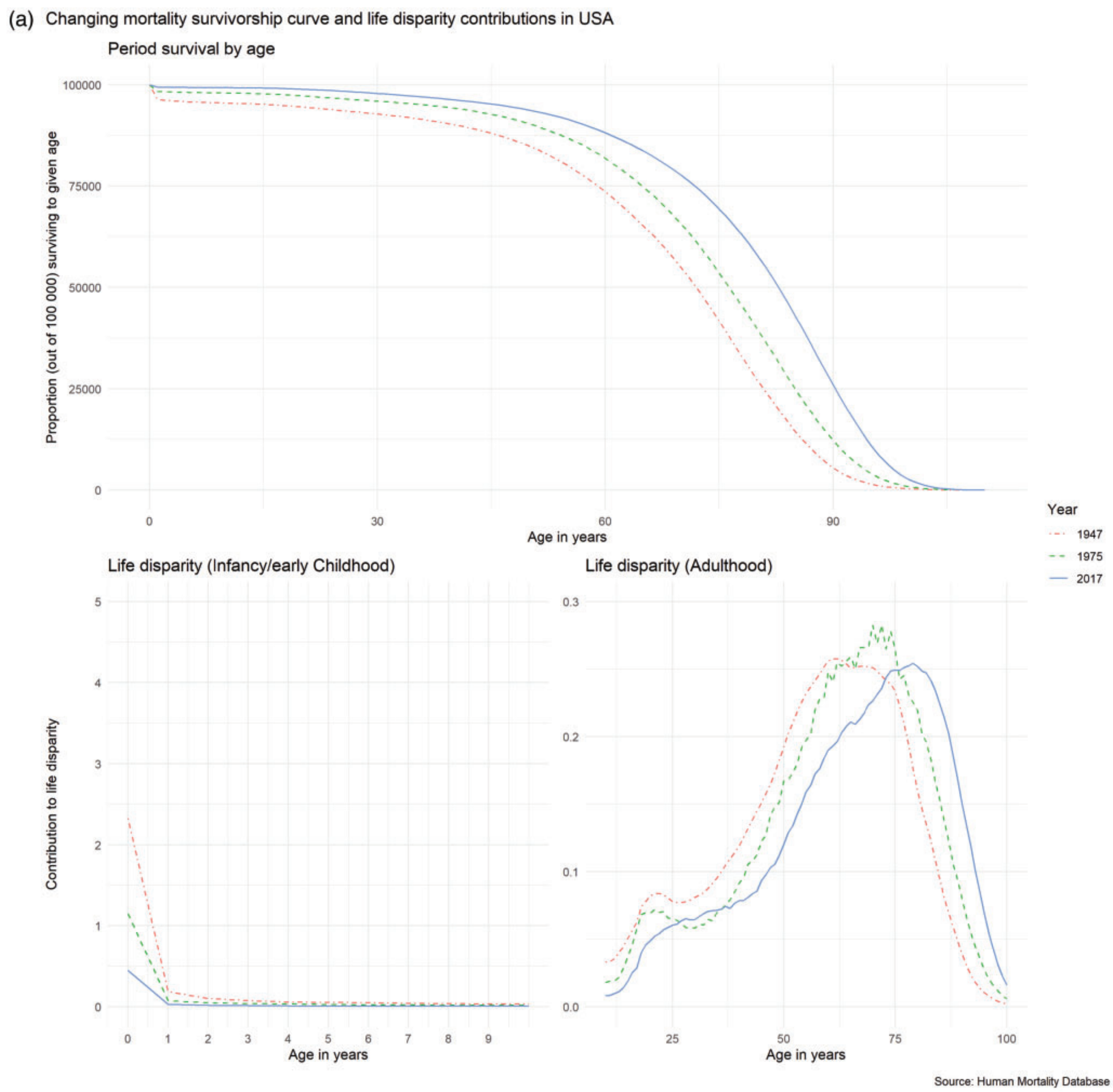
Life expectancy at birth (e0) and life disparity

Next, we present trends in e0 and life disparity for each country from 1975 to at least 2017. Japan has had the highest e0 for females since approximately 1980 and for males from 1975, improving annually, except for a brief fall after 2011 that coincided with the Tohoku earthquake and tsunami, when almost 16,000 people were killed on one day.[21] For females, the USA and UK consistently rank lower than the other countries, with stalling e0 from 2010 onwards. A similar pattern is seen for males, but with France following a similar trajectory to the UK. Canada shows steady improvements for both males and females, with a slight stalling seen for males in most recent years.

