Demographic Perspectives on the Rise of Longevity

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Abstract

This article summarizes the findings of the most significant demographic publications on 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 lifespans 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 years 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 lifespans are becoming more equal, reducing inequalities, with octogenarians and nonagenarians accounting for most deaths in countries with high life expectancy. If the current pace of progress in life expectancy continues, most children born this millennium will celebrate their 100th birthdays. Considerable uncertainty, however, clouds forecasts of life expectancy and maximum lifespans: life expectancy and maximum lifespan 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.

Key words: Forecasts, Life expectancy, Lifespan equality, Maximum lifespan, Mortality

Section 1: The Past and Present of Longevity

1.1 FIXED FRONTIER OF SURVIVAL

How much can human lifespan 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 years 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). 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" (4, p.131). At the end of the 20th century, the United Nations still assumed a fixed limit to life expectancy in their projections. Some scholars set the limit at age 85 (4, 5): "S. Jay Olshansky […] says we're near our upper limit for average life spans. 'Possibly we can get it up from 80 to 85,' he says, noting that already 'Japan is closing in on it'." (6). A controversial article from 2016 claimed evidence of a limit to human lifespan, at around 115 years (7).

One argument for a limit to human lifespan is that evolution does not care about old age because older women are post-reproductive and older men have few children. To some extent, older people help children survive and thereby contribute to maximizing the number of offspring (8), but this effect is small, especially over the long period of human evolution when few individuals reached age 70 (9). Hence, we are not designed to live into advanced old age (10, 11). 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 (12), in line with the work of Medawar (13), Williams (14) and Kirkwood (15), 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 lifespans. 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." (12, p.91)

1.2 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 (16, 17). Data for Sweden show that before 1950 there was little progress in reducing mortality for 85-year-old Swedes: Aristotle was more or less right until then. But afterwards there were dramatic improvements (16). For Swedish women, the risk of death at age 85 has been cut from about 17% in 1950 to 7% in 2018 (17, 18). There were similar progress for men, and at ages 90 and 95 for both women and men (16-18).

This finding has been replicated for many countries (19, 20) and is supported by the most recent data from the Human Mortality Database (17). Furthermore, Hamilton's assertion that deterioration with age is inevitable for all species has been theoretically proved to be wrong (21, 22), something that has also been demonstrated empirically (23, 24). Figure 1 shows the average annual improvements in age-specific death rates in the preceding ten years (20) 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 (25, 26). However, reductions in death rates (positive rates of mortality improvement) are observed in France and Japan at all ages in most years. In the US,

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 (27). This quasi-experimental evidence demonstrates that even very old people can benefit from improved conditions (28).

