ELSEVIER

Experimental Gerontology 35 (2000) 1111–1129

Experimental Gerontology

www.elsevier.nl/locate/expgero

Demography of longevity: past, present, and future trends

J.R. Wilmoth*

Department of Demography, University of California, 2232 Piedmont Avenue, Berkeley, CA 947202120, USA

Received 9 May 2000; received in revised form 17 August 2000; accepted 17 August 2000

Abstract

Life expectancy at birth has roughly tripled over the course of human history. Early gains were due to a general improvement in living standards and organized efforts to control the spread of infectious disease. Reductions in infant and child mortality in the late 19th and early 20th century led to a rapid increase in life expectancy at birth. Since 1970, the main factor driving continued gains in life expectancy in industrialized countries is a reduction in death rates among the elderly. In particular, death rates due to cardiovascular disease and cancer have declined in recent decades thanks to a variety of factors, including successful medical intervention. Based on available demographic evidence, the human life span shows no sign of approaching a fixed limit imposed by biology or other factors. Rather, both the average and the maximum human life span have increased steadily over time for more than a century. The complexity and historical stability of these changes suggest that the most reliable method of predicting the future is merely to extrapolate past trends. Such methods suggest that life expectancy at birth in industrialized countries will be about 85–87 years at the middle of the 21st century. © 2000 Elsevier Science Inc. All rights reserved.

Keywords: Human mortality; Longevity; Life expectancy; Life span; Mortality forecasts

---

Medical science has two fundamental purposes: to sustain life and to relieve suffering. If doctors are successful in their attempts to sustain life, the net effect is an increase in human longevity, achieved through the direct or indirect manipulation of otherwise “natural” processes. Obviously, human longevity is not only the concern of medical doctors. It has also been part of philosophy and literature since ancient times, and it is today the active concern of public health professionals (some of whom are medical doctors), of life insurance actuaries and other financial interests, and of demographers and other social scientists.

---

* Tel.: +1-5106429688; fax: +1-5106438558.
E-mail address: jrw@demog.berkeley.edu (J.R. Wilmoth).

PII: S0531-5565(00)00194-7

Demographers are interested in predicting the future course of population trends, including longevity, motivated both by a fundamental intellectual interest and by the necessities of social and fiscal planning. Although demographic science does not really allow us to predict the future, it does provide tools for extrapolating past trends in order to create more or less plausible scenarios of what the future might be like. Obviously, an actual prediction is more than a mere extrapolation of trends and is impossible to falsify except over time. For this reason prediction is legitimately the province of fortune tellers and policy analysts, not scientists. However, someone has to walk the line between science and policy, and demographers have made a point of inserting themselves into this niche.

In terms of fiscal planning, the main issue is the enormous cost of social security systems. Such systems may be defined to include old-age pensions, disability and survivorship benefits, and medical care for the aged. The cost of such programs is increasing very rapidly because of both population aging and the escalating costs of medical care, especially for the aged. Longer life is connected to medical costs in complicated ways. Obviously, when there are more old people, total medical costs will tend to be higher per capita. But with increasing longevity, survivors at any age may be more or less healthy on average than in the past. Thus, the effect of population aging on medical services may be magnified or attenuated by trends in morbidity and disability.

From a demographic point of view, there are two main questions about trends in mortality and health. First, how long do people live, why is longevity increasing, and how long will we live in the future? Second, given that we are living longer, are we mostly gaining healthy years of life, or are we “living longer but doing worse”? We know a lot more about the first question. For any organism, death is much easier to define and to measure than functional status. In the United States, we have health interview surveys since the late 1950s and a consistent series of direct measurements of health status since the 1970s, in both cases for a representative sample of the national population.[1]

On the other hand, we have detailed mortality data from many countries over much longer time periods. These data often include information on attributed cause of death, although this concept too is difficult to define and measure in a consistent fashion. There have even been some attempts to measure prehistoric human longevity based on skeletal remains (Acsádi and Nemeskéri, 1970). The most useful information on historical human mortality trends is derived from series of national data, collected since 1750 in some parts of Europe. The accuracy of data from such sources is variable, but we think we know which data are reliable or not. Ideally, we use cause-of-death data with great caution. Although some trends seem irrefutable (e.g. the decline of infectious disease), others appear contaminated by changes in diagnostic procedures and reporting practices (e.g. cancer trends, especially at older ages).

This paper will report on the demography of human longevity in the past, present, and future. It will not address the issue of “healthy life span”, although the interested reader can refer to other sources on this topic (Robine et al., 1996; Crimmins et al., 1997).

---

[1] The National Health Interview Survey began in 1957 and contains information on health status from individual self-evaluations. The National Health and Nutrition Examination Survey began in the early 1970s and provides information on the health and nutritional status of individuals based on direct measurement.

1. Human longevity in the past and present

1.1. Prehistoric estimates

We do not know much about how long humans lived before 1750. Around that time, the first national population data began being collected in Sweden and Finland. For earlier eras, we have some life tables constructed for municipal populations, members of the nobility, and other groups that were probably not representative of the national population at large (e.g. Lee et al., 1993; Hollingsworth, 1977). After 1750 and even today, we have extensive and highly reliable mortality information for only a subset of national populations.

For the Middle Ages and before, mortality levels have been estimated based on data gleaned from tombstone inscriptions, genealogical records, and skeletal remains (Acsádi and Nemeskéri, 1970). The accuracy of such estimates has been a subject of dispute (Johannson and Horowitz, 1986; Paine, 1989; Sattenspiel and Harpending, 1983; Wood et al., 1992). In studies based on skeletal remains, a key issue is the attribution of age based on bone fragments. Another problem for estimation based on either skeletal or tombstone data is uncertainty about the age structure of the population, which affects mortality estimates based solely on the distribution of ages at death. The only practical solution is to assume that the population was "stationary," implying a long-term zero growth rate and unchanging levels of fertility and mortality, and even an unchanging age pattern of mortality. Clearly, these assumptions are always violated, but whether that completely invalidates the estimation is another question.

For mortality data derived from sub-populations, there is also the issue of whether the data are representative of some larger population. Who gets buried in a society, and who gets a tombstone? Which societies have regular burial practices, as opposed to, say, burning their dead? What kinds of populations have complete genealogical records from a particular time period?

Thus, all estimates of mortality or longevity from the pre-industrial period (roughly, before 1750) should be viewed with caution. Of the many sources of bias in these estimates, there are both positive and negative factors, which tend to balance each other to some extent (Wilmoth, 1995). They are inaccurate and/or unrepresentative by amounts that cannot be well quantified. Although our estimates of early life expectancy may be either too high or too low, they give us nonetheless a general view of how far we have progressed historically in terms of longevity.

Early estimates of human longevity suggest that life expectancy at birth (or $\mathring{e}_0$, in the notation of demographers and actuaries) was probably in the 20s. Some very disadvantaged societies might have had life expectancies in their teens, whereas others may have been in their 30s. Since historical levels of life expectancy were in the 20s, compared to around 75–80 years today in wealthy countries, the average length of life has roughly tripled.