With life disparity, all countries demonstrate a downward trend between 1975 and 2000, albeit with a transient interruption among males in France and the USA in the 1980s and among females in Japan in the 1990s. Since 2010, life disparity has increased markedly in Canada and the USA, and slightly in the UK, also. In Japan, life disparity increased in 2011 for males especially, which may reflect the impact of the earthquake, before falling again.

Figure 3 zooms in on life disparity since 2000, since the majority of changes in e0 occur after 2010. Increases in life disparity in USA and Canada are clearer. The situation in the UK is less clear but for males there appears to be a divergence from the Japanese sustained downward trend, while for females they continue broadly in parallel, although care is necessary as there are fluctuations over time and changes in the UK after 2015 may reflect year-on-year variability.

Figure 1. (a) Changing mortality survivorship curve and contributions of deaths at different ages to life disparity contribution in the USA, 1947, 1975 and 2017. (b) Changing mortality survivorship curve and contributions of deaths at different ages to life disparity contribution in Japan, 1947, 1975 and 2017.

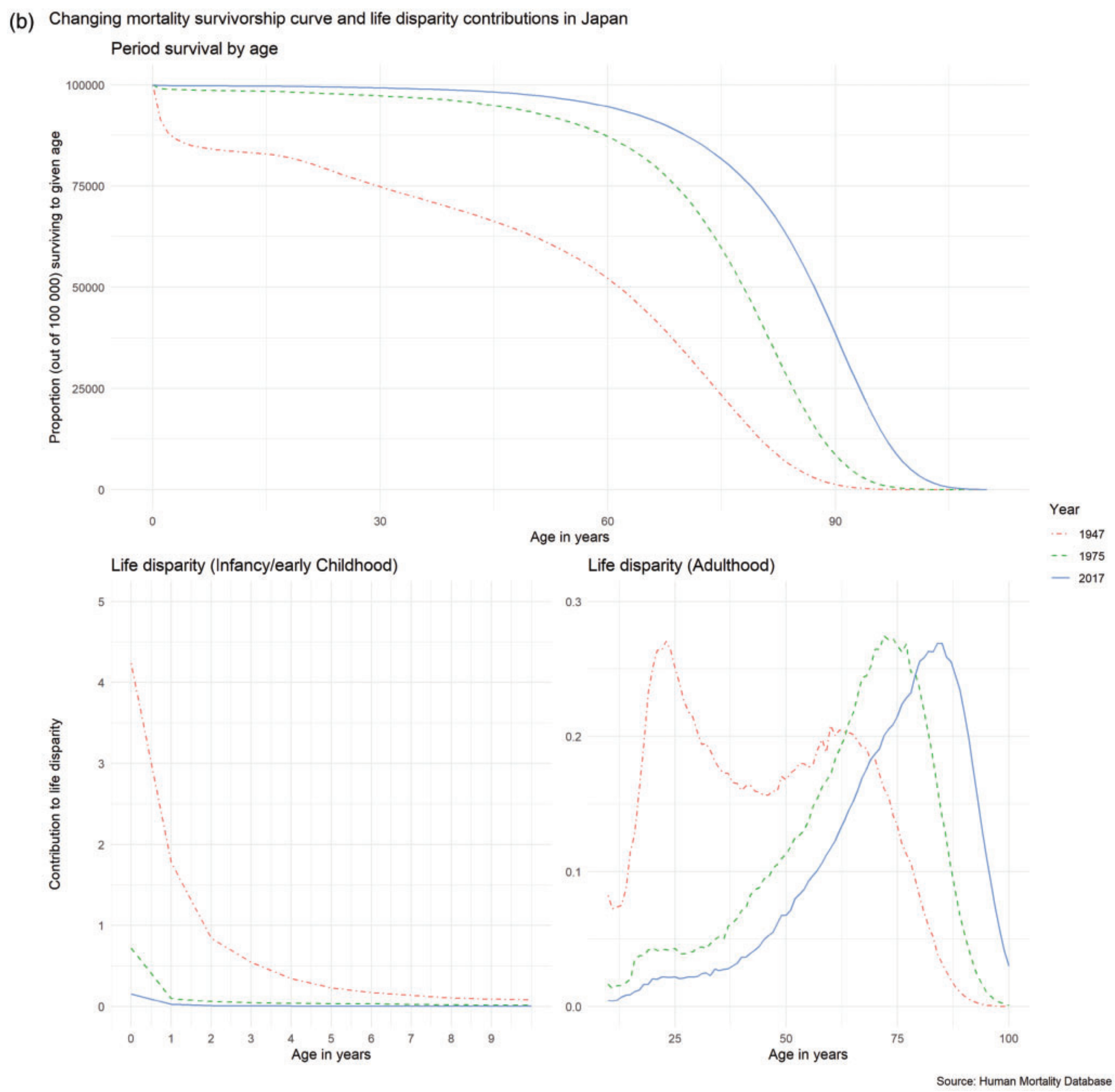


Probability of dying in the next 12 months

Deaths in which age groups are driving changes in life disparity? To answer this, we next examine 12-month death risks at birth, 40, 80 and 90 years of age (see White[22] and Christensen et al.