Figure 1

AVERAGE RATES OF MORTALITY IMPROVEMENT (RMI) IN THE PRECEDING TEN YEARS AT AGES 80 TO 100: FRENCH, JAPANESE, SWEDISH AND US FEMALES, 1980-2016
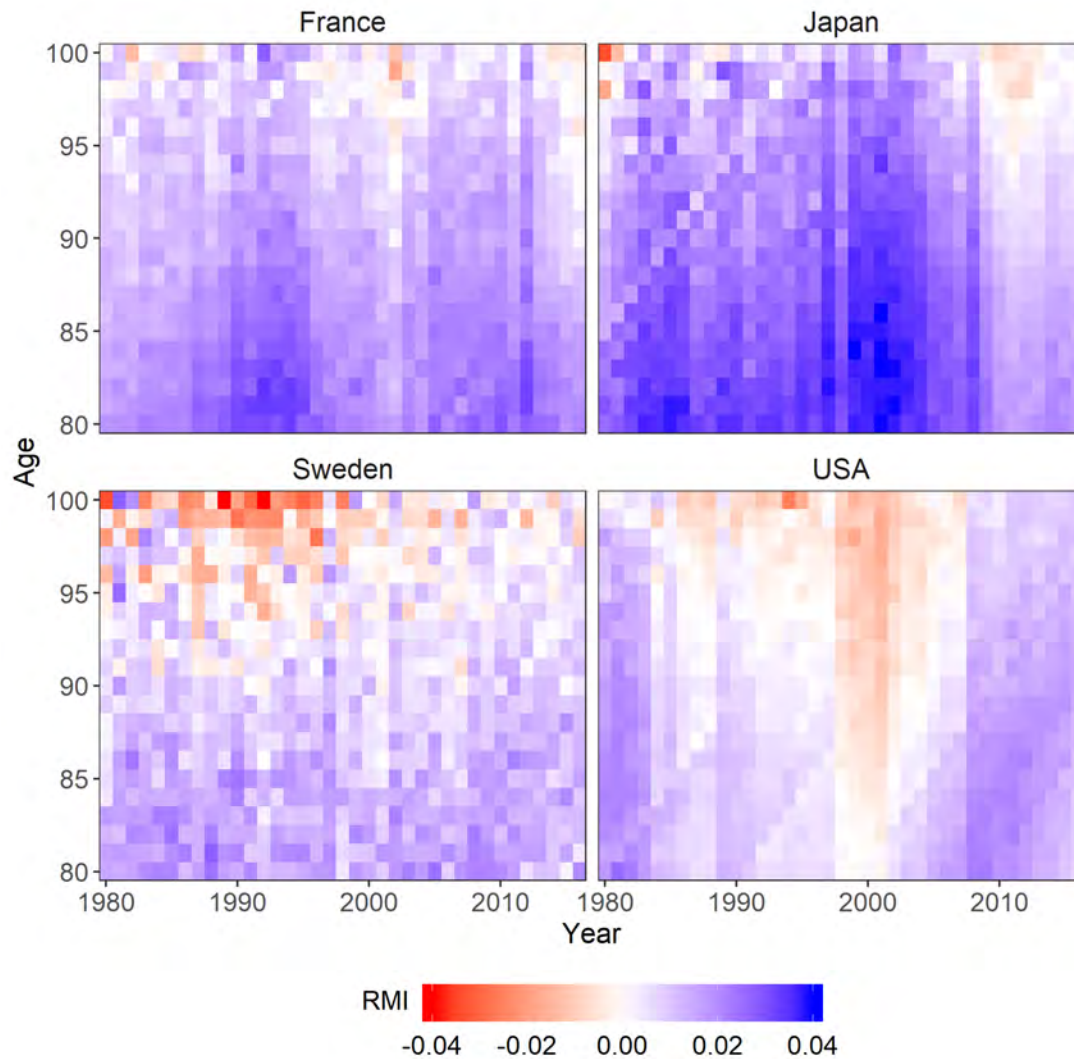
Note: Calculations by method in (20) using data from (17)

The improvements in survival at older ages are due to a postponement of mortality to older ages. That is, lifespans 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 (29). Table 1 provides an illustration. Note, for example, that in France the probability of death at age 70 in 2016 equals the probability of death at age 59 for females and 58 for males half a century ago (17). On average, for the countries and ages shown in Table 1, over the past 50 years mortality has been postponed by about a decade.

Table 1
CURRENT AGE (2016) AND AGE OF EQUIVALENT MORTALITY 50 YEARS AGO (1966)

	Equivalent age in 1966							
	Females				Males			
Age	France	Japan	Sweden	USA	France	Japan	Sweden	USA
50	40	37	42	44	40	37	42	43
60	51	45	53	53	51	49	52	51
70	59	55	63	63	58	59	61	59
80	71	67	73	74	69	69	73	71
90	84	80	85	84	84	82	86	84

Note: Mortality measured as the probability of death at a given age in 2016, and compared with the age with the same probability of death in 1966 using data from (17).

The advancing frontier of survival is part of a larger life-expectancy revolution (30). In 1840 Swedish women enjoyed the world's longest life expectancy at birth: 46 years. Over time the world record steadily increased, with different countries taking the lead. For the last three decades, Japan has been the record holder. Life expectancy at birth for Japanese women in 2016 was more than 87 years (17). So, 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, three months per year, six hours per day. 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 (31, 32). Still, at older ages, US mortality has been declining in recent years (32), as shown in Fig. 1.

If period life expectancy over time increases three months 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 (33). 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 from the 1880s to the 1920s, life expectancy rose about four to five years each decade (17, 33), as opposed to the almost 2.5 years per decade increase in best-practice life expectancy (Fig. 2).

