PERSPECTIVE

Demographic perspectives on the rise of longevity

James W. Vaupel[a,b,1], Francisco Villavicencio[c], and Marie-Pier Bergeron-Boucher[a,b]

Edited by Douglas S. Massey, Princeton University, Princeton, NJ, and approved December 6, 2020 (received for review October 29, 2020)

This article reviews some key strands of demographic research on past trends in human longevity and explores possible future trends in life expectancy at birth. Demographic data on age-specific mortality are used to estimate life expectancy, and validated data on exceptional life spans are used to study the maximum length of life. In the countries doing best each year, life expectancy started to increase around 1840 at a pace of almost 2.5 y per decade. This trend has continued until the present. Contrary to classical evolutionary theories of senescence and contrary to the predictions of many experts, the frontier of survival is advancing to higher ages. Furthermore, individual life spans are becoming more equal, reducing inequalities, with octogenarians and nonagenarians accounting for most deaths in countries with the highest life expectancy. If the current pace of progress in life expectancy continues, most children born this millennium will celebrate their 100th birthday. Considerable uncertainty, however, clouds forecasts: Life expectancy and maximum life span might increase very little if at all, or longevity might rise much faster than in the past. Substantial progress has been made over the past three decades in deepening understanding of how long humans have lived and how long they might live. The social, economic, health, cultural, and political consequences of further increases in longevity are so significant that the development of more powerful methods of forecasting is a priority.

forecasts | life expectancy | life span equality | maximum life span | mortality

The Past and Present of Longevity

Fixed Frontier of Survival. How much can human life span be extended? This is a top scientific question today (1)—and has been a topic of great interest at least since the exploits of Gilgamesh almost 5,000 y ago (2). Around 350 B.C., Aristotle provided a persuasive, pessimistic answer. He compared the "vital heat" of life to a fire that was burning down (3, 4). The fire could be put out prematurely by throwing sand or water on it—which was analogous to death from an epidemic or in war. Or the fire could die down naturally—which was analogous to old-age mortality. Premature mortality could be reduced, but the natural length of life could not be extended. This concept of a fixed frontier of survival was the dominant idea about longevity from 350 B.C. until recently. A highly cited article published in 1980 restated similar ideas to Aristotle's: "The inevitable result is natural death, even without disease. Although a disease process may appear to be the cause of death, the actual cause is loss of the organism's ability to maintain homeostasis" (ref. 5, p. 131).

Throughout the 20th century, there were many unsuccessful attempts at estimating the ultimate limit to human life expectancy; researchers and institutions such as the United Nations and the World Bank provided estimates that were surpassed, often within a few years of publication (6). Even today, some scholars still argue that life expectancy at birth is unlikely to ever exceed 85 y in any country (5, 7–9). A controversial article from 2016 claimed evidence of a limit to human life span at about 115 y of age (10, 11).

One argument for a limit to human life span is that evolution does not care about old age because older women are postreproductive and older men have few children. To some extent, older people help children

[a]Danish Centre for Demographic Research, University of Southern Denmark, 5230 Odense, Denmark; [b]Interdisciplinary Center on Population Dynamics, University of Southern Denmark, 5230 Odense, Denmark; and [c]Department of International Health, Bloomberg School of Public Health, Johns Hopkins University, Baltimore, MD 21205

Author contributions: J.W.V. designed research; J.W.V., F.V., and M.-P.B.-B. performed research; J.W.V. and M.-P.B.-B. contributed new reagents/analytic tools; F.V. and M.-P.B.-B. analyzed data; and J.W.V., F.V., and M.-P.B.-B. wrote the paper.

The authors declare no competing interest.

This article is a PNAS Direct Submission.

[1]To whom correspondence may be addressed. Email: jvaupel@sdu.dk.

Published February 10, 2021.

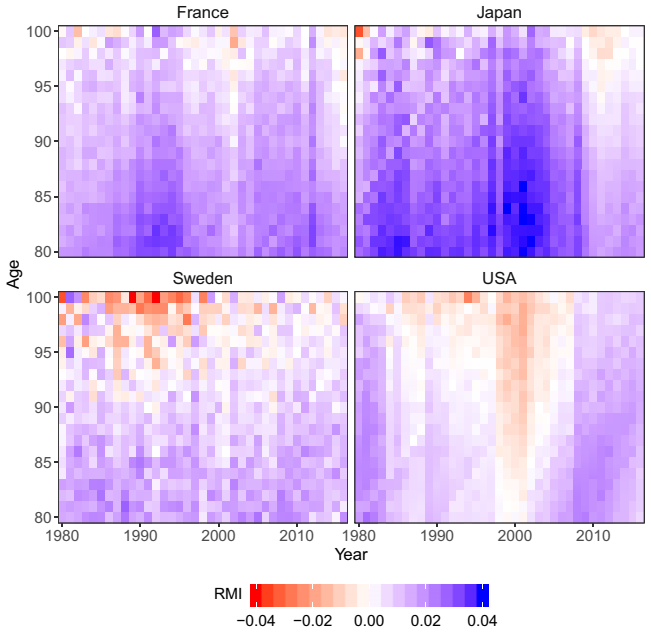

Fig. 1. Average rates of mortality improvement (RMI) in the preceding 10 y at ages 80–100: French, Japanese, Swedish, and US females, 1980–2017. Calculations by method in ref. 29 using data from the HMD (26).

survive and thereby contribute to maximizing the number of offspring (12), but this effect is small, especially over the long period of human evolution when few individuals reached age 70 (13). Hence, we are not designed to live into advanced old age (8, 14). Evolutionary processes favor genetic variants and physiological processes that enhance reproduction and survival at young ages. On the other hand, there is no strong evolutionary pressure against genetic variants or physiological processes that have deleterious effects at older ages, especially if these genes or physiological processes have positive effects at younger ages.

W. D. Hamilton (15), in line with the work of Medawar (16), Williams (17), and Kirkwood (18), captured this perspective by mathematical equations. He concluded that deterioration with age was inevitable for all species and that only radical genetic changes could extend life spans. In particular, "after a few hundred years of draconian eugenic measures . . . the human lifespan might be stretched out just a little . . . say [to] 75 instead of . . . 70." Hence, he asserted that research on "extension of active life seems to me comparable with the alchemists' search . . . [and] detracts both from unavoidable truth and from realistic social programs" (ref. 15, p. 91). Hamilton's claim, however, that mortality increases inexorably with age for all species has been proven wrong theoretically (19–23) and empirically (24).

The Advancing Frontier of Survival. The idea of a fixed frontier of survival is debated. Recent studies show progress in old age survival, weakening the concept of fixed limit, or at least foreseeable limit. Until the 1990s, serviceable data on death rates after age 85 were not available, but since then reliable statistics have been compiled for many countries and over many years, which contributed to the building of the Human Mortality Database (HMD) (25, 26). Data for Sweden show that before 1950 there was little progress in reducing mortality for 85-y-old Swedes: Aristotle was more or less right until then. However, afterward

Table 1. Current age (2017) and age of equivalent mortality 50 y ago (1967)

	Equivalent age in 1967							
	Females				Males			
Age	France	Japan	Sweden	United States	France	Japan	Sweden	United States
50	41	35	40	44	40	37	34	42
60	51	46	54	53	51	49	51	52
70	60	56	62	63	58	59	61	59
80	70	68	73	74	68	69	72	71
90	84	80	85	85	84	82	87	84

Mortality measured as the probability of death at a given age in 2017 and compared with the age with the same probability of death in 1967 using data from the HMD (26).

there were dramatic improvements (25). For Swedish women, the risk of death at age 85 has been cut from about 17% in 1950 to 7% in 2018 (26, 27). There was similar progress for men, and at ages 90 and 95 for both women and men (25–27).