Most of this increase was due to the reduction of infant and child mortality. It used to be the case, for example, that remaining life expectancy at age 1 was greater than at birth, because the toll of infant mortality was so high. The difference between pre-modern periods and now is less stark if we consider life expectancy at higher ages. Instead of

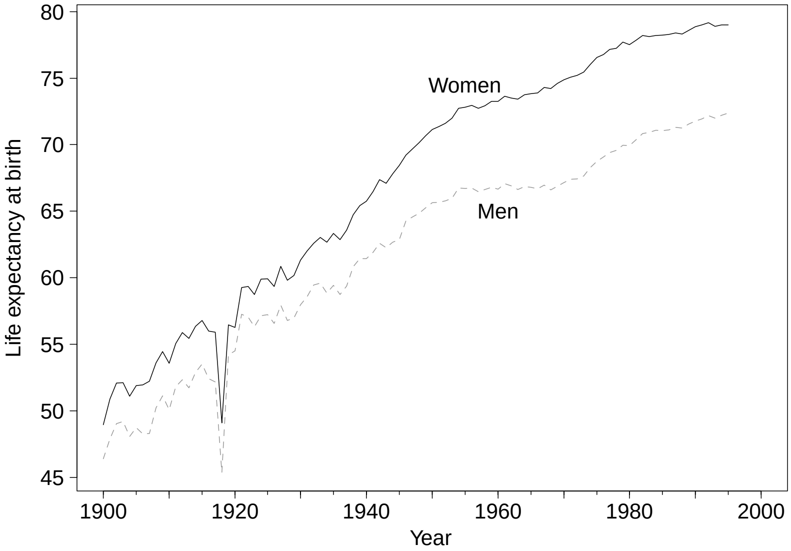


Fig. 1. Life expectancy at birth, United States, men and women, 1900–1995. Source: Social Security Administration (Bell et al., 1992; updated data available through the Berkeley Mortality Database http://demog.berkeley.edu/wilmoth/mortality).

the tripling of life expectancy at birth, remaining life expectancy at higher ages has roughly doubled over the course of human history. At age 10, for example, life expectancy (i.e. expected years after age 10) may have moved from the around 30–33 years to almost 70 years (Thatcher, 1980). At age 50, it may have gone from around 14 years to more than 30 years (Wilmoth, 1995).

1.2. Epidemiological transition

The epidemiological transition is the most important historical change affecting the level and pattern of human mortality. The transition refers to the decline of acute infectious disease and the rise of chronic degenerative disease (Omran, 1971). This shift does not imply that degenerative diseases became more common for individuals of a given age. It merely means that infectious disease nearly disappeared, so something else had to take its place. Increasingly, people survived through infancy and childhood, without succumbing to infectious disease (Preston and Haines, 1991). Once past these critical early years, survival to advanced ages is much more likely, and at older ages various degenerative diseases present mortality risks even when infection is well controlled. Thus, heart disease, cancer, and stroke became the most common causes of death in industrialized societies, as the age distribution of deaths shifted to older ages.

1.2.1. Trends in life expectancy

Life expectancy has been increasing not just in industrialized societies but around the world.[2] The rise in life expectancy at birth probably began before the industrial era, before national mortality statistics were first assembled in Sweden around 1750. As noted earlier, $\mathring{e}_0$ was probably in the 20s during the Middle Ages and earlier. By 1750 Sweden (and probably other parts of northwestern Europe) had attained an $\mathring{e}_0$ of 38, so the upward trend in longevity appears to have begun before the industrial era. Over the next century or more, there was a slow and irregular increase in life expectancy. After about 1870, however, the increase became stable and more rapid. During the first half of the 20th century, life expectancy in industrialized countries rose quite rapidly. More recently, the rise in life expectancy has slowed down, as seen in Fig. 1 for the United States.

The cause of the earlier rapid rise life expectancy and its subsequent deceleration is quite simple: the decline of juvenile mortality to historically very low levels. By around 1950, infant mortality in wealthy countries was in the range of 2–3% or births, compared to perhaps 20–30% historically. Since then, infant mortality has continued to decline and is now in the range of 0.5–1% of births in the healthiest parts of the world. As babies were saved from infectious disease, their chances of survival to old age were considerably improved. Once juvenile mortality was reduced substantially, improvements in life expectancy due to the reduction of mortality in this age range had to slow down, and further gains had to come mostly from mortality reductions at older ages.

The rise in life expectancy during the second half of the twentieth century was slower than during the first half simply because it depended on the reduction of death rates at older ages, rather than in infancy and childhood. Put simply, saving an infant or child from infectious disease, who then goes on to live to age 70, gains more in average life span than saving a 70 year old from heart disease, who may live another 10 years. Thus, the deceleration in the historical rise in life expectancy is a product of the J-shaped age pattern of human mortality: high in infancy and childhood, low through adolescence and early adulthood, then rising almost exponentially after age 30. Gains in $\mathring{e}_0$ that come from reducing juvenile mortality are quite large, whereas gains due to a reduction in old-age mortality are inevitably much smaller.