Figure 2
BEST-PRACTICE LIFE EXPECTANCY AT BIRTH, 1840-2016
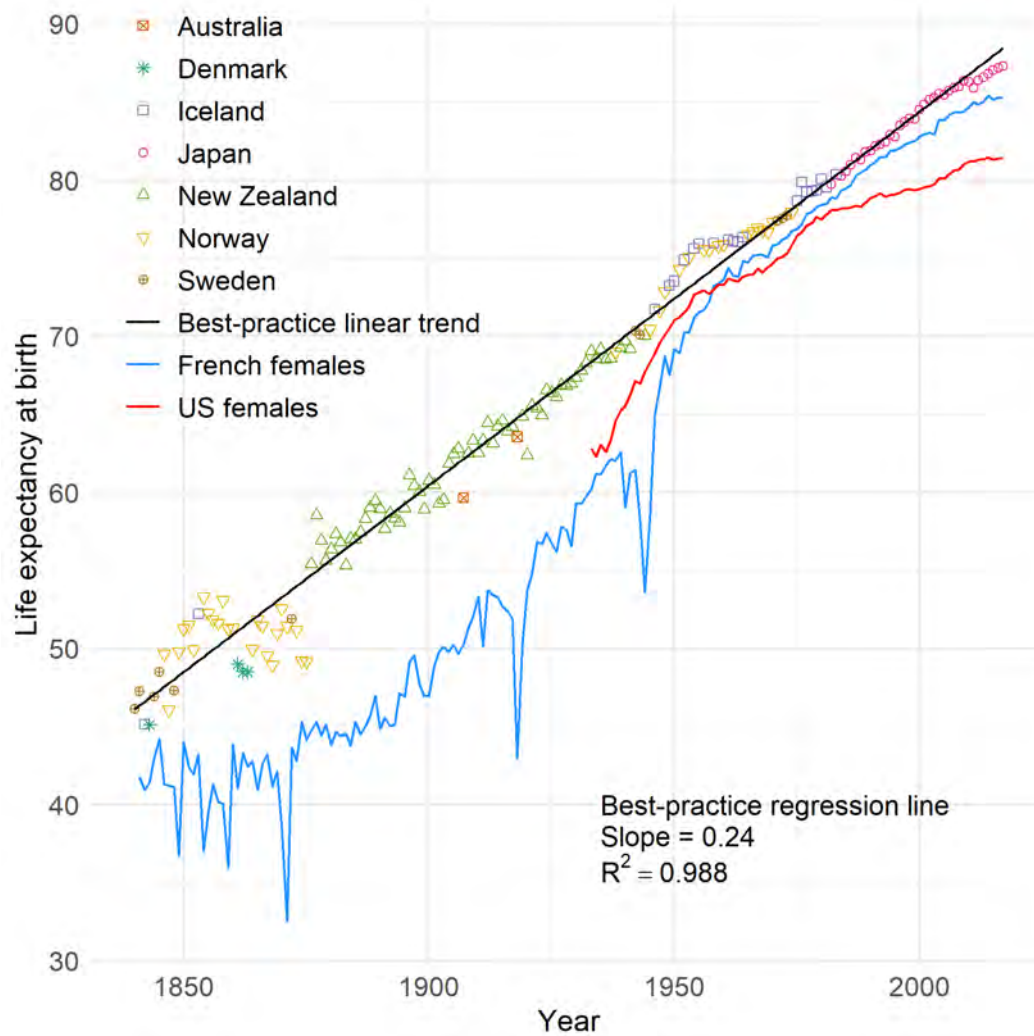
Note: Adapted from (30) using the most recent data from (17). In all cases, the values pertain to female life expectancy.

Studies of hunter-gatherers, people today who live more or less the way our ancestors lived thousands of years ago, provide evidence about the long-term history of human longevity. Various studies indicate a life expectancy at birth of less than 40 years for these populations (34). Studies of parish data from England over the period 1600 to 1725 show similarly short life expectancies (34) as do the data from Sweden from 1751 to the 1830s (17). 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 low, fluctuating life expectancies, until the life-expectancy revolution started around 1840, leading to life expectancies today of more than 80 in many countries (17, 30).