This finding has been replicated for many countries (28, 29) and is supported by the most recent data from the HMD (26). Fig. 1 shows the average annual improvements in age-specific death rates in the preceding 10 y (29) for French, Japanese, Swedish, and US females between ages 80 and 100. In Sweden, progress in mortality is observed between ages 80 and 95, but not after, as previously shown (30, 31). However, reductions in death rates (positive rates of mortality improvement) are observed in France and Japan at all ages in most years. In the United States, death rates increased around the year 2000, but decreased before the mid-1990s and since the mid-2000s, showing progress at older ages in recent years. For US females, the risk of death at age 85 decreased from 14% in 1950 to 7% in 2017. Similar progress was also observed at older ages (e.g., from 31 to 22% at age 95). Another example is provided by German unification: Before 1990, people in East Germany suffered higher death rates than people in West Germany. After unification, the East German disadvantage at ages above 65 rapidly disappeared (32). This quasi-experimental evidence demonstrates that even very old people can benefit from improved conditions (33).

The improvements in survival at older ages are due to a postponement of mortality to older ages. That is, life spans have been extended, and mortality risks have shifted toward higher ages. A recent article on the "Advancing Front of Old-Age Human Survival" cogently demonstrates this (34). Table 1 provides an illustration. Note, for example, that in France the probability of death at age 70 in 2017 equals the probability of death at age 60 for females and 58 for males half a century ago (26). On average, for the countries and ages shown in Table 1, over the past 50 y mortality has been postponed by about a decade.

The advancing frontier of survival is part of a larger life expectancy revolution (6). In 1840, Swedish women enjoyed the world's longest life expectancy at birth: 46 y. Over time the world record steadily increased, with different countries taking the lead. For the last three decades, Japan has been the record holder.*

*Since 2013, females in Hong Kong have a higher life expectancy than females in Japan, according to data from HMD (26). However, as Hong Kong is not a country, the comparability of its life expectancy at the country level is questionable.

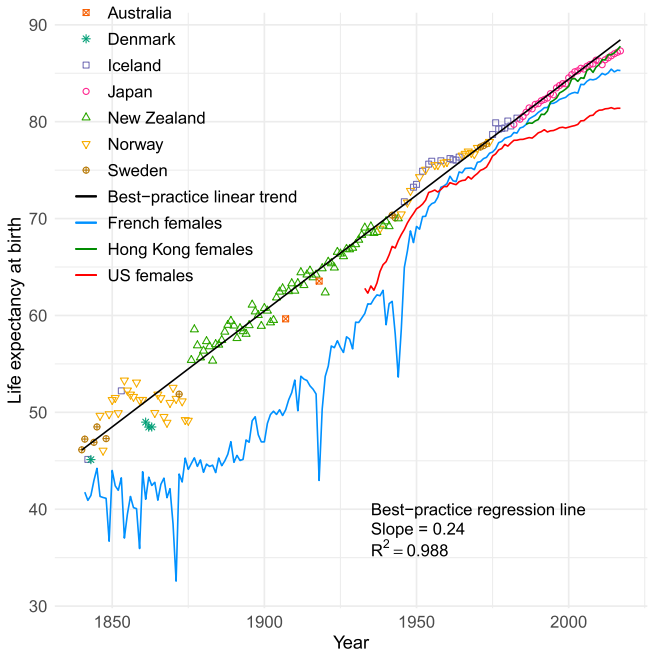

Fig. 2. Best-practice life expectancy at birth, 1840–2017. Adapted from ref. 6 using the most recent data from the HMD (26). In all cases, the values pertain to female life expectancy. Since 2013, Hong Kong females have a higher life expectancy than Japanese females in the HMD, but Hong Kong is not a country.

Life expectancy at birth for Japanese women in 2017 was more than 87 y (26). As a result, from 46 in 1840 to 87 today, best-practice life expectancy has almost doubled—rising at a remarkably steady pace of almost two and a half years per decade, 3 mo per year, 6 h per day. Fig. 2 shows the linear increase in the maximum life expectancy based on the work of Oeppen and Vaupel (6) and updated to the most recent data in HMD (26). Data quality issues have been raised regarding some years and countries used in this graph, especially Norway, 1810–1960, and New Zealand, 1876–1930. Using data from more sources and years and after removing the problematic country-years, Vallin and Meslé (35) provided a more nuanced look and found that the maximum life expectancy followed a segmented trend, with a slope of 0.32 between 1885 and 1960 and 0.23 since 1960. The latter segment is consistent with the slope observed in Fig. 2 since 1840, which persists with the addition of the most recent data. Particular countries followed more erratic trajectories than the straight-line best-practice increase, as illustrated for French and US women in Fig. 2. US life expectancy has stagnated in recent years, due to a rise in premature mortality and "deaths of despair" below age 65, including accidental poisoning, such as misuse of opioids and fentanyl (36, 37). Still, at older ages, US mortality has been declining in recent years (37), as shown in Fig. 1.

As Jonathan Swift observed, everyone wants to live long, but no one wants to be old. As life expectancy rises, what is happening to health at older ages? Studies have shown mixed results about whether the extra years of life are being lived in good health (38, 39) and no definite answer has been reached.

If period life expectancy over time increases 3 mo per year, then life expectancy for people born in successive years increases even more rapidly—because as a baby gets older, the person benefits from the progress being made over time (40). For instance, in part because of this effect and in part because France was catching up with best practice, for French females born in successive decades between the 1880s and the 1920s, life expectancy rose about 4 to 5 y each decade (26, 40), in contrast to the almost 2.5 y per decade increase in best-practice life expectancy (Fig. 2).

Studies of modern hunter-gatherers provide evidence about the long-term history of human longevity. Various estimates indicate a life expectancy at birth of less than 40 y for these populations (41). Studies of parish data from England over the period 1600–1725 show similarly short life expectancies (42) as do the data from Sweden between 1751 and the 1830s (26). Hence, it can be concluded that human life expectancy before 1840 generally fell below 40, and in situations of famine, epidemic, or war, the value could be much lower. The long-term history of human life expectancy is a history of high, fluctuating mortality, until the life expectancy revolution started around 1840, leading to life expectancies today of more than 80 in many countries (6, 26).

As life expectancy rose, life span equality—how similar life spans are—increased in lockstep. Seminal analysis by Edwards and Tuljapurkar (43) demonstrated the importance of studying life span equality, which is an indicator of population health disparities and of individual life span uncertainty (44, 45). As life spans became longer on average, they also became increasingly equal, something that has been found to hold on a life span continuum over millions of years of primate evolution, in many countries and between subgroups in a population (46). Fig. 3 depicts this relationship from historical to modern populations (e.g., Sweden over time in blue); from high (in red) to low mortality regime (in yellow); from hunter-gatherers (in green) to modern societies (in yellow); and even among nonhuman primates (in purple). Intriguingly, compared with the human populations with low life expectancy,

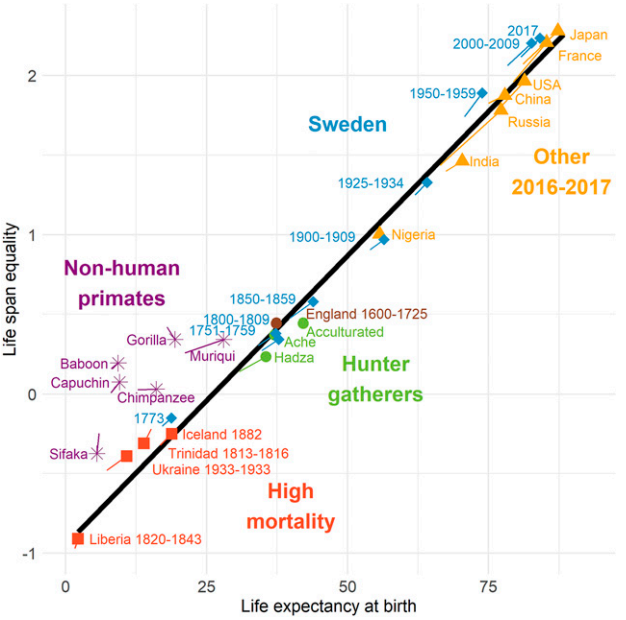

Fig. 3. The continuum of life expectancy at birth and life span equality in human populations. Adapted from the original figure by Fernando Colchero in ref. 46 to more recent data in refs. 26 and 116. Life span equality is measured by the logarithm of the inverse of life table entropy (47–49) and defined as $\ln(e_o/e^\dagger)$, where e_o is life expectancy at birth, and $e^\dagger$ is an indicator of life span disparity (46, 50). The lengths of the tadpoles represent the difference between females and males in the population, with the head being the females and the tale the males.

the nonhuman primates have higher levels of life span equality. Life span equality is low when some individuals live much longer than average. This is the case for the human populations with low life expectancy: Some individuals live to 80. In contrast, few if any of the nonhuman primates survived past age 50 (ref. 46, figure 1).