[23]). In Figure 4, the y axis is on a log scale; a straight line means constant percentage rate reduction per year over time. For some countries/ages, such as older Japanese females, the series looks like a straight line, but for others it does not. Figure 4 shows a reversal of improving trends in mortality at age 40 years for all countries since 2010, more marked in some populations.

At under one year (age 0), previously declining trends slowed in the USA, UK, France and Canada, in females, and in males in the UK and France. However, at age 40 years, the USA, again with a markedly higher risk for both males and females, shows a clear increase since 2010, more so in males. In Canada and the UK, risk at age 40 years increased more recently. In France, trends continued downwards. At ages 80 and 90 years, the USA no longer has the highest risk; the UK does.

Figure 1. Continued.



Discussion

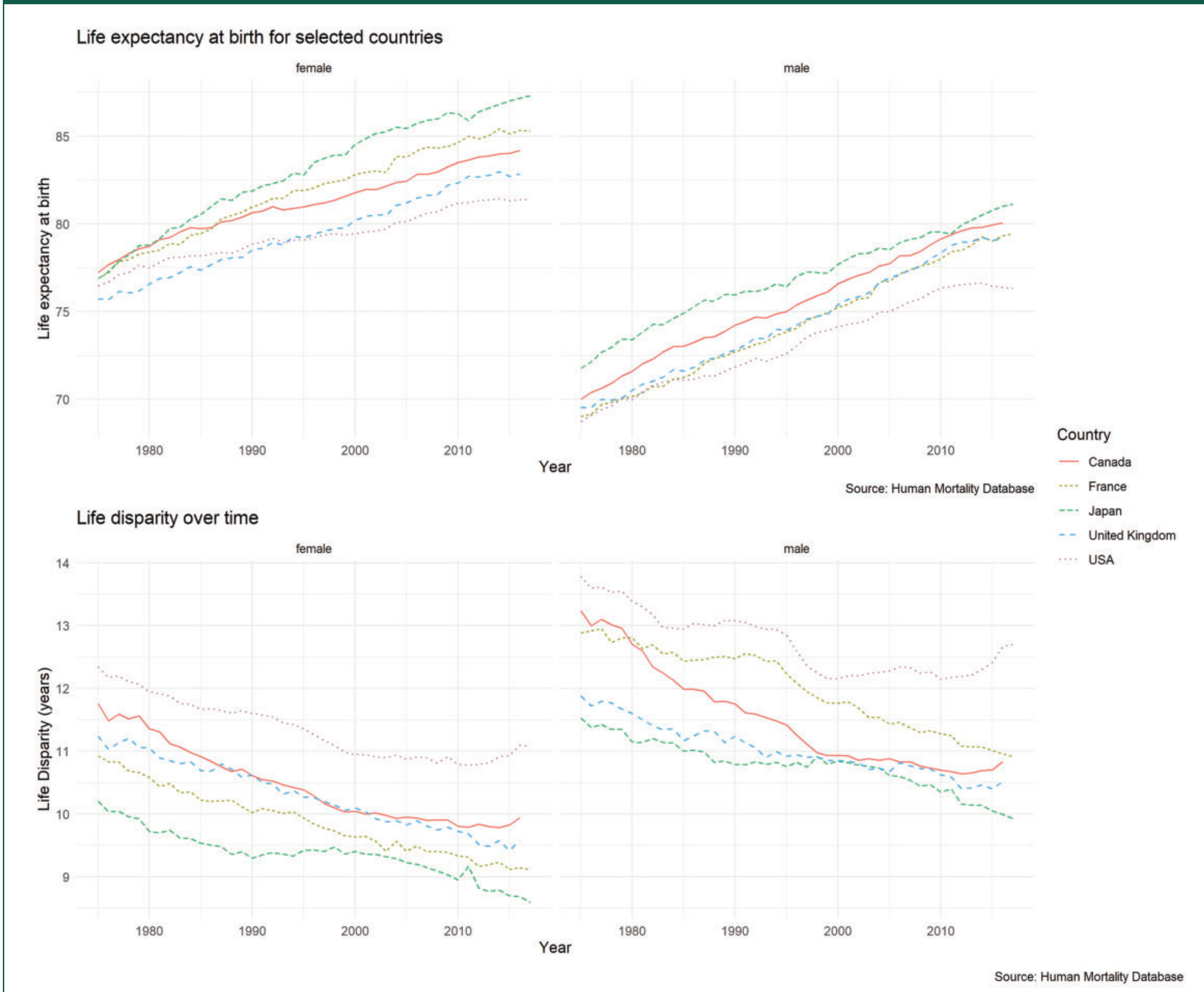
We asked whether lifespan variation, measured as life disparity, could (a) identify changes that otherwise would be missed and (b) detect changes in trends earlier, in the context of the recent divergence from earlier trends in e0 in five high-income countries, and thus whether life disparity should be considered alongside e0 in routine monitoring of population health. We found a deviation from earlier trends in the USA, UK and Canada in both e0 and life disparity, to varying degrees, but it is not clear that these were preceded by increasing life disparity in all cases. By contrast, existing trends largely held for Japan, and, to a lesser extent, France.