As life expectancy rose, lifespan equality—how similar lifespans are—increased in lockstep (34). Studying lifespan equality together with life expectancy is important, since lifespan equality is an indicator of population health inequality and of individual lifespan uncertainty (35). As lifespans became longer on average, they also became increasingly equal, something that has been found to hold in a lifespan continuum over millions of years of primate evolution, in many countries and between subgroups in a population (34). Figure 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 non-human primates (in purple). The relation between high life expectancy and lifespan equality has been attributed 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." (36, p.4) The measure of lifespan equality used in Fig. 3 is based on the concept of lifetable entropy, first developed by Leser (37) and further explored by Keyfitz (38) and Demetrius (39). Measures based on the coefficient of variation or the Gini coefficient yield the same lockstep pattern, and the change in life expectancy from one year to the next closely tracks the annual change in lifespan equality (40).

Figure 3

THE CONTINUUM OF LIFE EXPECTANCY AT BIRTH AND LIFESPAN EQUALITY IN HUMAN POPULATIONS
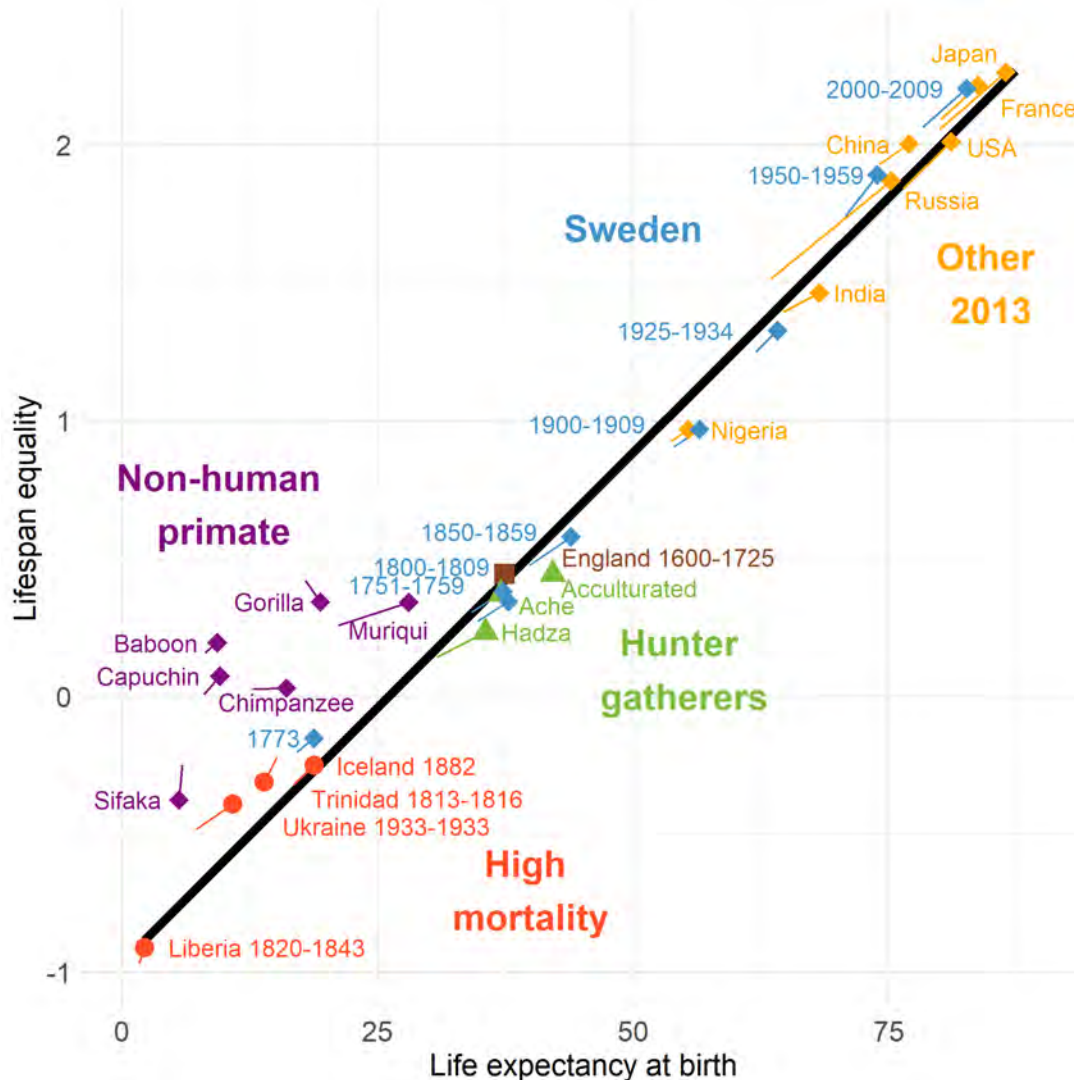
Note: Adapted from the original figure by Fernando Colchero in (34). Lifespan equality is measured by the logarithm of the inverse of lifetable entropy and defined as $h = \ln e_o - \ln e^{\dagger}$, where e_o is life expectancy at birth, and $e^{\dagger}$ is an indicator of lifespan disparity (34, 40). The length of the tadpoles represents the difference between females and males in the population, with the head being the females and the tale the males.