The relation between high life expectancy and life span equality is attributable to reductions in premature mortality. "The countries that have the highest life expectancy today are those which have been most successful at postponing the premature deaths that contribute to early-life disparity" (ref. 44, p. 4). The measure of life span equality used in Fig. 3 is based on the concept of life table entropy, first developed by Leser (47) and further explored by Demetrius (48) and Keyfitz (49). Measures based on the coefficient of variation or the Gini coefficient yield the same lockstep pattern, and the change in life expectancy from 1 y to the next closely tracks the annual change in life span equality (50).

The increase in life expectancy in the countries doing best has also been accompanied by an increase in maximum life span—the oldest age attained as verified by reliable data. Fig. 4 shows a roughly linear rise of maximum life span of about 1.5 mo (0.12 y) per year, lower than the 3-mo per year increase in maximum life expectancy, but still remarkable. The unbroken record of Jeanne Calment who died 122 y old in 1997 is interpreted by some as indicating that the limit to human life span has been reached. Such an interpretation, however, is misleading. Between 1899 and 2014, the mean interrecord time was around 11.9 y, with three records lasting for more than 20 y (including Calment's) and the longest lasting record being a little over 52 y (51). A study by Lenart et al. (52) estimates that there was only a 20% chance that Calment's record would have been broken between 1997 and 2017. Using a different analytical strategy, Medford and Vaupel suggest that "there was a 75% chance of observing a new record in the time since the last one so it is somewhat surprising that the record still holds. However, 20.7 y is still quite low when compared to the most durable record, which lasted 52 y" (ref. 51, p. 6). The data in Fig. 4 and ancillary data on exceptional life spans (53) do not support the claim that the maximum attainable life span has been reached (10, 11). This claim is also inconsistent with observed plateaus at a level of about 50% per year of the annual probability of death after age 105 in Italy (54) and after age 110 in a group of countries (55, 56): If the mortality plateau exists, the maximum life span will be determined by the number of people reaching that plateau, which is likely to increase as more people attain advanced ages. Moreover, the analysis of exceptional life spans using extreme value theory does not support the existence of any limit (57).

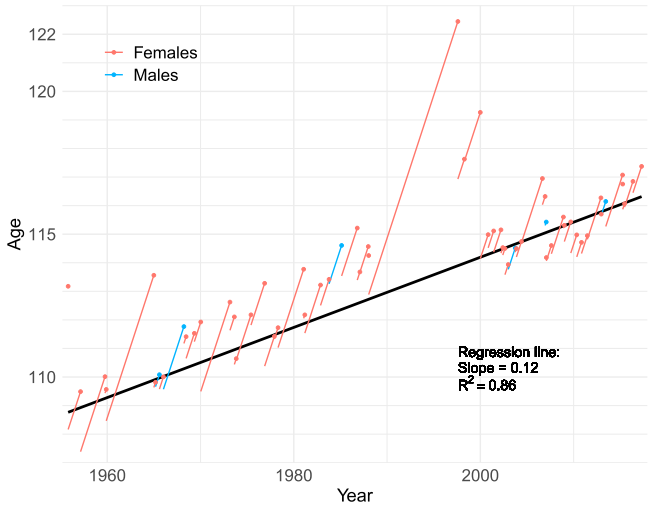

Fig. 4. Linearly increasing age of the world's oldest person. Adapted from a figure by Jonas Schöley—inspired by a graph by Robert D. Young (https://grg.org/sc/graphs/wop2.png)—using data from ref. 117. Additional studies of supercentenarians and the world´s oldest persons are found in ref. 53.

The Future of Longevity

By projecting the historical pace of progress into the future, it is possible to estimate the age that at least 50% of babies born in some country in some year will attain. Such forecasts can be found in the study by Christensen et al. (38) and show that most children born in the last two decades in countries with high life expectancy will, if past progress continues, celebrate their 100th birthday. Very long lives are the likely destiny of children alive today, provided life expectancy continues to increase at the historical pace of more than 2 y per decade. These forecasts depend, however, on substantial improvements being made in reducing death rates at high ages. An important question is whether such improvements will happen.

Among researchers who are willing to speculate about the future of life expectancy, there are, broadly speaking, three views (58): 1) Some argue that life expectancy will rise more slowly than in the past, perhaps approaching a limit that is not much greater than the current best-practice level, with some chance that life expectancy will fall (14); 2) others think that life expectancy will continue to rise and mortality to decline at the historical pace for the next several decades, and perhaps longer (59, 60); 3) finally, some futurologists predict that life expectancy will rise substantially faster than this because of major biomedical breakthroughs (61).

Most demographers, actuaries, and gerontologists appear to think that the future will be somewhere between the first and second scenarios. Although some think that the second view is more plausible, many support the first and a few are open to the third. Why is there such a wide range of forecasts among experts on life expectancy?

It can be expected that the future of longevity will be different from the past—but it is not known how different. Since 1840, the country with the highest life expectancy has shifted from Sweden to Japan, and a different country—perhaps Singapore or Spain (62)—might become the leader in the future. The causes of death against which progress has been made have shifted from infectious to chronic diseases (63). Before 1950, the rise in life expectancy was largely fueled by reductions in infant, child, and young adult mortality. Today, the rise is largely attributable to declines in death rates after age 65, and especially after age 80 when the majority of deaths now occur in the most developed countries (38, 64).

What kinds of mortality improvements might occur in the future? Experts know a great deal about the past but have difficulty foreseeing events in the future, especially the surprising kinds of events that have occurred so often in the past but were unforeseen and even unforeseeable.

- More effective public health strategies might be devised (perhaps as a consequence of the COVID-19 pandemic) that could improve health, e.g., by reducing the spread of infectious disease, controlling obesity and drug abuse, and slowing smoking initiation (65).

- In the next decade or two, substantial progress might be made in reducing the incidence of cancer and in treating it. Various diseases, including cancer, multiple sclerosis, and HIV, might be treated by enhanced immune therapies (66).
- There is evidence that over recent decades dementia has been postponed by roughly 2 to 4 y per decade (67), and this trend might continue.
- The new initiative of "precision medicine" aims to develop alternative treatments that are optimal for people with various genetic makeups (68). Such therapies might substantially reduce mortality. Furthermore, recent breakthroughs in CRISPR technology might lead to strategies for replacing deleterious genes a person might have with variants that decrease disease risks.
- Extensive research on reconstructing or regenerating tissues and organs, such as reconstructing skin or regenerating heart tissue damaged by a heart attack, might lead to better treatment and perhaps, in several decades, even to strategies for rejuvenating tissues and organs.
- Research on nanotechnology might eventually lead to the development of new tools for the manipulation of submicroscopic particles to repair damage or to destroy pathogens or cancerous cells (69, 70).
- Most significantly, but perhaps less likely, research on the basic biology of aging might lead to interventions that slow down the rate of aging (71). For example, breakthroughs might be achieved such that it would take 2 y for a person to suffer the deterioration that older people currently experience in 1 y: that is, roughly speaking, it would take 2 y to grow 1 y older.

On the other hand, it is not difficult to imagine developments that would slow or even reverse the rise of life expectancy. Economic growth in the future might be slower than in the past. There might be less money available for the prevention and treatment of disease. Because of slower economic growth and because of competing needs—such as the cost of pensions—the resources available for biomedical research might decline. New diseases worse than AIDS might emerge. Wars might break out. An increasing epidemic of obesity, or other behavioral risk factors (e.g., overdose), might severely damage health (36, 72). The biomedical breakthroughs adumbrated above might not occur. It might not be possible to reduce mortality after age 100.