When mortality by age was examined, it seems the increase in life disparity in the USA and Canada may be driven by an increase in young- and mid-age mortality. This is consistent with theory and other evidence on how reductions in premature mortality contribute to the decreases in life disparity seen in many countries.[6,18]

What are the practical implications of our findings?

In the USA, we show that rising life disparity coincided with falling e0, with increases seen in young- and mid-age mortality, consistent with previous findings.[10] These findings occur in the context of the unprecedented reversal in e0 in the USA since

Figure 2. Life expectancy at birth (top) and life disparity over time (bottom), 1975–2017.



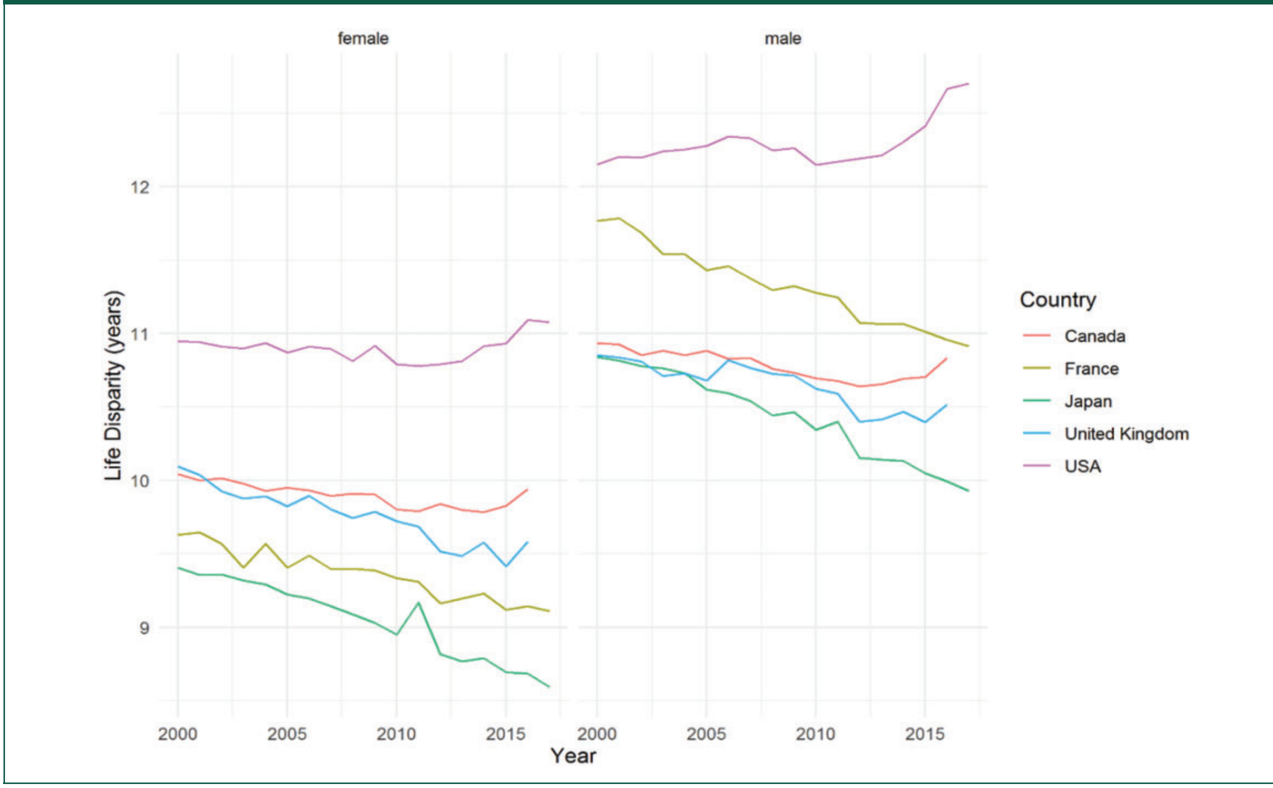
2015.[24] In the USA and, more recently, the UK, a rise in mid-age mortality from 'deaths of despair'[12,13,25] plus stagnating rates in improvements from cardiovascular disease moratltity[26,27] appear to be important contributors to stagnating and declining e0. US research suggests that these largely reflect 'worsening health among working-age individuals of lower socioeconomic status' consistent with evidence that increasing numbers of people are experiencing ever more precarious lives.[28]

Our findings are also consistent with evidence from Statistics Canada,[29] which found that while death rates were falling at older ages, at ages 20–44 years, especially among men, they were increasing. This was attributed largely to the opioid crisis which was afflicting several provinces.[30] Indeed, e0 for men fell in British Columbia and remained unchanged in Ontario, while it continued to increase in others.

An historical example of 'mortality crises' comes from the breakdown of the USSR in the 1990s in Central and Eastern Europe. Aburto and van Raalte found that changes in life disparity were greater than those in e0, with the changes in life disparity driven by increasing midlife mortality.[31] Furthermore, e0 and life disparity varied independently of each other. It may be that something similar is occurring in mid-life in the USA and Canada.

In contrast, except for when the earthquake struck in 2011, Japan continued to make good progress in both e0 and life disparity in the 2010s even during

Figure 3. Life disparity for females and males, 2010–2017.