The increase in life expectancy in the countries doing best has been accompanied by an increase in maximum lifespan—the oldest age attained as verified by reliable data. Figure 4 shows a roughly linear rise of maximum lifespan

of about 1.5 months (0.12 years) per year, lower than the 3-month per year increase in maximum life expectancy, but still remarkable. The unbroken record of Jeanne Calment who died in 1997 is interpreted by some as the limit to human lifespan. However, such an interpretation is misleading. Between 1899 and 2014, the mean inter-record time was around 11.9 years, with three records lasting for more than 20 years (including Calment's) and the longest lasting record being a little over 52 years (41). A study by Lenart and colleagues (42) shows that there was only a 20.4% chance that Calment's record would have been broken between 1997 and 2017. Medford and Vaupel rather 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 years is still quite low when compared to the most durable record, which lasted 52 years" (41 p.6). The data in Fig. 4 (43) and ancillary data on exceptional lifespans (44) do not support the claim that the maximum attainable lifespan has been reached (7). This claim is also inconsistent with observed plateaus at a level of about 50%/year of the annual probability of death after age 105 in Italy (45) and after age 110 in a group of countries (44).

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? To understand this, it is helpful to distinguish three states of health: healthy, unhealthy and dead. It was feared that rescuing people from death would increase the number of unhealthy people. Studies have shown mixed results, depending on the measure of health, the population and the age-range studied, and the data used, with no definite answer to whether the extra years of life are being lived in good health (46). If "healthy" and "unhealthy" are determined by a person's ability to live independently and to manage the activities of daily living (ADL), mixed results are found across studies and populations (47, 48). If health is measured in terms of chronic diseases indicators, many chronic conditions and cognitive impairment tend to rise in the US and other countries (48). However, as we live longer, the onset of cognitive impairment and dementia is being postponed to older ages (49). Health can also be self-reported. Self-reported healthy life expectancy has generally been rising (47, 50, 51). So more people are healthy—and because of saving lives, more people are unhealthy. The balance may have remained roughly about the same. More people are taking medicine to reduce blood pressure, more people have pacemakers, and so on—these people are better off, alive rather than dead, but they are clinically ill.