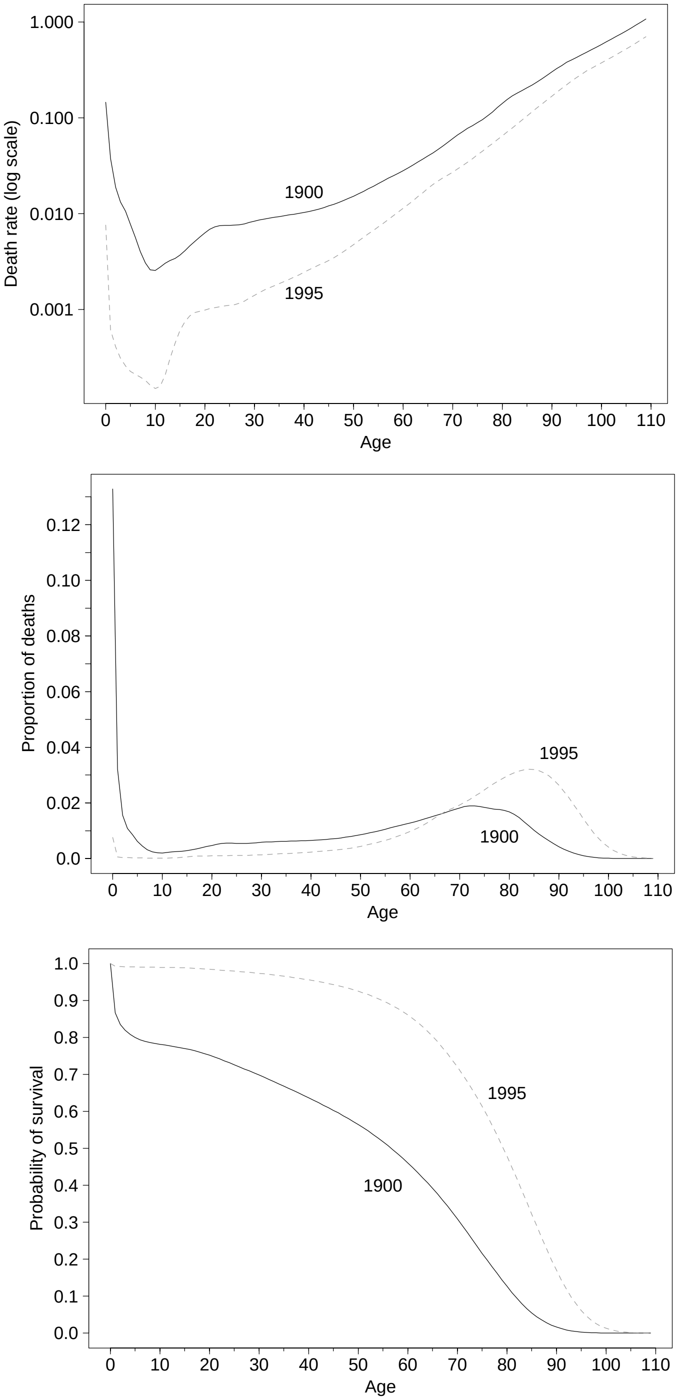
A common mistake is to assert that the deceleration in the rise of $\mathring{e}_0$ reflects a slowdown in progress against mortality. In fact, the reduction of death rates has changed its character in recent decades, but it has not slowed down. At older ages the decline of mortality has accelerated since around 1970 (as discussed later). So long as the decline of old age mortality continues, life expectancy will continue to increase, driven now by the extension of life at later ages rather than by saving juveniles from premature death.

1.2.2. Rectangularization

The age pattern of human mortality can be characterized in various ways. Fig. 2 shows the mortality of American women in 1900 and 1995 from three perspectives. The first panel shows death rates by age. These death rates are used to construct a life table, which describes the experience of a hypothetical cohort subject throughout its life to the death

---

[2] During the 1990s the two major exceptions to the worldwide increase in life expectancy were a stagnation and even reversal of earlier progress in parts of Africa, due to the AIDS epidemic, and in parts of the former Soviet bloc (especially Russia) due to social disruptions and instability.


Death rate (log scale)
1.000
0.100
0.010
0.001
1900
1995
0 10 20 30 40 50 60 70 80 90 100 110
Age
Proportion of deaths
0.12
0.10
0.08
0.06
0.04
0.02
0.0
1995
1900
0 10 20 30 40 50 60 70 80 90 100 110
Age
Probability of survival
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
1995
1900
0 10 20 30 40 50 60 70 80 90 100 110
Age

rates of a given year. Thus, the middle and last panels show the distribution of deaths and the proportion of survivors at each age among members of such a hypothetical cohort.

Together, these three panels illustrate some major features of the mortality decline that has taken place over this time interval. First, death rates have fallen across the age range, but they have fallen most sharply (in relative terms, since the graph has a semi-logarithmic scale) at younger ages. The distribution of ages at death has shifted to the right and become much more compressed. At the same time, the survival curve has shifted to the right and become more "rectangular" in shape. This last change is often referred to as the "rectangularization" of the human survival curve.

It was once asserted that this process of rectangularization reflected the existence of biological limits affecting human longevity (Fries, 1980). This notion of limits to the human life span enjoys little empirical support, as discussed below. Nevertheless, the historical process of rectangularization was both real and extremely significant. It is perhaps best thought of as a "compression of mortality," as documented in the middle panel of Fig. 2. As the average level of longevity has increased, so has our certainty about the timing of death.

One measure of this variability is the interquartile range of deaths in the life table, or the age span of the middle 50% of deaths over the life course. In the 1750s in Sweden, the life table interquartile range was about 65 years, so that deaths were spread out widely across the age range. The distribution of age at death became more and more compressed over the next two centuries, until the life table interquartile range was around 15 years in industrialized countries by the 1950s. Since 1960, there has been little further reduction in the variability of age at death in the developed world, even though the average age at death (as reflected in life expectancy at birth) has continued to increase (Wilmoth and Horiuchi, 1999).

Like the rise of life expectancy, this compression of mortality has been due largely to the reduction of juvenile mortality. Once most juveniles were saved from premature death, a pattern emerged in which deaths are concentrated in the older age ranges. As mortality falls today among the elderly, the distribution of ages at death continues to rise but is no longer becoming more compressed.

1.3. Mortality decline among the elderly

The most significant trend now affecting longevity in industrialized societies is the decline of death rates among the elderly. Until the late 1960s, death rates at older ages had declined slowly, if at all. Traditionally, rates of mortality decline were much higher at younger than at older ages. Since about 1970, however, there has been an "aging of mortality decline," meaning that some of the most rapid declines in death rates are now occurring at older ages (Wilmoth, 1997; Horiuchi and Wilmoth, 1995). Thus, the decade of the 1960s marks a turning point, from an earlier era of longevity increase due primarily to the decline of acute infectious disease among juveniles, to a more recent era involving the decline of chronic degenerative disease among the elderly.

Fig. 2. Age pattern of mortality from three perspectives, United States, women, 1900 and 1995. (a) Observed death rates by age. (b) Distribution of deaths by age (in a life table). (c) Proportion surviving by age (in a life table). Source: see source for Fig. 1.

1.3.1. Cardiovascular disease

The most significant component of the mortality decline at older ages is the reduction of death rates due to cardiovascular disease (CVD), including both heart disease and stroke. In the United States, heart disease has been the leading cause of death since 1921, and stroke has been the third most common cause since 1938. From 1950 to 1996, age-adjusted death rates for these two causes declined by more than half (by 56% for heart disease, and by 70% for stroke). It is estimated that 73% of the decline in total death rates over this time period was due to this reduction in CVD mortality (Centers for Disease Control, 1999).

The exact cause of the decline in CVD mortality is open to debate, although it is surely due to a combination of factors. For the United States, all of the following have been cited as factors contributing to this decline: (1) a decline in cigarette smoking among adults; (2) a decrease in mean blood pressure levels; (3) increasing control of hypertension through treatment;(4) changes in diet, especially a reduction in the consumption of saturated fat and cholesterol; (5) improvements in medical care, including better diagnosis and treatment of heart disease and stroke, the development of effective medications for treatment of hypertension and hypercholesterolemia, and an increase in coronary-care units and in emergency medical services for heart disease and stroke (Centers for Disease Control, 1999).

The rapid decline in CVD mortality began around 1968 in the United States and other industrialized nations. Given the precipitous nature of this decline, it has been argued that therapeutic interventions were the most important factor, since changes in diet and lifestyle should have led to a more gradual pattern of change (Crimmins, 1981). It is worth noting that landmark investigations, like the Framingham Heart Study, began in the late 1940s and began to provide significant breakthroughs in our scientific understanding of CVD during the 1960s (National Heart, Lung, and Blood Institute, 2000).