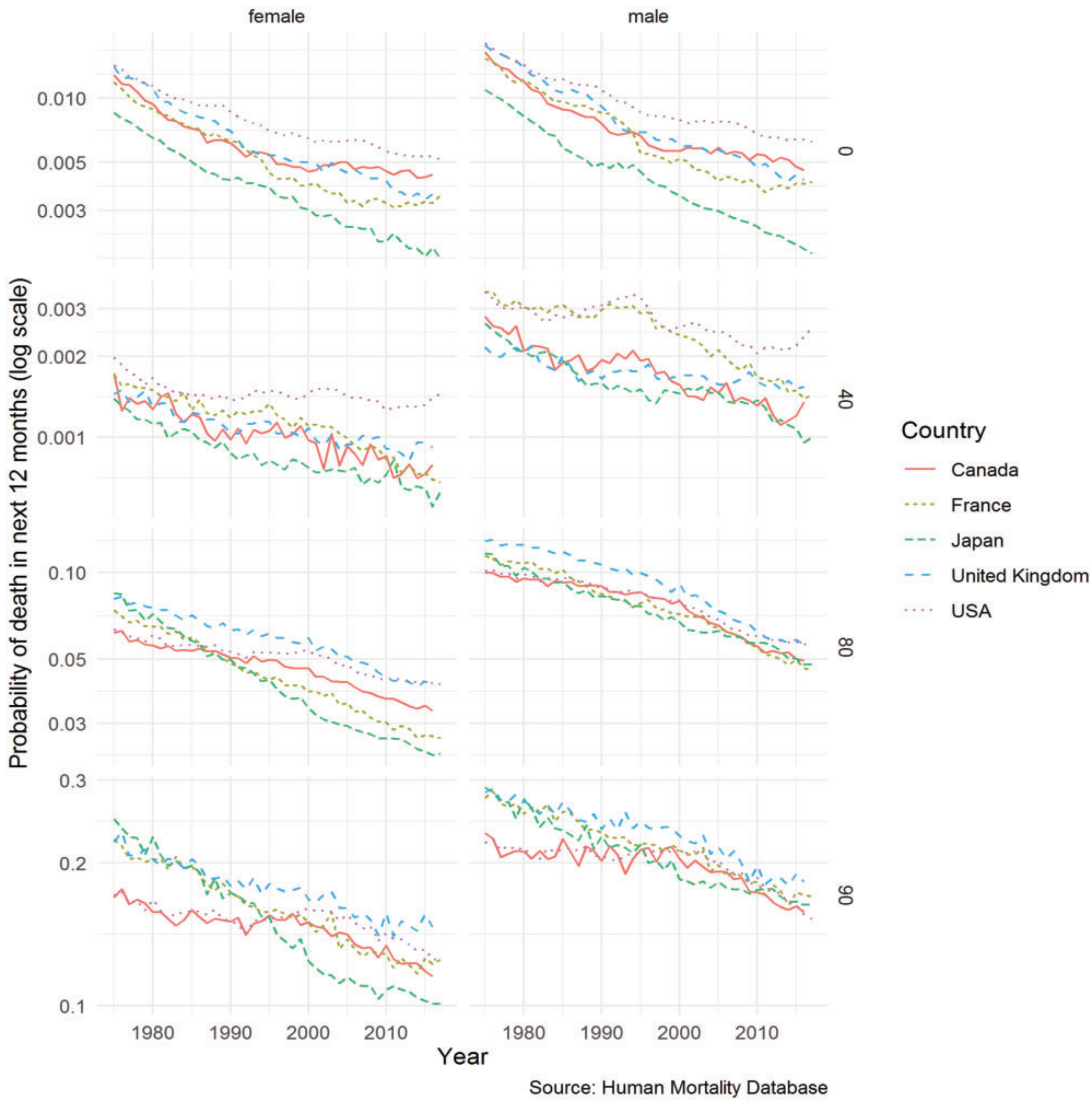
periods of long-term low economic growth, and health inequalities did not worsen.[32]

Can life disparity be used to detect changes in population health trends earlier?

We show increasing life disparity coincided with changes in e0, but cannot conclude that monitoring life disparity would have detected or predicted stalling and falling of e0 earlier in the countries examined. Indeed, existing research demonstrates that an increase in life disparity in isolation may cause a public health 'false alarm'. A study of two populations with increasing longevity, Japan and Hong Kong, showed that life disparity can increase where no adverse trends in mortality are occurring at any age, and while e0 continues to increase.[8] Conversely, analysis of the burden of COVID-19 on mortality in the UK found lifespan inequality decreased during the first year of the pandemic, while e0 also decreased.[3] In both examples, the utility of life disparity is as complementary to e0 – a rising life disparity in the context of stagnating or falling e0 may indicate emerging public health challenges in a given population but a decreasing life disparity in isolation does not indicate a healthy population. In this respect, our findings support the emerging concerns about the situation in Canada.

The concept of the 'threshold age' is another measure which may complement the utility of life disparity in monitoring population health. The negative correlation between increasing e0 and reducing life disparity is typically due to progress in reducing premature mortality – reducing deaths at older ages can increase life disparity,[6] as demonstrated in the Hong Kong example.[8] Zhang and Vaupel classified the different effects of 'early' deaths from 'late' deaths on life disparity, separated by the calculation of a 'threshold age' – averting deaths before that age reduces life disparity, while averting deaths after increases life disparity.[18] Vaupel et al. show the 'threshold age' classifies deaths at late ages as premature or early: for example, in Japanese females, deaths up to the age of 85 years were considered premature.[6] While considering a death aged 85 years as premature may be counterintuitive for public health and policy makers, monitoring of the 'threshold age' through life tables may provide additional insights. In Hong Kong, life disparity increased alongside increased threshold age with no apparent slowdown in e0 gains.[8] By contrast, we show that in the USA, life disparity increased alongside slowdown and decreases

Figure 4. Probability of dying in the next 12 months by age in years, 1975–2017.



in e0. Thus, it may be that the threshold age in the USA also fell, in contrast to the increase in Hong Kong, and a rising life disparity in the context of stalling or falling threshold age may also indicate population health challenges.