This last risk is perhaps the most significant (73). As noted earlier, progress in increasing life expectancy since 1950 has resulted from a postponement of mortality, such that 70- and 80-y-olds have the mortality risk of people a decade younger half a century ago (Table 1). There is evidence that the pace of progress in reducing death rates for nonagenarians is accelerating (Fig. 1). There appears, however, to be little change in death rates after age 100. Perhaps improvements among centenarians will become more apparent as people reach age 100 in better states of health because of progress at younger ages. It is also possible, however, that it will not be feasible to substantially reduce centenarian mortality. If so, life expectancy will not rise to 100.

The Present and Future of Forecasting Longevity

Until recently, most forecasts of life expectancy were based on a judgment about its ultimate limit, which was assumed to be not much higher than current best-practice life expectancy (6, 40). Values of life expectancy from the present into the future were interpolated between present life expectancy and the assumed limit, with faster increases in the near future and slowing increases as the asymptote was approached. However, there is evidence that this strategy has consistently produced forecasts that are too low (6, 60, 74). Despite repeated failure, many mortality experts continue to use their judgments to make forecasts. Judgments and scenarios used to forecast fertility, migration, and national and global population sizes have also often been wrong. Booth argues that "[b]oth the patent inability of demographers to foresee demographic change and the rigidity of the scenario-based approach contributed to the assertion that traditional population projections are merely 'what-if' illustrations" (ref. 75, p. 550).

A cogent argument can be made that the first step in making a longevity forecast should be to extrapolate historical data. "Although imperfect, the appeal of extrapolation lies in the long-term stability of the historical mortality decline, which can be attributed to the complex character of the underlying process. This combination of stability and complexity should discourage us from believing that singular interventions or barriers will substantially alter the course of mortality decline in the future" (ref. 76, p. 397).

The future may be turbulent but so was the past. Consider the 20th century, marked by two world wars, the Spanish flu, the ascent and retreat of fascism and communism, the great depression, or the AIDS epidemic, all tragic events that did not undermine the increasing trend in life expectancy (Fig. 2). With the novel COVID-19 illness, for instance, new scenarios may arise, but it is still uncertain how the pandemic will affect longevity in the future: Although it may have a short-term impact on life expectancy similar to the Spanish flu in 1918, its effects could be small or even positive in the longer term thanks to behavioral and policy changes. Health improvements in the future may be slowed by deleterious trends (obesity), but health improvements in the past were also slowed by deleterious trends (the rise of cigarette smoking). The future may bring biomedical breakthroughs in preventing and treating cancer, dementia, and perhaps senescence; the past was also marked by remarkable advances in reducing mortality from infectious and cardiovascular diseases.

Change in life expectancy is a complicated function of change in age-specific mortality (77). The number of deaths at some age and time depends on each death—and each death results from a complicated mix of many factors—proximate, contributing, and underlying causes including the lingering legacies of past behaviors, exposures, and biomedical advances (78). Influences on mortality include economic, social, and political conditions, genetics, events in utero and early childhood, educational levels, diet, smoking and other aspects of personal behavior, epidemics, public health interventions, the quality of health care, the development of more effective pharmaceutical products, improvements in medical treatments and surgical procedures, and revolutionary biomedical breakthroughs (79–81). Using changes in risk factors and economic and epidemiological trends to help make forecasts is appealing, but difficult as their future values and their immediate and delayed relationships with mortality and with each other are often imperfectly understood, making their use in forecasting problematic (60). Simple extrapolative approaches of past trends have generally been more compelling, given the historical regularities (60, 76, 82). Reasons why the future might be better or worse than the past or more uncertain can be considered, but adjustments should be made with caution.

Extrapolative Methods to Forecast Life Expectancy. Extrapolative methods are often being used to forecast life expectancy based on historical data on age-specific death rates. Alho (83) and

Lee and Carter (84) played key roles in developing such methods, which have three major advantages: 1) They extrapolate empirical data that often show long-term regularities; 2) they are more objective; and 3) they produce probability distributions of future life expectancy rather than simple point estimates. The method suggested by Lee and Carter in 1992 (84) is the most commonly known, and an array of somewhat similar approaches has been developed (60, 85–88). These methods generally assume that the age-specific pace of decline in death rates will persist into the future, sometimes with some modest acceleration. Because death rates at advanced ages have declined at a slower pace than death rates at younger ages, the methods generally yield what most experts believe, namely that life expectancy will rise more slowly in the future.

Alternative models have been suggested to forecast mortality. Methods similar to Lee and Carter's (84), but using the age distributions of deaths rather than death rates, reduce forecast bias by allowing the pace of mortality decline to accelerate over time (89). A direct approach is to forecast life expectancy by extrapolating historical data on life expectancy (6). Some pioneering research has been done on this approach that takes advantage of the remarkable regularity of time trends in best-practice life expectancy (59, 90). If best-practice life expectancy is forecast linearly, then the gap between it and life expectancy for a given population can be forecast using data on gaps in the past. Age-specific death rates can be forecast by exploiting the strong relationship between life expectancy and the pattern of age-specific mortality (91, 92).

This use of the best-practice life expectancy in forecasting is part of a broader approach that recognizes that mortality trajectories are not independent between populations. Methods have been developed to integrate this coherence between populations in the forecasts (85, 89, 90), generally assuming that population-specific life expectancies are converging toward an average or toward best practice.

It is important to note that extrapolative approaches are not assumption-free. Each model is based on specific assumptions about future mortality, e.g., constant rate of improvement, convergence toward a benchmark, etc. These models are also often sensitive to different factors or choices made by the forecasters, such as the length of the fitting period, the indicator used, or if a coherent model is used, to the choice of the reference populations (93–95).

Fig. 5 shows forecasts of life expectancy for females in France, Japan, Sweden, and the United States up until 2070, using six extrapolative methods: 1) the Lee–Carter approach (84) and 2) its coherent version based on the work of Li and Lee assuming that population-specific trends are converging toward an average (85); 3) forecasts based on the extrapolation of death distributions (a method known as CoDA) and 4) its coherent version assuming that population-specific trends are converging toward an average (89); 5) direct extrapolation of life expectancy at birth and 6) its coherent version forecasting the gap between the best-practice and the population-specific trends (known as the "double-gap" method) (90).[†]

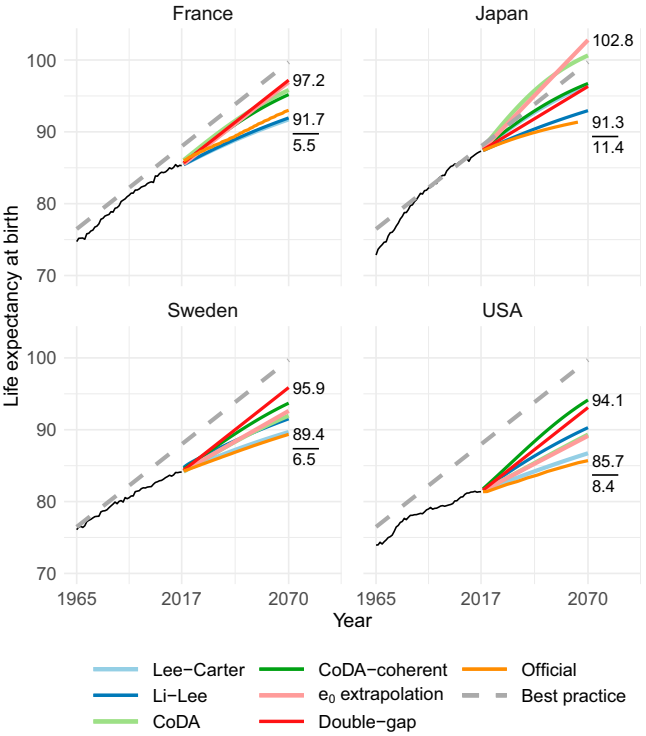

Fig. 5. Female life expectancy at birth, historical levels, and forecasts 2018–2070, with lowest and highest value in 2070 and their difference indicated. The linear trend in best-practice life expectancy is shown as a dashed line. The best-practice estimates for 2018–2070 are extrapolations of the 1840–2017 linear trend. Forecasts for the period 2018–2070 with time-series data for 1960–2017 from the HMD (26). Forecasts and prediction intervals (Table 2) are computed using six models (84, 85, 89, 90) or extracted from official national forecast (96–99).