1.3.2. Cancer

In most developed countries, cancer mortality has begun to decline only within the last 10–15 years, although in the Japan death rates from cancer began falling as early as the 1960s (Cole and Rodu, 1996; Levi et al., 1997; Gersten and Wilmoth, 2000). Of course, cancer takes many different forms, and trends vary greatly by site of the primary tumor. Lung cancer has become more common due to increased smoking habits, while stomach cancer has been in decline. Among women, mortality due to cervical cancer has fallen dramatically thanks to successful medical intervention (screening and early treatment), while breast cancer has been on the rise due apparently to a number of interrelated factors (lower and later fertility, changes in diet, and possibly other factors as well).

It is sometimes overlooked that some common forms of cancer may be caused by infection. For example, stomach cancer is often brought on by infection with *Helicobacter pylori*. Infection with *H. pylori*, and hence stomach cancer, was especially common in Japan prior to the widespread availability of refrigeration (Asaka et al., 1997; Replogle et al., 1996). Liver cancer is related to hepatitis infection (both the B and C strains of the virus), and thus reductions in liver cancer hinge on the control of infection, as well as curbing excess drinking. A third example is infection by the human papilloma virus, which can cause cervical cancer (World Health Organization, 1996).

These three forms of cancer have tended to decline in recent decades and should decline further as the relevant infectious agents are brought under control (e.g. hepatitis B and C). On the other hand, cancers that have become more common include those strongly influenced by individual behaviors (e.g. lung and pancreatic cancer are linked to smoking, and both have tended to increase over time) and some others whose causes are mysterious or poorly understood (e.g. breast cancer and colorectal cancer, both rising but for unknown or uncertain reasons).

As noted earlier, trends in mortality among the elderly are the main factor behind the continued increase in life expectancy in developed countries. Furthermore, the main components of mortality at these ages are CVD and cancer. These two causes have been in decline during recent decades for reasons that are complex and not entirely understood. It is clear that there are multiple causes involved in bringing down death rates due to CVD and cancer. Medical science has played a part, but so have changes in diet and personal habits, as well as community efforts and economic changes that have reduced the spread of infectious agents. It is important to keep this complex causality in mind when speculating about future trends in human mortality.

2. Outlooks for the future

It is impossible to make a firm scientific statement about what will happen in the future. As scientists, demographers can only present the details of well-specified scenarios, which serve as forecasts or projections of the future. They may also help by clearly defining the terms of the debate — for example, by discussing what is meant by the notion of "limits to life span." Limits possibly affecting the increase of human longevity are the first topic of this section, followed by a discussion of extrapolative techniques of mortality projection or forecasting. Our discussion of the future of mortality concludes with a comparison of "optimistic" and "pessimistic" points of view on this topic.

2.1. Limits to the human life span

If there are limits to the human life span, what do they look like? There are two ways to define such limits: maximum *average* life span and maximum *individual* life span (Wilmoth, 1997).

2.1.1. Maximum average life span

Let us consider whether there might be an upper limit to the average life span that could be achieved by a large human population. Average life span, or life expectancy at birth, refers to how long people live on average in a population. In the United States life expectancy is currently around 74 for men and 79 for women (Population Reference Bureau, 1999). Accordingly, these numbers describe the average length of life that can be anticipated given the mortality conditions of today. For example, baby boys born this year will live an average of 74 years, assuming that death rates do not change in the future. Just as occurs today, some of these newborns will die in infancy from congenital ailments, some will be killed in car accidents as young adults, and some will succumb in old age to cancer or heart disease.

As noted earlier, death rates have been falling for several centuries. At every age the risk or probability of dying is much lower than in the past. Thus, when we talk about life expectancy at birth, we are being conservative and asking what the average life span will be assuming that death rates do not fall any further in the future. However, it is likely that death rates will continue to decline at least somewhat in future years, so baby boys born today in the US will probably live longer than 74 years on average.

The question about limits to the average life span can be posed as follows: Can death rates keep falling forever, or will they hit some fixed lower bound? Perhaps biological forces impose a certain inevitable risk of mortality at every age. Thus, there might be some age-specific minimum risk of dying that could never be eliminated (Wilmoth, 1997).

On the other hand, perhaps death rates will keep falling until they hit zero at some ages. Zero death rates at some ages will not make us immortal, however. Immortality would be achieved only if the risk of dying fell to zero at every age, and most people have trouble accepting the notion of a zero death rate at even a single age. In this regard, it is worth noting that no 8-year-old girl died in the entire country of Sweden during the twelve months of 1994. Thus, for that year in Sweden the observed female death rate at age 8 was zero. Of course, this would be hard to maintain for several years, and even harder to maintain forever. Moreover, we should remember that Sweden is a relatively small country with a population of around 9 million. In a sufficiently large population, it seems likely that some unfortunate individual will die at every age in any given year, and thus the notion of a true underlying zero death rate at any age seems implausible. Therefore, in the discussion that follows, we refer always to the underlying death rate, or the long-term average death rate for a large population.

Even if such death rates cannot equal zero, can they keep declining toward zero? In other words, zero might be the limit to how far death rates can drop, even if death rates can never attain zero. Or is there a higher limit? Perhaps there is some number, like one in a million, such that it is simply inevitable that one in a million people — say, one in a million 50-year-olds — will succumb to death over the course of a year. If true, then the death rate at age 50 can never fall below one in a million. According to this view, we have a limited capability as a society, or as a species: we cannot push the risk of death any lower than some fixed level.

If a non-zero lower limit for death rates exists, how much is it at age 50 or at any age? If we know the lower limit for death rates at every age, we can compute the maximum life expectancy at birth. In this way we would know the upper limit of the *average* human life span. It may seem implausible that there exists a non-zero lower bound on death rates. Yet, if there is no lower limit to death rates except zero, then there is no upper limit to life expectancy except infinity. The absence of such limits, however, does not mean that large increases in average life span are imminent. It just means that life expectancy *can* continue to increase, as death rates are pushed down further and further.

Why do some people think that an upper limit to life expectancy exists? In fact, there is little empirical support for such a belief. An argument frequently put forward is that life expectancy at birth seems to be reaching a plateau. As shown earlier, however, the deceleration in the rise of life expectancy at birth results merely from a shift in the main source of the historical mortality decline from younger to older ages. Although the rise in life expectancy has decelerated, the decline in death rates at older ages has accelerated in recent decades (Kannisto et al., 1994).

Furthermore, if death rates are approaching their lower limit, one might expect a positive correlation between the current level of mortality in a given country and the speed mortality decline (so that those populations with the lowest level of mortality would also experience the slowest rates of mortality decline). In fact, no such correlation exists for death rates at older ages. In some cases the fastest reduction in death rates is occurring in those countries with the lowest levels of old-age mortality, just the opposite of what we would expect if death rates were pushing against a fixed lower bound (Kannisto et al., 1994).