We propose that future research could focus on the relationship over time between changes in life disparity, perhaps alongside stalling or falling threshold age, and in e0. If life disparity increases alongside falling threshold age, followed by stalling or declining e0, with a lag impact on e0, this may provide a warning of declining population health, itself often a marker of societal problems. This also gives caution to viewing e0 as a measure of population health in isolation – while this is not a substitute for detailed demographic analysis, we suggest that life disparity does offer a simple measure that can provide useful information when undertaking international comparisons of trends over time.

Strengths and limitations of the study

The Human Mortality Database has rigorous data quality requirements and standardisation procedures and is widely accepted as reliable for international comparison.[33] The methods used to calculate life disparity and probability of dying at 12 months replicate those of experts in the field, and were checked against code supplied by one of the pioneers in using these methods.[6,22,23] We compared the countries with the best and worst rates of average annual increase in period life expectancy at birth, as identified by the

Office for National Statistics,[14] thus removing bias from country selection; comparison with geographically and politically similar nations demonstrated reversal of trends is not inevitable.

There are some limitations. For example, the UK is treated as a single entity, concealing differences between the devolved nations. Research comparing inequality in age of death in Scotland to England and Wales found Scotland had higher lifespan variation due to lower old age mortality and higher premature mortality.[34]

Furthermore, the data are aggregated, so it is not possible to examine differences by factors such as race, gender or the social determinants of health such as employment status. This is undoubtedly relevant: evidence from Denmark and Finland showed inequalities in improvements in lifespan variation, with stagnation in lower income quartiles and manual occupational classes compared to mortality compression, i.e. lifespan variation decreases among those in 'more favourable social positions'.[20,35] In addition, evidence from Europe shows those with lower educational attainment not only experience shorter life expectancies, but also greater uncertainty about the age they will die due to higher lifespan variation.[36]

Finally, examining five countries precluded considering each individual trajectory in depth, or exploring all fluctuations.

As such, future research might consider two broad areas. First, the development and testing of complementary measures to e0 for monitoring population health, as outlined above. Second, the public health and policy implications of the findings presented here at both international and national level in order to inform appropriate public health interventions and health policy.

Conclusion

The data presented here show trends in population health, measured as e0 and life disparity, in five high-income countries. They support the existing evidence that the worsening of e0 and life disparity in the USA and, of e0 in the UK, were not inevitable, and neither are continuing adverse trends. France and Japan both experienced periods of downturn but recovered and have been able to continue with improving trajectories in both e0 and life disparity. They also indicate that in those nations where e0 is stalling or falling – Canada, the UK and USA – rising mid-age mortality (such as at age 40) may be a key contributor. This highlights that when measuring the progress of nations, it is important to look not only at overall deaths but their distribution.

Life disparity can complement life expectancy at birth in monitoring population health, but should not be viewed in isolation.

Data availability

- Data are available in a public, open access repository.
- Data are available from the Human Mortality Database. See https://www.mortality.org/ (last checked 10 April 2021).
- Code and analyses used are available from GitHub. See https://github.com/JonMinton/rising_tide (last checked 9 March 2021).

Declarations

Competing Interests: None declared.

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Ethics approval: Not required – data are aggregate, open access and non-identifiable.

Guarantor: JM.

Contributorship: JM conceived the idea for this paper and carried out all the data extraction and analyses. LH drafted the first version, with significant edits and input from JM and MM.

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Provenance: Not commissioned; reviewed by Eric Brunner, Alyson van Raalte, and Julie Morris.

Notes:

a. Figure 7.1 of the HMD methods protocol outlines the use of the Kannisto–Thatcher method to smooth observed deaths rates for ages 80 and above. See www.mortality.org/Public/Docs/MethodsProtocol.pdf (last checked 8 March 2021).

b https://github.com/JonMinton/rising_tide (last checked 22 September 2020).

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