Figure 4
LINEARLY INCREASING AGE OF THE WORLD'S OLDEST PERSON
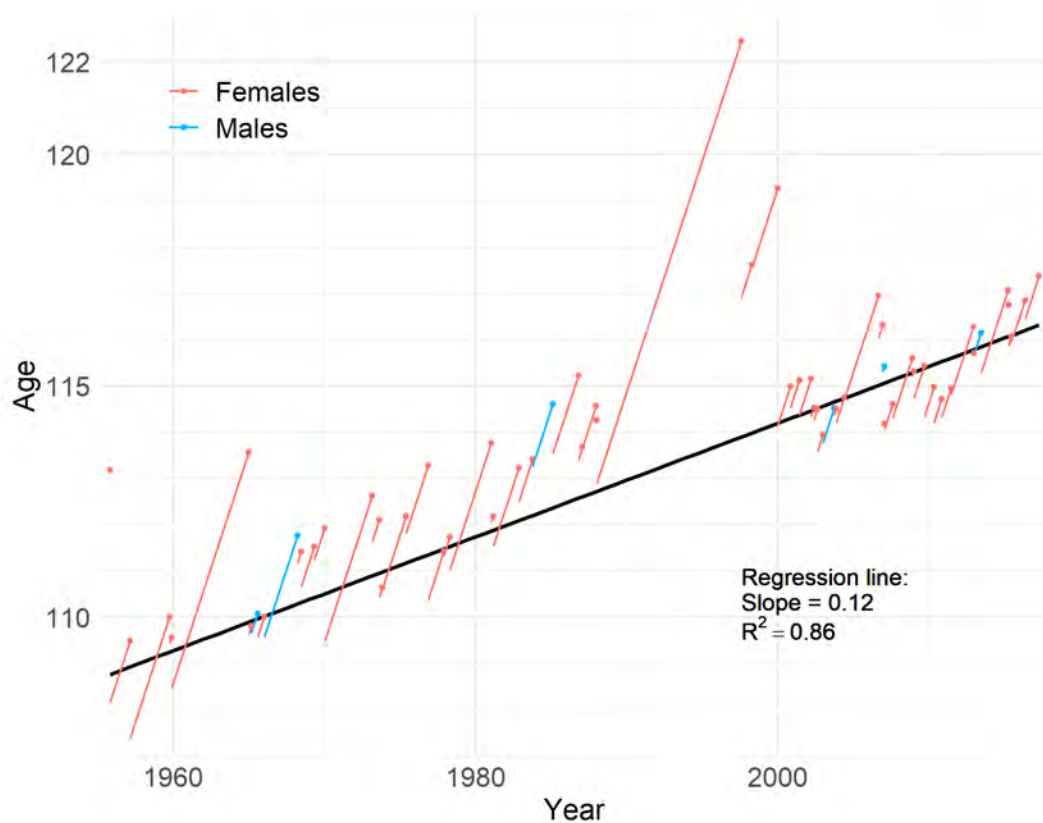
Note: Adapted from a figure by Jonas Schöley—inspired by a graph by Robert D. Young (http://www.grg.org/sc/graphs/wop2.png)—using data from (43). Additional studies on supercentenarians and the world´s oldest persons are found in (44).

Section 2: 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. Table 2 shows some illustrative results, assuming a pace of progress in life expectancy of 2 years per decade, representing the average of improvements for France, Japan, Sweden and US since the mid-20th century. This approach yield similar results to that of some earlier forecasts (47). As the table indicates, most children alive today in countries with high life expectancy will, if past progress continues, celebrate their 100th birthdays. Very long lives are the likely destiny of children alive today, provided life expectancy continues to increase at the historical pace of about two years per decade.

Table 2
OLDEST AGE AT WHICH AT LEAST 50% OF A BIRTH COHORT WILL STILL BE ALIVE

Year of birth	2000	2005	2010	2015
France	101	102	103	105
Japan	103	105	106	108
Sweden	100	101	102	103
USA	97	98	99	100

Note: Calculations by method similar to (47) using data from (17).

Among researchers who are willing to speculate about the future of life expectancy there are, broadly speaking, three views (52):

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 (10).
2. Others think that life expectancy will continue to rise and mortality to decline at historical pace for the next several decades and perhaps longer (53, 54).
3. Finally, some futurologists predict that life expectancy will rise substantially faster than this, because of major biomedical breakthroughs (55).

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, some strongly 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 (56)—might become the leader in the future. The causes of death against which progress has been made have shifted from infectious diseases to chronic diseases (57). Before 1950, the rise in life expectancy was largely fueled by reductions in infant, childhood and younger adult mortality. Today, the rise is largely attributable to declines in death rates after age 65 and especially after age 80, when most deaths now occur in the most developed countries (47, 58).

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.

- In the next decade or two, substantial progress might be made in reducing the incidence of cancer and in treating cancer. Various diseases, including cancer, multiple sclerosis and HIV, might be treated by enhanced immune therapies (59).

- There is evidence that over recent decades dementia has been postponed by roughly two to four years per decade (49) 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 (60). 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 find 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 (61, 62).

- Most significantly, research on the basic biology of aging might lead to interventions that slow down the rate of aging (63). For example, breakthroughs might be achieved such that it would take two years for a person to suffer the deterioration that older people currently experience in one year: That is, roughly speaking, it would take two years to grow one year 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 (31, 64). 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. As noted earlier, progress in increasing life expectancy since 1950 has resulted from a postponement of mortality, such that 70 and 80-year-olds have the mortality risk of people a decade younger half a century ago. 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.

Section 3: The Present and Future of Forecasting Longevity

Until recently, most forecasts of life expectancy were based on a judgment about the ultimate limit of life expectancy, which was assumed to be not much higher than current best-practice life expectancy (30, 33). 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. This strategy has consistently produced forecasts that are too low (30, 54, 65). Despite repeated failure, many mortality experts continue to use their judgments to make forecasts.