So long as death rates at older ages keep falling, life expectancy (at birth or at any age) will continue to increase. As discussed below, current forecasts suggest that life expectancy at birth may rise only a few years above current levels over the next half century. Nevertheless, there is simply no demographic evidence that life expectancy is approaching a fixed upper limit. Certainly, such a limit may exist, but it is nowhere in sight at the present time (Wilmoth, 1997).

2.1.2. Maximum individual life span

Limits to average life span, or life expectancy at birth, are one issue. Often when people talk about limits to the human life span, however, they have another idea in mind. There is also an issue of limits to an individual's life span. Instead of asking, "How long can we live on average?", we might ask, "How long can any one lucky individual live?" This concept is actually much easier to understand than the notion of an upper limit to life expectancy.

Who is the oldest person who has ever lived? Even if we can never have a definitive answer to this question, we can at least imagine the existence of such a person. Maybe he or she (probably she) is still alive today. Or maybe she lived hundreds of years ago but vanished without leaving a trace–no birth certificate, no census record, and not even a newspaper article about her incredible feat of longevity.

Who is the oldest person alive today? That person might or might not be the oldest person ever. However, identifying the world's oldest person is very difficult even today, because of the widespread practice of what demographers politely call "age misstatement" (Myers and Manton, 1983). Putting it less politely, some people lie about their age. Others, if asked, give the wrong age because they do not remember, because they are not numerate, or because they simply never paid attention to such matters. Such age misstatement often occurs in the absence of written records to prove or disprove the reported age.

Should we believe people who claim to be extremely old, but without proper documentation? Certainly, we should believe them, since there is no point in calling anyone a liar, or questioning their memory. In terms of a scientific discussion about longevity, however, experts on this subject agree that it is best to ignore undocumented cases of extreme longevity. Thus, when we make statements about who is the oldest person alive today or in the past, we limit ourselves to cases where solid evidence exists (Jeune and Vaupel, 1999).

To be accepted as a valid instance of extreme longevity, thorough documentation is required — not just a birth certificate, but a series of documents and a life history that is consistent with the written records. Ideally, if the person is still living and mentally able, an oral history is obtained and checked against all available evidence, making sure, for example, that this person is not the son or daughter of the person in question.

Indeed, there are numerous examples of supposed extreme longevity that turned out to be cases of mistaken identity (Jeune and Vaupel, 1999). Perhaps the most notorious example was a French Canadian named Pierre Joubert, who was supposed to have died at the age of 113 years in 1814. This case was listed for many years by the *Guinness Book of World Records* (McWhirter, 1995). When genealogical records were examined closely, however, two men named Pierre Joubert were identified — a father and his son. It was the son who died in 1814, 113 years after the birth of the father (Charbonneau, 1990). Such mistakes are not uncommon, and whether they are the result of deliberate misrepresentation or honest error is irrelevant. In either case a complete investigation should be required before accepting such reports as factual.

At present, there is a report of a woman named Eva Morris living in the United Kingdom who is now 114 years old. This case is apparently quite well documented, though I have not checked it out closely myself (Louis Epstein, personal communication, 5/1/00).

The historical record is held by a Frenchwoman, Jeanne Calment, who died at age 122 in August of 1997 (Robine and Allard, 1995, 1999). Madame Calment lived in Arles, France, a town with very complete civil records (births, deaths, marriages, baptisms, etc.) going back several centuries. Fortunately, these records were not destroyed in any war, so it has been possible to trace the life of Jeanne Calment very closely. It was also possible to reconstruct her family genealogy and to document that a disproportionate number of her ancestors were long-lived as well. Of course, it is only one example, but the case of Jeanne Calment suggests that extreme longevity may have at least some hereditary component (Robine and Allard, 1998).

The oldest man whose age was thoroughly verified was Christian Mortensen, who died in 1998 at the age of 115 (Wilmoth et al., 1996; Skytthe et al., 1999). A Japanese man named Shigechiyo Izumi was reportedly 120 years old when he died in 1986. According to the Guinness Book of World Records, Izumi is still the oldest man on record (McWhirter, 1995). However, this case has now been rejected by almost all experts who are familiar with it, including the Japanese man who originally brought it to the attention of Guinness (Wilmoth and Lundström, 1996; Matsuzaki, 1988; Kannisto and Thatcher, 1993), and the common belief is that Izumi was in fact “only” 105 years old at the time of his death.

It is reasonable to ask what we have learned in general from these few cases of exceptionally long-lived individuals. In one sense, the cases of Calment and Mortensen tell us nothing about the trend in maximum longevity. Maybe these are just two cases that we have had the good fortune of documenting in recent years. Maybe there were other individuals who were just as old as Calment or Mortensen who lived years ago, and we missed them. These are valid points, so we must turn to other evidence if we want to know about trends in extreme longevity.

In order to study historical trends in extreme longevity, we need a well-defined population with reliable records over a long period of time. For that purpose, we turn to a small subset of countries that have kept reliable population statistics for many years. The longest series of such data comes from Sweden. These records are thought to be extremely reliable since 1861, even in terms of the age reporting of individuals at very old ages (Wilmoth and Lundström, 1996). Vital records have a very old history in Sweden, where Lutheran priests were required to start collecting such information at the parish level in 1686. Such records were eventually brought together into a national system in 1749. In 1858, the present-day National Central Bureau of Statistics was formed, which led to further improvements in data quality. Furthermore, by the 1860s the national system of population statistics was already more than 100 years old, so it was possible to check claims of extreme longevity against birth records

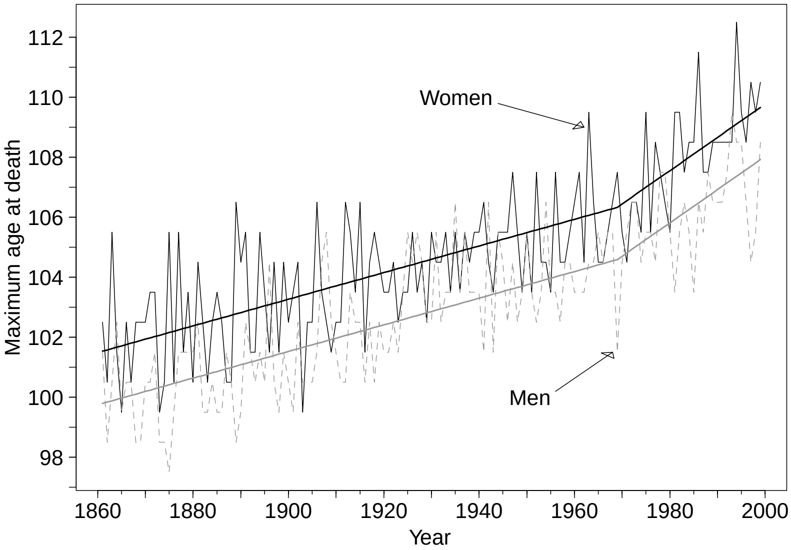


Fig. 3. Maximum reported age at death, Sweden, 1861–1999. Graph shows maximum reported age at death for women and men, along with estimated parallel regression lines according to the following equation:

$$Age = 101.5369 + 0.0444\,(Year - 1861) + 0.0667\,(Year - 1969)I_{Year>1969} - 1.741I_{male}.$$

The breakpoint for the slope, in 1969, was chosen to maximize the goodness-of-fit (as measured by R^2). Source: Wilmoth et al., 2000.

from a century before. These historical developments account for the unique quality of the Swedish mortality data.