In addition, Fig. 5 shows the official national forecasts for each selected country (96–99). The methods and assumptions between country vary (100). For example, Japan's official forecast is based on a Lee–Carter model combined with a model that shifts mortality curves to advanced ages, using a fitting period from 1970 (rather than from 1960 as in our forecasts), to reflect the changes in mortality that gradually slowed down in recent years (98). Sweden also uses a variant of the Lee–Carter model for their forecasts (97). The official forecasts for France are based on a mixture of expert opinions and extrapolation (99). For the United States, ultimate average annual percentage reductions in death rates are assumed by age groups and causes of death. Starting from annual reductions in central death rates observed in recent years, these annual reductions transition rapidly toward the ultimate annual percentage reductions assumed by 2043 (96). The official forecasts are generally lower (except for France) than the extrapolative approaches presented in Fig. 5, either because of assumptions or judgements, or the use of a fitting period yielding slower mortality improvements.

The life expectancy value and 95% prediction intervals (or high–low variants for official forecasts) in 2050 and 2070 are shown in Table 2 for both sexes. The calculation of credible prediction intervals is necessary to assess the uncertainty around the point estimates. The future is uncertain and so are the forecasts. Prediction intervals measure the precision of a forecast and how rapidly this precision decreases in the more distant future (101). The 95% prediction intervals in Table 2 widen over time and

[†]The model is slightly different from that of Pascariu et al. (90) as a drift term is not used in the autoregressive integrated moving average (ARIMA) model to forecast the gap between the best-practice and population-specific trends. This approach was chosen to prevent population-specific trends from indefinitely diverging from the best practice.

Table 2. Forecasts of life expectancy at birth with prediction intervals, 2050 and 2070

	Lee–Carter	Li–Lee	CoDA	CoDA-coherent	e_0 extrapol.	Double gap	Official forecast
Females							
France							
2050	89.6 (88.2, 91.0)	89.8 (88.1, 91.1)	92.6 (91.4, 93.8)	92.2 (91.1, 93.4)	92.5 (88.3, 96.6)	92.8 (90.1, 95.6)	90.3 (88.3, 93.0)
2070	91.7 (89.9, 93.2)	92.0 (90.2, 93.3)	95.7 (94.4, 96.8)	95.2 (94.0, 96.5)	96.9 (91.5, 102.3)	97.2 (93.7, 100.3)	93.0 (90.0, 96.0)
Japan							
2050	93.8 (90.7, 95.9)	91.1 (88.2, 93.2)	97.3 (94.8, 99.4)	94.0 (91.2, 97.7)	96.9 (87.3, 106.8)	92.9 (90.2, 95.8)	90.4 (89.4, 91.4)
2070	96.6 (93.8, 98.6)	92.9 (90.0, 95.3)	100.6 (98.5, 102.3)	96.7 (93.2, 100.4)	102.8 (90.5, 115.4)	96.3 (92.8, 99.5)	91.3* (90.2, 92.5)
Sweden							
2050	87.9 (85.7, 89.7)	89.3 (88.0, 90.6)	89.3 (87.9, 90.8)	90.6 (89.8, 91.7)	89.4 (86.2, 92.4)	91.4 (89.7, 93.3)	87.5 NA
2070	89.7 (87.3, 91.6)	91.5 (90.2, 92.9)	92.0 (90.4, 93.4)	93.7 (92.4, 95.3)	92.6 (88.7, 96.4)	95.9 (93.6, 98.1)	89.4 NA
United States							
2050	84.9 (83.6, 86.0)	87.4 (85.2, 89.2)	86.4 (84.5, 88.6)	90.0 (87.6, 92.5)	86.2 (79.8, 92.2)	88.7 (86.7, 90.5)	84.2 (82.7, 85.9)
2070	86.8 (85.2, 88.1)	90.3 (87.9, 92.1)	89.4 (86.9, 92.3)	94.1 (91.6, 96.5)	89.2 (80.9, 97.0)	93.1 (90.7, 95.4)	85.7 (83.6, 88.0)
Males							
France							
2050	84.4 (82.5, 86.1)	84.6 (82.8,86.1)	87.8 (86.6, 89.2)	87.2 (85.9, 89.0)	87.2 (82.6, 92.3)	88.1 (83.4, 93.7)	86.8 (84.5, 89.5)
2070	86.9 (84.8, 88.8)	87.1 (85.2, 88.8)	91.8 (90.5, 93.1)	91.0 (89.2,92.8)	92.0 (86.2, 98.7)	92.6 (86.4, 99.2)	90.1 (87.1, 93.1)
Japan							
2050	87.3 (85.0, 89.4)	85.6 (83.7,87.3)	91.2 (88.5, 94.2)	88.3 (85.9, 92.9)	89.6 (80.4, 99.3)	87.8 (82.8, 92.9)	84.0 (83.0, 85.0)
2070	90.2 (87.9, 92.2)	87.9 (85.7, 89.6)	95.4 (92.4, 97.8)	91.7 (88.0, 96.8)	94.7 (83.2, 107.2)	91.2 (84.1, 97.7)	85.0* (83.8, 86.1)
Sweden							
2050	84.8 (81.5, 87.5)	85.3 (83.9,86.0)	85.6 (84.8, 86.4)	87.1 (86.7, 87.6)	86.7 (80.5, 93.7)	88.7 (83.5, 94.2)	85.2 NA
2070	86.8 (82.9, 89.5)	87.6 (86.0, 89.1)	88.3 (87.6, 89.1)	90.3 (89.6, 91.4)	90.3 (82.7, 98.9)	93.1 (86.3, 100.3)	87.2 NA
United States							
2050	80.9 (79.0, 82.6)	82.8 (80.2, 83.4)	82.8 (80.9, 84.5)	85.7 (84.1, 87.5)	83.0 (78.1, 87.8)	84.5 (79.2, 89.4)	80.1 (78.2, 82.2)
2070	83.4 (81.0, 85.2)	86.0 (83.4, 88.1)	86.7 (84.1, 89.0)	90.5 (88.7, 92.5)	87.1 (80.6, 93.2)	89.2 (82.0, 95.2)	82.0 (79.3, 84.7)

Forecasts for the period in 2050 and 2070 with time-series data for 1960–2017 from the HMD (26). Forecasts and prediction intervals are computed using six models (84, 85, 89, 90) or extracted from official national forecast (96–99). For the life expectancy extrapolation, the double-gap model, and the official forecasts, the age-specific death rates are derived with methods from ref. 92.
*The official population forecast for Japan ends in 2065.

overlap. The methods produce different forecasts and prediction intervals. The range of forecast values reflects the uncertainty about future life expectancy trends.

Prediction intervals are generally calculated based on fitting errors. A model, however, that fits the data well is not the same as a model that predicts well. The fit of a model can always be improved with additional parameters. Instead of using fitting errors, historical forecast errors can be used. The forecaster choses a date in the past, forecasts from it to a date in the more recent past, and compares the forecast with what actually happened to evaluate the model's accuracy and to calculate prediction intervals (102, 103).

The best performing model varies across populations and time periods, making model selection problematic. Assessing whether progress in mortality at older ages, when most deaths occur, will stay constant or will accelerate is of crucial importance in selecting the appropriate forecast model. The models, including the national forecasts, produce very different forecasts at high ages. For example, the lowest death rate forecast by 2070 for the age group 90–99 is between 1.7 (United States) and 4.7 (Japan) times lower than the highest forecast. Note that the linear best-practice life expectancy trend from 1840 to 2017 rises close to 100 by 2070.

Some Future Directions in Longevity Forecasting. Other strategies than those presented in Fig. 5 and Table 2 exist or could be developed. Directions for research include the following options for better exploiting empirical data about trends in the past.