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 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" (66). Reasons why the future might be better or worse than the past or more uncertain can then be considered, but adjustments should be made with caution.

Many factors influence mortality, including economic, social and political conditions, 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. Using changes in risk factors and economic and epidemiological trends to help make forecasts is appealing, but difficult as their future values and their relationships with mortality and with each other are often imperfectly understood, making their use in forecasting problematic (54). Simple extrapolative approaches of past trends have generally been more compelling, given the historical regularities (54, 66). 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, the AIDS epidemic, etc. Health improvements in the future may be slowed by deleterious trends (obesity), but health improvements in the past also were 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.

Extrapolative methods are often being used to forecast life expectancy based on historical data on age-specific mortality. Lee, Alho and colleagues (65, 67) have pioneered 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. An array of somewhat similar methods has been developed (54, 68-70), with the most commonly known being the method developed by Lee and Carter in 1992 (67). These methods generally assume that 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 based on a similar approach of that of Lee and Carter, but using the age-distributions of deaths rather than death rates have been shown to reduce forecast bias by allowing the pace of mortality decline to accelerate over time (71). A direct approach is to forecast life expectancy by extrapolating historical data on life expectancy (30). Some pioneering research has been done on this approach that takes advantage of the remarkable regularity of time trends in best-practice life expectancy (53, 72). 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 (73).
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 (68, 71, 72), generally assuming that population-specific life expectancies are converging toward an average or toward best-practice.

Figure 5 shows forecasts of life expectancy for total populations (females and males combined) in France, Japan, Sweden and the United States up until 2070, using six methods: 1) the Lee-Carter approach (67) and 2) its coherent version based on the work of Li and Lee assuming that population-specific trends are converging towards an average (68); 3) forecasts based on the extrapolation of death distributions, a method known as Compositional Data Analysis (CoDA), and 4) its coherent version assuming that population-specific trends are converging toward an average (71); 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 (72).

In addition, Fig. 5 shows the official national forecasts for each selected country (74-77). The methods and assumptions between country vary (78). For example, Japan official forecast is based on a Lee-Carter model, 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 (76). Sweden also uses a variant of the Lee-Carter model for their forecasts (75). The official forecasts for France are based on a mixture of expert opinions and extrapolation (77). For the United States, ultimate average annual percentage reduction in mortality 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 towards the ultimate annual percentage reductions assumed by 2043 (74). The official forecasts are generally lower (except for France) than the extrapolative approaches presented in Fig. 5, either because of their 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 3 for both sexes. The 95% prediction intervals widen over time and overlap. The methods produce different forecasts and prediction intervals. The range of forecast values reflects the uncertainty about future life expectancy trends. Assessing which models produce the most accurate forecast is of importance, but the best performing model varies across populations and time periods. Knowing if progress in mortality at older ages, where most deaths occur, will stay constant or will be accelerating is of crucial importance in selecting the appropriate forecast model. Note that the linear best-practice life expectancy trend from 1840 to 2017 rises close to 100 by 2070.