Fig. 3 shows the trend in the maximum age at death for men and women in Sweden during 1861–1999. The trend is clearly upward over this time period, with an acceleration after about 1969. The rise in this trend is estimated to be 0.44 years (of age) per decade prior to 1969, and 1.1 years per decade after that date. More than two thirds of this increase can be attributed to reductions in death rates above age 70, with the rest due to mortality decline at younger ages and increases in the size of birth cohorts (Wilmoth et al., 2000).

These Swedish data provide the best available evidence for the gradual extension of the maximum human life span that has occurred over this time period. Similar trends are evident for other countries as well, although patterns of age misstatement present greater problems of interpretation (Wilmoth and Lundström, 1996).

2.2. Extrapolation of demographic trends

Demographers claim some expertise in predicting future mortality levels. Sometimes, the method of choice is a mere extrapolation of past trends. Biologists and others are often critical of this approach because it seems to ignore underlying mechanisms. However, this critique is valid only insofar as such mechanisms are understood with sufficient precision to offer a legitimate alternative method of prediction. Although many components of human aging and mortality have been well described, our understanding of the complex interactions of social and biological factors that determine mortality levels is still imprecise. Furthermore, even if we understood these interactions and wanted to predict future mortality on the basis of a theoretical model, we would still need to anticipate trends in each of its components.

The extrapolative approach to prediction is particularly compelling in the case of human mortality. First, mortality decline is driven by a widespread, perhaps universal, desire for a longer, healthier life. Second, historical evidence demonstrates that mortality has been falling steadily, and life span increasing, for more than 100 years in economically advanced societies. Third, these gains in longevity are the result of a complex array of changes (standards of living, public health, personal hygiene and medical care), with different factors playing major or minor roles in different time periods. Fourth, much of this decline can be attributed to the directed actions of individuals and institutions, whose conscious efforts to improve health and reduce mortality will continue in the future.

Even accepting this argument, there is still a question of what to extrapolate. Demographers tend to view death rates as the fundamental unit of analysis in the study of mortality patterns, because these rates are estimates of the underlying "force of mortality," or the risk of death at any moment in a person's lifetime. These risks change over age and time, and vary across social groupings (by sex, race, education, income, etc.). Life expectancy and the expected maximum age at death (for a cohort of a given size) can be expressed as a mathematical function of death rates by age. Thus, the usual strategy is to extrapolate age-specific death rates into the future and then to use the results of such an extrapolation to compute forecasts of life expectancy or other parameters of interest.

Predictions of future life expectancy by such methods yield values that are not too different from what is observed today. Recent forecasts by the US Social Security Administration put life expectancy in 2050 at 77.5 years for men and 82.9 years for women, compared to 72.6 and 79.0 years in 1995 (Bell, 1997). These Social Security Administration forecasts are not true extrapolations, however, because they assume a slowdown in age-specific rates of mortality decline in the future. An independent study, based on a purely extrapolative technique, yielded more optimistic results — US life expectancies at birth in 2050 of 84.3 years for both sexes combined (Lee and Carter, 1992). Projections for Japan are only slightly higher: life expectancy at birth in 2050 of 81.3 years for men and 88.7 years for women, compared to 76.4 and 82.9 years in 1995 (Wilmoth, 1996).

An important issue for consideration in forecasting mortality is the time frame — both the time frame of the data that form the input to an extrapolation and the time horizon of the projection itself. Although short-term fluctuations have been common, long-term mortality trends in industrialized countries have been remarkably stable. When mortality decline slowed temporarily during the 1950s and 1960s (in the United States and other developed countries), predictions that the rise in human life expectancy had come to an end were commonplace. Similarly, the unusually rapid decline of mortality rates after 1968 fostered expectations of unprecedented gains in longevity that would continue for decades. With the benefit of hindsight, these were both overreactions to rather short-lived episodes in the history of mortality change.

Another common error results from an undue emphasis on trends in life expectancy. Although it continues to increase, the pace of change in life expectancy at birth has slowed in recent decades relative to the first half of the 20th century (see Fig. 1). As noted earlier, this slowdown was inevitable once juvenile mortality was reduced to historically low levels. However, it does not follow from this observation that gains against mortality in the future will be slower than in the past. Although the increase in life expectancy has slowed down, the decline in death rates at older ages (where most deaths now occur) has quickened (Kannisto et al., 1994). An extrapolation of current trends in death rates suggests that life expectancy will continue to increase, though not as quickly as during the first half of the 20th century. This slow but stable increase in average life span will be driven by the accelerating pace of mortality decline at older ages.

2.3. Optimism vs pessimism

In recent years, the extrapolative approach to mortality prediction has been challenged by assertions that future changes in average human life span may come more or less quickly than in the past. The more optimistic view that life span will increase rapidly in the near future is partly a result of the acceleration in rates of mortality decline among the elderly in developed countries during the past few decades. From an historical perspective, however, this change is relatively recent and should be extrapolated into the future with caution. If the new pattern persists for several more decades, it will then constitute strong evidence that the old trends have been replaced by new ones.

Another source of optimism about future mortality rates lies in the potential application of existing technologies (e.g. nutritional supplements, reductions in smoking) or the unusual longevity of certain groups, such as Mormons and Seventh Day Adventists (Ames et al., 1993; Manton et al., 1991). Such discussions may be a good way to improve health behaviors, but they are not so good at informing predictions, largely because this same sort of advocacy influenced past trends as well. For purposes of prediction, we need to ask whether future positive reforms in lifestyle are likely to be implemented faster or more effectively than were similar reforms in the past.

From time to time, technological breakthroughs provide another source of optimism about future mortality rates. In 1998 the manipulation of a gene that halts the shortening of telomeres during the replication of human cells in vitro was a source of great optimism in the popular media, provoking rather extraordinary claims about the possibility of surviving to unprecedented ages in the near future.[3] Talk of cures for cancer and vaccines against AIDS promotes similar hopes. Such discussions should not be dismissed as mere wishful thinking but should also be seen in historical perspective.