- The causes of the linear rise in best-practice life expectancy since 1840 are not well understood.
- How can cohort effects be incorporated in longevity forecasts (104, 105)?
- Extensive data over age, time, population, and sex are available on proximate, underlying, and contributing causes of death. A wealth of information is also available on various aspects of individuals' health over age and time. How can this information be used to improve mortality forecasts?
- As mortality patterns are explained by different behavioral, epidemiological, and biological factors, better ways to integrate morbidity and biology into mortality models should be explored.
- Extreme value theory could be used to study patterns and trends of survival among the pioneers on the advancing frontier of survival—those older than 100 or 110 (57, 106).
- Populations are heterogeneous. The frail tend to die first. This is related to tempo effects on mortality (107). Some innovative research suggests that it might be feasible to model heterogeneity in forecasting models (108).
- How can information on life span equality be integrated to improve or evaluate forecasts (109)?
- More research is necessary to improve methods for estimating the uncertainty around population forecasts. The 95% prediction interval should capture the true value of life expectancy 95% of the time. This can be checked by using data over some interval in the past to forecast life expectancy at some subsequent time in the past. If this is done repeatedly, with different intervals and perhaps different populations, then x% of the forecasts should fall into the estimated x% prediction interval—and 100 − x% should fall outside.

- Forecasts are used to estimate future needs and assess policies, e.g., estimate future pension costs. More research should be done on analyzing the impact of forecast errors on these estimates and to develop better ways to communicate the impact of uncertainty (101).
- Other methods for mortality forecasting are also being developed, including microsimulation (110) and Bayesian population projections (111, 112). Bayesian approaches have gained interest in the last decade, in part thanks to the Bayesian probabilistic projections adopted by the United Nations since the 2012 revision of the World Populations Prospects (113, 114).

In addition to the development of more powerful strategies for exploiting empirical data on past health and mortality trends, research is also needed on how to take better advantage of the knowledge of experts. As noted above, experts have been abysmally poor at assessing limits to human life expectancy. It might, however, be possible to make structured use of expert judgments to develop forecasts based on alternative scenarios about future economic, political, and social conditions. Furthermore, experts might provide useful information about the probability and timing of research advances that result, say, in interventions that slow the rate of aging (115).

The ongoing and unprecedented rise of longevity over the past two centuries is so remarkable that the future of longevity may be similarly rich in unexpected developments (13). The future will almost certainly be surprising, but it might be possible to anticipate some general trends. The social, economic, health, cultural, and political consequences of further increases in longevity are of such significance that the development of more powerful methods of forecasting is a priority.

Data Availability. Code, data, and readme file have been deposited in Github (https://github.com/panchoVG/RiseOfLongevity-PNAS2021).

Acknowledgments

We thank Erwin Tan, Jesús-Adrián Alvarez, Annette Baudisch, Kaare Christensen, Fernando Colchero, Ilya Kashnitsky, Marius Pascariu, and Jonas Schöley for input. This research was supported by the AXA Research Fund, AARP, and the National Institute on Aging at NIH (Grant P01 AG031719).

1 J. Couzin, How much can human life span be extended? *Science* **309**, 83 (2005).
2 A. R. George, *The Epic of Gilgamesh: The Babylonian Epic Poem and Other Texts in Akkadian and Sumerian* (Penguin, London, 2002).
3 Aristotle, "On length and shortness of life" in *The Complete Works of Aristotle: The Revised Oxford Translation*, J. Barnes, Ed. (Princeton University Press, Princeton, 1984), vol. 1, pp. 740–744.
4 Aristotle, "On youth, old age, life and death, and respiration" in *The Complete Works of Aristotle: The Revised Oxford Translation*, J. Barnes, Ed. (Princeton University Press, Princeton, 1984), vol. 1, pp. 745–763.
5 J. F. Fries, Aging, natural death, and the compression of morbidity. *N. Engl. J. Med.* **303**, 130–135 (1980).
6 J. Oeppen, J. W. Vaupel, Demography. Broken limits to life expectancy. *Science* **296**, 1029–1031 (2002).
7 S. J. Olshansky, B. A. Carnes, C. Cassel, In search of Methuselah: Estimating the upper limits to human longevity. *Science* **250**, 634–640 (1990).
8 B. A. Carnes, S. J. Olshansky, A realist view of aging, mortality, and future longevity. *Popul. Dev. Rev.* **33**, 367–381 (2007).
9 S. J. Olshansky, B. A. Carnes, Inconvenient truths about human longevity. *J. Gerontol. A Biol. Sci. Med. Sci.* **74**, S7–S12 (2019).
10 X. Dong, B. Milholland, J. Vijg, Evidence for a limit to human lifespan. *Nature* **538**, 257–259 (2016).
11 A. Lenart, J. W. Vaupel, Questionable evidence for a limit to human lifespan. *Nature* **546**, E13–E14 (2017).
12 K. Hawkes, Grandmothers and the evolution of human longevity. *Am. J. Hum. Biol.* **15**, 380–400 (2003).
13 J. W. Vaupel, Biodemography of human ageing. *Nature* **464**, 536–542 (2010).
14 S. J. Olshansky, B. A. Carnes, A. Désesquelles, Prospects for human longevity. *Science* **291**, 1491–1492 (2001).
15 W. D. Hamilton, "Live now, pay later: The moulding of senescence by natural selection" in *Narrow Roads of Gene Land*, W. D. Hamilton, Ed. (Freeman, New York, 1996), vol. 1, chap. 3, pp. 85–128.
16 P. B. Medawar, *An Unsolved Problem of Biology* (Lewis, London, 1952).
17 G. C. Williams, Pleiotropy, natural selection, and the evolution of senescence. *Evolution* **11**, 398–411 (1957).
18 T. B. Kirkwood, Evolution of ageing. *Nature* **270**, 301–304 (1977).
19 J. W. Vaupel, A. Baudisch, M. Dölling, D. A. Roach, J. Gampe, The case for negative senescence. *Theor. Popul. Biol.* **65**, 339–351 (2004).
20 A. Baudisch, Hamilton's indicators of the force of selection. *Proc. Natl. Acad. Sci. U.S.A.* **102**, 8263–8268 (2005).
21 A. Baudisch, *Inevitable Aging? Contributions to Evolutionary-Demographic Theory* (Springer, Berlin, 2008).
22 A. Baudisch, J. W. Vaupel, Evolution. Getting to the root of aging. *Science* **338**, 618–619 (2012).
23 K. W. Wachter, S. N. Evans, D. Steinsaltz, The age-specific force of natural selection and biodemographic walls of death. *Proc. Natl. Acad. Sci. U.S.A.* **110**, 10141–10146 (2013).
24 O. R. Jones, A. Scheuerlein *et al.*, Diversity of ageing across the tree of life. *Nature* **505**, 169–173 (2014).
25 J. W. Vaupel, H. Lundstrom, "Longer life expectancy? Evidence from Sweden of reductions in mortality rates at advanced ages" in *Studies in the Economics of Aging*, D. A. Wise, Ed. (University of Chicago Press, Chicago, 1994), pp. 79–102.
26 University of California, Berkeley; Max Planck Institute for Demographic Research, Rostock, Human Mortality Database (HMD). https://www.mortality.org/. Accessed 27 March 2020.
27 Statisics Sweden, Statistical database. http://www.statistikdatabasen.scb.se/pxweb/en/ssd/. Accessed 23 February 2020.
28 V. Kannisto, J. Lauritsen, A. R. Thatcher, J. W. Vaupel, Reductions in mortality at advanced ages: Several decades of evidence from 27 countries. *Popul. Dev. Rev.* **20**, 793–810 (1994).
29 R. Rau, E. Soroko, D. Jasilionis, J. W. Vaupel, Continued reductions in mortality at advanced ages. *Popul. Dev. Rev.* **34**, 747–768 (2008).
30 A. Medford, K. Christensen, A. Skytthe, J. W. Vaupel, A cohort comparison of lifespan after age 100 in Denmark and Sweden: Are only the oldest getting older? *Demography* **56**, 665–677 (2019).
31 K. Modig, T. Andersson, J. Vaupel, R. Rau, A. Ahlbom, How long do centenarians survive? Life expectancy and maximum lifespan. *J. Intern. Med.* **282**, 156–163 (2017).
32 J. W. Vaupel, J. R. Carey, K. Christensen, It's never too late. *Science* **301**, 1679–1681 (2003).
33 T. C. Vogt, F. A. Kluge, Can public spending reduce mortality disparities? Findings from East Germany after reunification. *J. Econ. Ageing* **5**, 7–13 (2015).
34 W. Zuo, S. Jiang, Z. Guo, M. W. Feldman, S. Tuljapurkar, Advancing front of old-age human survival. *Proc. Natl. Acad. Sci. U.S.A.* **115**, 11209–11214 (2018).
35 J. Vallin, F. Meslé, The segmented trend line of highest life expectancies. *Popul. Dev. Rev.* **35**, 159–187 (2009).
36 J. Y. Ho, A. S. Hendi, Recent trends in life expectancy across high income countries: Retrospective observational study. *BMJ* **362**, k2562 (2018).
37 E. M. Stein, K. P. Gennuso, D. C. Ugboaja, P. L. Remington, The epidemic of despair among white Americans: Trends in the leading causes of premature death, 1999–2015. *Am. J. Public Health* **107**, 1541–1547 (2017).