Figure 5
LIFE EXPECTANCY AT BIRTH, HISTORICAL LEVELS AND FORECASTS 2018-2070
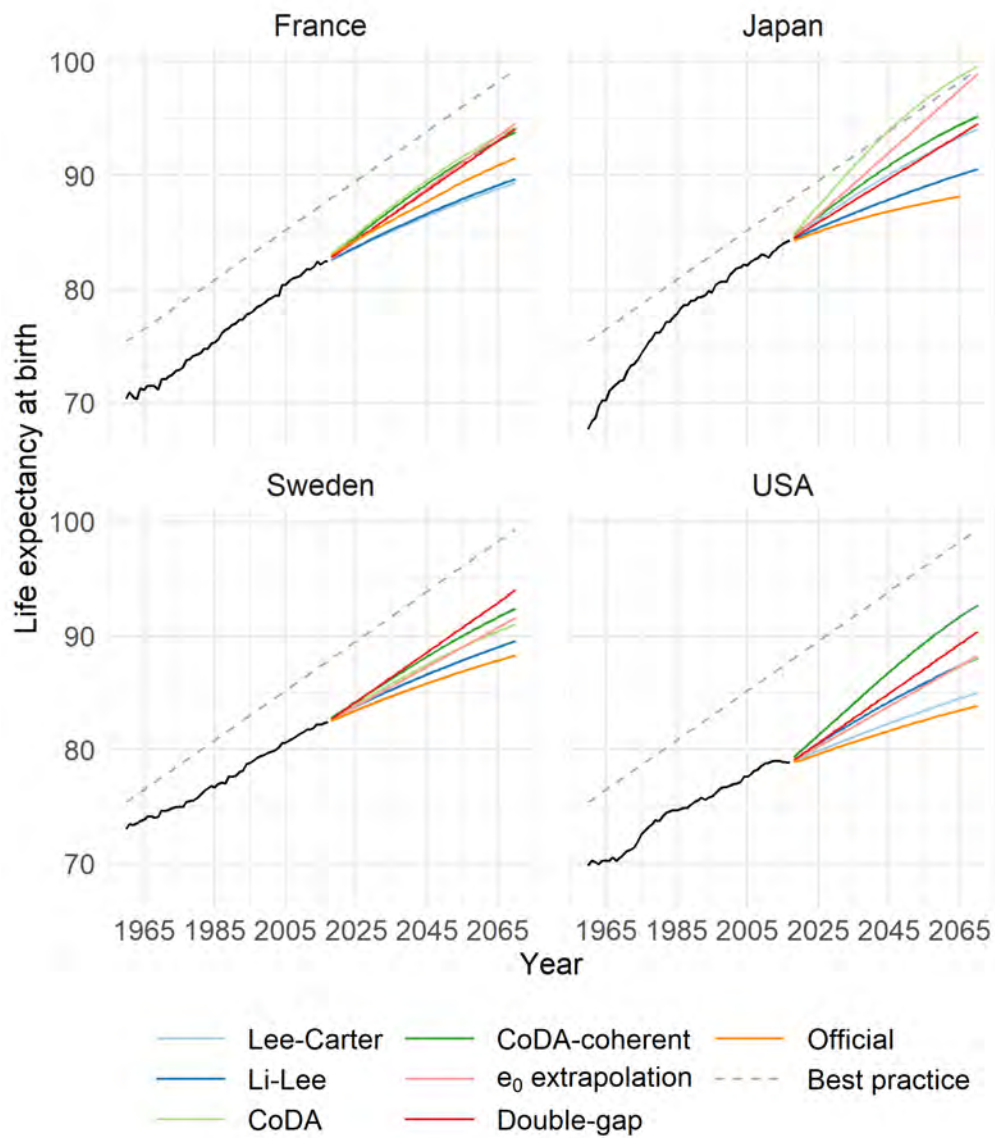
Note: The linear trend in best-practice life expectancy is shown as a dashed line. The best-practice estimates for 2018-2070 are extrapolations of the 1840-2016 linear trend. Forecasts for the period 2018-2070 with time-series data for 1960-2017 from (17). Forecasts and prediction intervals (see Table 3) are computed using six models (67, 68, 71, 72) or extracted from official national forecast (74-77).

Table 3
FORECASTS OF LIFE EXPECTANCY AT BIRTH WITH PREDICTION INTERVALS, 2050 AND 2070

		Lee-Carter	Li-Lee	CoDA	CoDA-coherent	e_o 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)	91.4* (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
USA								
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)	94.2 (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
USA								
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)

* The official population forecast for Japan ends in 2065.

Note: Forecasts for the period in 2050 and 2070 with time-series data for 1960-2017 from (17). Forecasts and prediction intervals are computed using six models (67, 68, 71, 72) or extracted from official national forecast (74-77).

Other strategies than those presented in Fig. 5 and Table 3 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? (79, 80).

- 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?

- 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 (81).

- Populations are heterogeneous. The frail tend to die first. This is related to tempo effects on mortality (82). Some innovative research suggests that it might be feasible to model heterogeneity in forecasting models (83).

- 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.

- Other possible methods for mortality forecasting also could be developed, including microsimulation (84) and Bayesian population projections (85).

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 (86).

The on-going and unprecedented rise of longevity over the past two centuries is so remarkable that the future of longevity may be rich in similarly outstanding developments (9). The future will almost certainly be surprising, but it might be possible to anticipate some 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.

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