As wondrous as they may be, recent scientific advances should be compared, for example, to Koch's isolation of the tubercle bacillus in 1882, which provided confirmation of the germ theory of disease and led to a great flourishing of public health initiatives around the turn of the century, or to Fleming's discovery of the antibacterial properties of penicillin in 1928, an event that led to the antibiotic drug therapies introduced in the 1940s. Extrapolations of past mortality trends assume, implicitly, a continuation of social and technological advance on a par with these earlier achievements.

---

[3] For example, a segment of ABC's 20/20 (broadcast on 16 January 1998) reported that this discovery would lead to the development of anti-aging drugs within 5–10 years, and one researcher interviewed on camera predicted healthy life spans of several hundred years. The finding itself was reported in *Science* magazine (Bodnar et al., 1998).

More pessimistic scenarios of the future course of human longevity are based on notions of biological determinism or arguments about practicality, yielding the now-familiar claim that life expectancy at birth cannot exceed 85 years (Fries, 1980; Olshansky et al., 1990). Sometimes, evolutionary arguments are invoked in support of the notion that further extension of the human life span is impossible, even though existing theories say little about whether and to what degree the level of human mortality is amenable to manipulation (Partridge, 1997).

Current patterns of survival indicate that death rates in later life can be altered considerably by environmental influences, and there is little conclusive evidence that further reductions are impossible. Furthermore, as noted before, trends in death rates and in maximal ages at death show no sign of approaching a finite limit. Nevertheless, although claims about fixed limits to human longevity have little scientific basis, a life expectancy at birth of around 85 years is within the range of values predicted by extrapolative methods for the middle of the next century. In contrast, more optimistic claims are typically much farther afield and would require a much larger deviation from past trends.

3. Conclusion

The rise of longevity is one of the greatest achievements of human history. It is the result of a complex set of changes beginning several centuries ago. Prior to the 1930s, most of this decline was due to factors other than medical therapy (McKeown, 1979) and is generally attributed to improvements in living conditions and public health. With the advent of anti-bacterial drugs in the 1930s and 1940s, medical treatment began to play an important role in these changes, and this role has expanded in recent decades thanks to interventions in CVD and cancer, which have contributed to the rapid decline of old-age mortality.

It seems reasonable to expect that future mortality trends in wealthy nations will resemble past changes. Although the focus of our efforts will evolve, the net effect on death rates will probably be similar. For this reason, demographers tend to rely on extrapolation as a means of predicting the future. This strategy rides the steady course of past mortality trends, whereas popular and scientific discussions of mortality often buck these historical trends, in either an optimistic or pessimistic direction. History teaches us to be cautious. Pessimism about the continuation of mortality decline is not new, and earlier arguments about an imminent end to gains in human longevity have often been overturned, sometimes quite soon after they were put forth.[4] On the other hand, dubious claims about the road to immortality are probably as old as human culture itself, even though they have not influenced official mortality forecasts as much as their more pessimistic counterparts.

Of course, extrapolation is not without its flaws. It could not, for example, have anticipated the rise of mortality in the former Soviet Union after 1990, the emergence

---

[4] A French demographer asserted in 1978 that the biological limit to human life expectancy at birth was 73.8 years for men and 80.3 years for women. Life expectancy in Japan exceeded these values in 1982 for men and in 1985 for women (Bourgeois-Pichat, 1978; Wilmoth, 2000). Similarly, the United Nations predicted in 1973 that life expectancy at birth for developed countries would equal 72.6 years in 1985–90, though later estimates showed that the life expectancy actually attained was 74.0 years. Corresponding figures are 58.7 and 60.5 years for developing countries, and 60.7 and 63.0 years for the world (United Nations, 1977, 1995).

of AIDS in certain populations during the 1980s, or the divergence of mortality trends between Eastern and Western Europe after 1960. However, such observations are less an indictment of extrapolation than a demonstration that the greatest uncertainties affecting future mortality trends derive from social and political, rather than technological, factors.

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. In this situation, the burden of proof lies with those who predict sharp deviations from past trends. Such predictions should be based on theoretical results that are firmly established and widely accepted by the scientific community. Certainly, history can be overruled by a genuine consensus within the scientific community, but not by unproven theories, intuition, or speculation.

Acknowledgements

This work was supported by a grant from the National Institute on Aging, R01-AG11552.

References

Acsádi, G., Nemeskéri, J., 1970. History of Human Life Span and Mortality. Akadémiai Kiadó, Budapest.

Ames, B.N., Shigenaga, M.K., Hagen, T.M., 1993. Oxidants, antioxidants and the degenerative diseases of aging. Proceedings of the National Academy of Sciences 90, 7915–7922.

Asaka, M., Takeda, H., Sugiyama, T., Kato, M., 1997. What role does *Helicobacter pylori* play in gastric cancer? Gastroenterology 113, S56–S60.

Bell, F.C., 1997. Social Security Area Population Projections: 1997. Washington, DC: Social Security Administration, Office of the Chief Actuary, Actuarial Study No. 112, SSA Pub. No. 11-11553.

Bell, F.C., Wade, A.H., Goss, S.E., 1992. Life Tables for the United States Social Security Area 1900–2080. Washington, DC: Social Security Administration, Office of the Chief Actuary, Actuarial Study No. 107, SSA Pub. No. 11-11536.

Bodnar, A.G., Ouellette, M., Frolkis, M., Holt, S.E., Chiu, C.P., Morin, G.B., Harley, C.B., Shay, J.W., Lichtsteiner, S., Wright, W.E., 1998. Extension of life span by introduction of teolmerase into normal human cells. Science 279, 349–352.

Bourgeois-Pichat, J., 1978. Future outlook for mortality decline in the world. Population Bulletin of the U.N., 11.

Centers for Disease Control, 1999. Decline in deaths from heart disease and stroke — United States, 1900–1999. Morbidity and Mortality Weekly Report, vol. 48, pp. 649–656.

Charbonneau, H., 1990. Pierre Joubert a-t-il vécu 113 ans? Mémoires de la Société Généalogique Canadienne-Française 41, 45–48.

Cole, P., Rodu, B., 1996. Declining cancer mortality in the United States. Cancer 78, 2045–2048.

Crimmins, E.M., 1981. The changing pattern of American mortality decline, 1940–77, and its implications for the future. Population and Development Review 7, 229–254.

Crimmins, E.M., Saito, Y., Ingengeri, D., 1997. Trends in disability — free life expectancy in the United States, 1970–90. Population and Development Review 23, 555–572.

Fries, J.F., 1980. Aging, natural death, and the compression of morbidity. New England Journal of Medicine 303, 130–135.

Gersten, O., Wilmoth, J.R., 2000. Cancer mortality in Japan since 1951: trends, causes, and implications. Unpublished manuscript.

Hollingsworth, T.H., 1977. Mortality in the British peerage families since 1600. Population 32, 323–351.

Horiuchi, S., Wilmoth, J.R., 1995. The aging of mortality decline. Annual Meetings of the Population Association of America, San Francisco, 6–8 April 1995, and the Gerontological Society of America, 15–19 November.