38 K. Christensen, G. Doblhammer, R. Rau, J. W. Vaupel, Ageing populations: The challenges ahead. *Lancet* **374**, 1196–1208 (2009).
39 H. Beltrán-Sánchez, S. Soneji, E. M. Crimmins, Past, present, and future of healthy life expectancy. *Cold Spring Harb. Perspect. Med.* **5**, a025957 (2015).
40 V. M. Shkolnikov, D. A. Jdanov, E. M. Andreev, J. W. Vaupel, Steep increase in best-practice cohort life expectancy. *Popul. Dev. Rev.* **37**, 419–434 (2011).
41 M. Gurven, H. Kaplan, Longevity among hunter-gatherers: A cross-cultural examination. *Popul. Dev. Rev.* **33**, 321–365 (2007).
42 E. A. Wrigley, R. S. Davies, J. Oeppen, R. Schofield, *English Population History from Family Reconstitution 1580–1837* (Cambridge University Press, Cambridge, UK, 1997).
43 R. D. Edwards, S. Tuljapurkar, Inequality in life spans and a new perspective on mortality convergence across industrialized countries. *Popul. Dev. Rev.* **31**, 645–674 (2005).
44 J. W. Vaupel, Z. Zhang, A. A. van Raalte, Life expectancy and disparity: An international comparison of life table data. *BMJ Open* **1**, e000128 (2011).
45 A. A. van Raalte, I. Sasson, P. Martikainen, The case for monitoring life-span inequality. *Science* **362**, 1002–1004 (2018).
46 F. Colchero *et al.*, The emergence of longevous populations. *Proc. Natl. Acad. Sci. U.S.A.* **113**, E7681–E7690 (2016).
47 C. E. V. Leser, Variations in mortality and life expectation. *Population Studies* **9**, 67–71 (1955).
48 L. Demetrius, Demographic parameters and natural selection. *Proc. Natl. Acad. Sci. U.S.A.* **71**, 4645–4647 (1974).
49 N. Keyfitz, *Applied Mathematical Demography* (Wiley, New York, 1977).
50 J. M. Aburto, F. Villavicencio, U. Basellini, S. Kjærgaard, J. W. Vaupel, Dynamics of life expectancy and life span equality. *Proc. Natl. Acad. Sci. U.S.A.* **117**, 5250–5259 (2020).
51 A. Medford, J. W. Vaupel, Human lifespan records are not remarkable but their durations are. *PLoS One* **14**, e0212345 (2019).
52 A. Lenart, J. M. Aburto, A. Stockmarr, J. W. Vaupel, "*The human longevity record may hold for decades: Jeanne Calment's extraordinary record is not evidence for an upper limit to human lifespan*" in *Exceptional Lifespans*, H. Maier, B. Jeune, J. W. Vaupel, Eds. (Springer, Cham, Switzerland, 2021), pp. 49–55.
53 H. Maier, B. Jeune, J. W. Vaupel, Eds., *Exceptional Lifespans* (Springer, Cham, Switzerland, 2021).
54 E. Barbi, F. Lagona, M. Marsili, J. W. Vaupel, K. W. Wachter, The plateau of human mortality: Demography of longevity pioneers. *Science* **360**, 1459–1461 (2018).
55 J. Gampe, "Human mortality beyond age 110" in *Supercentenarians*, H. Maier, J. Gampe, B. Jeune, J.-M. Robine, J. W. Vaupel, Eds. (Springer, Berlin, 2010), pp. 219–230.
56 J. Gampe, "Mortality of supercentenarians: Estimates from the updated IDL" in *Exceptional Lifespans*, H. Maier, B. Jeune, J. W. Vaupel, Eds. (Springer, Cham, Switzerland, 2021), chap. 3, pp. 29–35.
57 H. Rootzén, D. Zholud, Human life is unlimited—but short. *Extremes* **20**, 713–728 (2017).
58 K. G. Manton, E. Stallard, H. D. Tolley, Limits to human life expectancy: Evidence, prospects, and implications. *Popul. Dev. Rev.* **17**, 603–637 (1991).
59 T. Torri, J. W. Vaupel, Forecasting life expectancy in an international context. *Int. J. Forecast.* **28**, 519–531 (2012).
60 H. Booth, L. Tickle, Mortality modelling and forecasting: A review of methods. *Annals of Actuarial Science* **3**, 3–43 (2008).
61 A. De Grey, M. Rae, *Ending Aging: The Rejuvenation Breakthroughs That Could Reverse Human Aging in Our Lifetime* (St. Martin's Press, London, 2007).
62 K. J. Foreman *et al.*, Forecasting life expectancy, years of life lost, and all-cause and cause-specific mortality for 250 causes of death: Reference and alternative scenarios for 2016–40 for 195 countries and territories. *Lancet* **392**, 2052–2090 (2018).
63 A. R. Omran, The epidemiologic transition: A theory of the epidemiology of population change. 1971. *Milbank Q.* **83**, 731–757 (2005).
64 F. Meslé, J. Vallin, Transition sanitaire: Tendances et perspectives. *Med. Sci. (Paris)* **16**, 1161–1171 (2000).
65 J. P. Pierce, V. M. White, S. L. Emery, What public health strategies are needed to reduce smoking initiation? *Tob. Control* **21**, 258–264 (2012).
66 K. Naran, T. Nundalall, S. Chetty, S. Barth, Principles of immunotherapy: Implications for treatment strategies in cancer and infectious diseases. *Front. Microbiol.* **9**, 3158 (2018).
67 E. Stallard, Update on the LTC morbidity improvement study. *Long Term Care News* **36**, 23–27 (2014).
68 G. R. Gameiro, V. Sinkunas, G. R. Liguori, J. O. C. Auler-Júnior, Precision medicine: Changing the way we think about healthcare. *Clinics (São Paulo)* **73**, e723 (2018).
69 C. L. Ventola, The nanomedicine revolution: Part 1: Emerging concepts. *P&T* **37**, 512–525 (2012).
70 C. L. Ventola, The nanomedicine revolution: Part 2: Current and future clinical applications. *P&T* **37**, 582–591 (2012).
71 B. K. Kennedy *et al.*, Geroscience: Linking aging to chronic disease. *Cell* **159**, 709–713 (2014).
72 S. J. Olshansky *et al.*, A potential decline in life expectancy in the United States in the 21st century. *N. Engl. J. Med.* **352**, 1138–1145 (2005).
73 S. Horiuchi, J. R. Wilmoth, Deceleration in the age pattern of mortality at older ages. *Demography* **35**, 391–412 (1998).
74 J. M. Alho, B. D. Spencer, Error models for official mortality forecasts. *J. Am. Stat. Assoc.* **85**, 609–616 (1990).
75 H. Booth, Demographic forecasting: 1980 to 2005 in review. *Int. J. Forecast.* **22**, 547–581 (2006).
76 J. R. Wilmoth, The future of human longevity: A demographer's perspective. *Science* **280**, 395–397 (1998).
77 T. F. Wrycza, A. Baudisch, How life expectancy varies with perturbations in age-specific mortality. *Demogr. Res.* **27**, 365–376 (2012).
78 M. Wensink, R. G. Westendorp, A. Baudisch, The causal pie model: An epidemiological method applied to evolutionary biology and ecology. *Ecol. Evol.* **4**, 1924–1930 (2014).
79 S. H. Preston, The changing relation between mortality and level of economic development. *Popul. Stud. (Camb.)* **29**, 231–248 (1975).
80 S. H. Preston, The changing relation between mortality and level of economic development. Population Studies, Vol. 29, No. 2, July 1975. *Int. J. Epidemiol.* **36**, 484–490 (2007).
81 K. Christensen, J. W. Vaupel, Determinants of longevity: Genetic, environmental and medical factors. *J. Intern. Med.* **240**, 333–341 (1996).
82 J. R. Wilmoth, Demography of longevity: Past, present, and future trends. *Exp. Gerontol.* **35**, 1111–1129 (2000).
83 J. M. Alho, Stochastic methods in population forecasting. *Int. J. Forecast.* **6**, 521–530 (1990).
84 R. D. Lee, L. R. Carter, Modeling and forecasting US mortality. *J. Am. Stat. Assoc.* **87**, 659–671 (1992).
85 N. Li, R. Lee, Coherent mortality forecasts for a group of populations: An extension of the Lee-Carter method. *Demography* **42**, 575–594 (2005).
86 H. Booth, R. J. Hyndman, L. Tickle, P. De Jong, Lee-Carter mortality forecasting: A multi-country comparison of variants and extensions. *Demogr. Res.* **15**, 289–310 (2006).
87 R. Lee, T. Miller, Evaluating the performance of the Lee-Carter method for forecasting mortality. *Demography* **38**, 537–549 (2001).
88 T. Bengtsson, N. Keilman, Eds., *Old and New Perspectives on Mortality Forecasting* (Springer, Cham, Switzerland, 2019).
89 M.-P. Bergeron-Boucher, V. Canudas-Romo, J. Oeppen, J. W. Vaupel, Coherent forecasts of mortality with compositional data analysis. *Demogr. Res.* **37**, 527–566 (2017).
90 M. D. Pascariu, V. Canudas-Romo, J. W. Vaupel, The double-gap life expectancy forecasting model. *Insur. Math. Econ.* **78**, 339–350 (2018).
91 H. Ševčíková, N. Li, V. Kantorová, P. Gerland, A. E. Raftery, "Age-specific mortality and fertility rates for probabilistic population projections" in *Dynamic Demographic Analysis*, R. Schoen, Ed. (Springer, 2016), pp. 285–310.
92 M. D. Pascariu, "Modelling and forecasting mortality," PhD thesis, University of Southern Denmark, Odense (2018).
93 M.-P. Bergeron-Boucher, S. Kjærgaard, J. Oeppen, J. W. Vaupel, The impact of the choice of life table statistics when forecasting mortality. *Demogr. Res.* **41**, 1235–1268 (2019).
94 F. Janssen, A. Kunst, The choice among past trends as a basis for the prediction of future trends in old-age mortality. *Popul. Stud. (Camb.)* **61**, 315–326 (2007).
95 M.-P. Bergeron-Boucher *et al.*, "Alternative forecasts of Danish life expectancy" in *Developments in Demographic Forecasting*, N. Neilman, S. Mazzuco, Eds. (The Springer Series on Demographic Methods and Population Analysis, Springer, 2020), vol. 49, chap. 7, pp. 131-151.