Jeune, B., Vaupel, J.W., 1999. Validation of Exceptional Longevity. Odense University Press, Odense.

Johannson, S.R., Horowitz, S., 1986. Estimating mortality in skeletal populations: Influence of the growth rate on the interpretation of levels and trends during the transition to agriculture. American Journal of Physical Anthropology 71, 233–250.

Kannisto, V., A.R. Thatcher, 1993. The plausibility of certain reported cases of extreme longevity. Paper presented at the Research Workshop on the Oldest-Old, Duke University, March.

Kannisto, V., Lauritsen, J., Thatcher, A.R., Vaupel, J.W., 1994. Reduction in mortality at advanced ages. Population and Development Review 20, 793–810.

Lee, J., Campbell, C., Feng, W., 1993. The last emperors: an introduction to the demography of the Qing (1644–1911) imperial lineage. In: Reher, D., Schofield, R. (Eds.). Old and New Methods in Historical Demography. Clarendon Press, Oxford, pp. 361–382.

Lee, R.D., Carter, L.R., 1992. Modeling and forecasting U.S. mortality. Journal of the American Statistical Association 87, 659–671.

Levi, F., La Vecchia, C., Negri, E., Lucchini, F., 1997. Declining cancer mortality in European Union. Lancet 349, 508–509.

Manton, K.G., Stallard, E., Tolley, H.D., 1991. Limits to human life expectancy: Evidence, prospects, and implications. Population and Development Review 17, 603–637.

Matsuzaki, T., 1988. Examination of centenarians and factors affecting longevity in Japan. In: Hishinuma, S. (Ed.). Why do the Japanese live long?. Dobun, Tokyo, pp. 120–123 (in Japanese).

McKeown, T., 1979. The Role of Medicine: Dream, Mirage, or Nemesis?. Basil Blackwell, Oxford.

McWhirter, N., 1995. Guinness Book of World Records. Guinness Publishing, Barcelona.

Myers, G.C., Manton, K.G., 1983. Accuracy of death certification. Proceedings of the Social Statistics Section. American Statistical Association, pp. 321–330.

National Heart, Lung, and Blood Institute, 2000. Research Milestones: Framingham Heart Study. http://www.nhlbi.nih.gov/about/framingham/timeline.htm.

Olshansky, S.J., Carnes, B.A., Cassel, C., 1990. In search of Methuselah: estimating the upper limits to human longevity. Science 250, 634–640.

Omran, A., 1971. The epidemiological transition. Milbank Memorial Fund Quarterly 49, 509–538.

Paine, R.R., 1989. Model life table fitting by maximum likelihood estimation: a procedure to reconstruct paleodemographic characteristics from skeletal age distributions. American Journal of Physical Anthropology 79, 51–61.

Partridge, L., 1997. Evolutionary biology and age-related mortality. In: Wachter, K.W., Finch, C.E. (Eds.). Between Zeus and the Salmon: the Biodemography of Longevity. National Academy Press, Washington, DC, pp. 78–95.

Population Reference Bureau, 1999. World Population Data Sheet, P.R.B., Washington, DC.

Preston, S.H., Haines, M.R., 1991. Fatal Years: Child Mortality in Late Nineteenth-Century America. Princeton University Press, Princeton, NJ.

Replogle, M.L., Kasumi, W., Ishikawa, K.B., Yang, S.F., Juji, T., Miki, K., Kabat, G.C., Parsonnet, J., 1996. Increased risk of Heliocobacter pylori associated with birth in wartime and post-war Japan. International Journal of Epidemiology 25, 210–214.

Robine, J.-M., Allard, M., 1995. Validation of the exceptional longevity case of a 120 year old woman. Facts and Research in Gerontology, 363–367.

Robine, J.-M., Allard, M., 1998. Letter to the editor. Science 279, 1831.

Robine, J.-M., Allard, M., 1999. Jeanne Calment: validation of the duration of her life. In: Jeune, B., Vaupel, J.W. (Eds.). Validation of Exceptional Longevity. Odense University Press, Odense, pp. 145–172.

Robine, J.-M., Mathers, C., Brouard, N., 1996. Trends and differentials in disability-free life expectancy. In: Caselli, G., Lopez, A. (Eds.). Heath and Mortality among Elderly Populations. Clarendon Press, Oxford, pp. 182–201.

Sattenspiel, L., Harpending, H., 1983. Stable populations and skeletal age. American Antiquity 48, 489–498.

Skytthe, A., Jeune, B., Wilmoth, J.R., 1999. Age validation of the oldest man. In: Jeune, B., Vaupel, J.W. (Eds.). Validation of Exceptional Longevity. Odense University Press, Odense, pp. 173–188.

Thatcher, A.R., 1980. Life tables from the Stone Age to William Farr. Unpublished manuscript.

United Nations, 1977. World Population Prospects as Assessed in 1973, United Nations, New York.

United Nations, 1995. World Population Prospects: The 1994 Revision, United Nations, New York.

Wilmoth, J.R., 1995. The Earliest Centenarians: a statistical analysis. In: Jeune, B., Vaupel, J.W. (Eds.). Exceptional Longevity: From Prehistory to the Present. Odense University Press, Odense, pp. 125–169.

Wilmoth, J.R., 1996. Mortality projections for Japan: a comparison of four methods. In: Caselli, G., Lopez, A. (Eds.). Health and Mortality among Elderly Populations. Clarendon Press, Oxford, pp. 266–287.

Wilmoth, J.R., 1997. In search of limits. In: Wachter, K.W., Finch, C.E. (Eds.). Between Zeus and the Salmon: the Biodemography of Longevity. National Academy Press, Washington, DC, pp. 38–64.

Wilmoth, J.R., 2000. Berkeley Mortality Database. University of California, Berkeley, Department of Demography, http://demog.berkeley.edu/wilmoth/mortality/.

Wilmoth, J.R., Lundström, H., 1996. Extreme longevity in five countries: Presentation of trends with special attention to issues of data quality. European Journal of Population 12, 63–93.

Wilmoth, J.R., Horiuchi, S., 1999. Rectangularization revisited: variability of age at death within human populations. Demography 36, 475–495.

Wilmoth, J.R., Skytthe, A., Friou, D., Jeune, B., 1996. The oldest man ever? A case study of exceptional longevity. The Gerontologist 36, 783–788.

Wilmoth, J.R., Deegan, L.J., Lundström, H., Horiuchi, S., 2000. Increase of maximum life-span in Sweden, 1861–1999. Science 2366–2368.

Wood, J.W., Milner, G.R., Harpending, H.C., Weiss, K.M., 1992. The osteological paradox: problems of inferring prehistoric health from skeletal samples. Current Anthropology 33, 343–370.

World Health Organization, 1996. The World Health Report, 1996: Fighting Disease, Fostering Development, WHO, Geneva.