96 The Board of Trustees, Federal Old-Age and Survivors Insurance and Federal Disability Insurance Trust Funds, "The 2019 Annual Report of the Board of Trustees of the Federal Old-Age and Survivors Insurance and Federal Disability Insurance Trust Funds" (US Social Security Administration, Washington, DC, 2019). https://www.ssa.gov/OACT/TR/2019/tr2019.pdf. Accessed 20 June 2020.

97 Statistics Sweden, "The future population of Sweden 2019–2070" (Statistics Sweden, Sweden, 2019). https://www.scb.se/publication/36487. Accessed 2 May 2020.

98 National Institute of Population and Social Security Research, Population projections for Japan: 2016 to 2065. http://www.ipss.go.jp/pp-zenkoku/e/zenkoku_e2017/pp_zenkoku2017e.asp. Accessed 1 August 2018.

99 N. Blanpain, G. Buisson, "Projections de population 2013–2070 pour la France: Méthode et principaux résultats" (Rep. No. F1606, Institut National de la Statistique et des Études Économiques, Direction des statistiques démographiques et sociales, Unité des Études Démographiques et Sociales, Paris, France, 2018). https://hal.archives-ouvertes.fr/hal-02150595/document. Accessed 11 June 2020.

100 L. Stoeldraijer, C. van Duin, L. van Wissen, F. Janssen, Impact of different mortality forecasting methods and explicit assumptions on projected future life expectancy: The case of The Netherlands. *Demogr. Res.* **29**, 323–354 (2013).

101 S. Tuljapurkar, "Stochastic forecasts of mortality, population and pension systems" in *Old and New Perspectives on Mortality Forecasting*, T. Bengtsson, N. Keilman, Eds. (Springer, Cham, Switzerland, 2019), pp. 145–155.

102 R. J. Hyndman, G. Athanasopoulos, *Forecasting: Principles and Practice* (OTexts, 2018).

103 Y. S. Lee, S. Scholtes, Empirical prediction intervals revisited. *Int. J. Forecast.* **30**, 217–234 (2014).

104 R. Lindahl-Jacobsen *et al.*, Rise, stagnation, and rise of Danish women's life expectancy. *Proc. Natl. Acad. Sci. U.S.A.* **113**, 4015–4020 (2016).

105 A. E. Renshaw, S. Haberman, A cohort-based extension to the Lee–Carter model for mortality reduction factors. *Insur. Math. Econ.* **38**, 556–570 (2006).

106 A. Medford, Best-practice life expectancy: An extreme value approach. *Demogr. Res.* **36**, 989–1014 (2017).

107 E. Barbi, J. R. Bongaarts, J. W. Vaupel, *How Long Do We Live? Demographic Models and Reflections on Tempo Effects* (Springer, Berlin, 2008).

108 S. F. Jarner, E. M. Kryger, Modelling adult mortality in small populations: The SAINT model. *ASTIN Bull.* **41**, 377–418 (2011).

109 C. Bohk-Ewald, M. Ebeling, R. Rau, Lifespan disparity as an additional indicator for evaluating mortality forecasts. *Demography* **54**, 1559–1577 (2017).

110 M. C. Wolfson, POHEM–A framework for understanding and modelling the health of human populations. *World Health Stat. Q.* **47**, 157–176 (1994).

111 A. E. Raftery, N. Li, H. Ševčíková, P. Gerland, G. K. Heilig, Bayesian probabilistic population projections for all countries. *Proc. Natl. Acad. Sci. U.S.A.* **109**, 13915–13921 (2012).

112 A. E. Raftery, J. L. Chunn, P. Gerland, H. Sevčíková, Bayesian probabilistic projections of life expectancy for all countries. *Demography* **50**, 777–801 (2013).

113 A. E. Raftery, L. Alkema, P. Gerland, Bayesian population projections for the United Nations. *Stat. Sci.* **29**, 58–68 (2014).

114 P. Gerland *et al.*, World population stabilization unlikely this century. *Science* **346**, 234–237 (2014).

115 V. Canudas-Romo, E. DuGoff, A. W. Wu, S. Ahmed, G. Anderson, Life expectancy in 2040: What do clinical experts expect? *N. Am. Actuar. J.* **20**, 276–285 (2016).

116 World Health Organization, Global health estimates: Life expectancy and leading causes of death and disability (2020). https://www.who.int/data/gho/data/themes/mortality-and-global-health-estimates. Accessed 12 August 2020.

117 Gerontology Research Group, GRG Supercentenarian Research and Database Division. https://grg.org/SC/SCindex.html. Accessed 27 February 2019.