

Demographic Insights into Longevity

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This stimulating special issue of *Population* is not – and was not intended to be – a systematic, comprehensive overview of the biodemography of human longevity. The contributors were asked to present new concepts and results and most took on this challenge with verve and imagination. Hence, this issue is a bouquet of bright ideas and fresh findings. In this concluding chapter, I put these contributions into the context of what is currently known about the survival of the very old. The material is organized under seven rubrics: (I) reductions in mortality after age 80, (II) growth of oldest-old populations, (III) the advancing frontier of longevity, (IV) age-trajectories of oldest-old mortality, (V) theories about longevity, (VI) determinants of longevity, and (VII) forecasts of longevity. In each section I adumbrate what demographers currently know and then summarize how the articles in this special volume add to our knowledge.

I. Reductions in Mortality after Age 80

For females in developed countries, central death rates in the period from 1900 to 1950 at ages 85, 90, and 95 were about 0.2, 0.3, and 0.4 per year. By the close of the 20th century the corresponding death rates were about 0.1, 0.2, and 0.3 (Vaupel, 1997; Vaupel *et al.*, 1998). Figure 1 shows the trend in mortality decline since 1950 for female octogenarians in four representative countries: France, Japan, Sweden, and the United States. In Japan the pace of improvement has been particularly rapid and in France improvements also have been more rapid than in Sweden or the United States.

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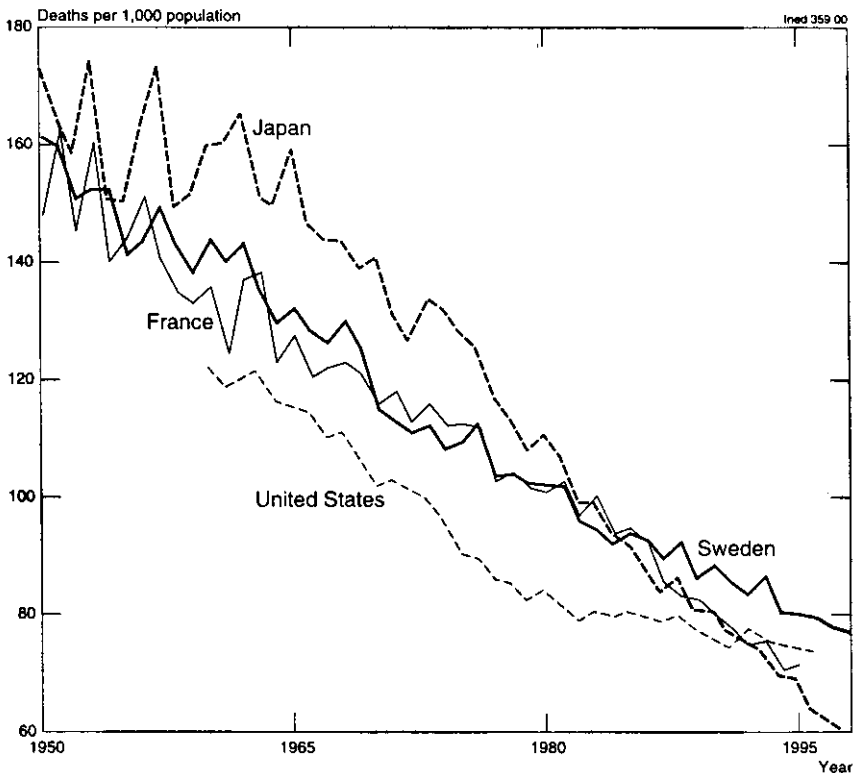


Figure 1.— Death rates for female octogenarians from 1950 to the late 1990s in France, Sweden, the United States, and Japan

The U.S. data may be unreliable before 1970.

Male mortality is higher than female mortality even at ages above 100. Analysis of Western European data indicates that the annual average rate of improvement in female death rates since 1950 declined from about 2% at age 80 to about 1% for centenarians. For males the rate of improvement was roughly constant at oldest-old ages (above 80) at about 1% per year (Kannisto, 1994, 1996).

Changes in the pace of oldest-old mortality improvement from 1950 to the late 1990s have been analyzed for Western Europe and Japan (Kannisto, 1994, 1996; Vaupel, 1997). For female octogenarians, the rate of reduction, which was about 1% per year in the 1950s, accelerated to more than 2% per year in the 1990s. Rates of reduction for nonagenarian females and octogenarian and nonagenarian males also roughly doubled, from levels of well under 1% per year in the 1950s to levels well above 1% per year in the 1990s. Female death rates in Japan since 1970 and France since 1980 have declined at annual rates of about 3% for octogenarians and 2%

for nonagenarians. There is no correlation between levels of mortality and rates of reduction in countries with low oldest-old mortality.

Almost all available data on oldest-old mortality pertain to countries in Europe or to the United States, Canada, Australia, New Zealand, and Japan. Little is known about oldest-old mortality in developing countries, in part because age reports are unreliable. The major exception is China, where acceptably reliable data on the majority Han population has been compiled. In 1990 Han Chinese death rates for men and women in their 80s and 90s were somewhat higher than in Sweden or Japan (Zeng and Vaupel, 2000).

As shown in Figure 1, oldest-old mortality in the United States has been low compared with most other developed countries but improvements have been slow. The apparent U.S. advantage was generally considered, until recently, to be an artifact of age misreporting. New evidence now indicates that U.S. data for whites are acceptably reliable at least up through ages in the late 90s and at least since 1980 (Hill, Preston and Rosenwaike, 2000; Manton and Vaupel, 1995). Death rates for the U.S. white population closely match those shown in Figure 1. Reliable data indicate that oldest-old death rates in Iceland are about the same as shown in Figure 1 for the United States (Vaupel *et al.*, 1998). It appears that oldest-old death rates in Canada, Australia, and New Zealand may follow a similar pattern.

In Eastern Europe, reductions in oldest-old mortality were relatively small between 1960 and the end of the 1990s, and in some countries in some decades mortality increased, particularly for males (Kannisto, 1992, 1994). East Germany followed this general pattern until reunification with West Germany in 1990. Thereafter substantial improvements were achieved (Gjonca, Brockmann and Maier, 2000).

The various statistics cited above are largely derived from the Oldest-Old Mortality Database, which was organized and compiled by Väinö Kannisto and Roger Thatcher and which is maintained at the Max Planck Institute for Demographic Research in Rostock, Germany (Kannisto, 1992, 1994). Until these data were assembled in the 1990s, little information was available about oldest-old mortality over age and time and across countries. Both Kannisto and Thatcher have contributed interesting articles with some new results to this special issue of *Population*.

As Kannisto notes, the distribution of ages at death is typically bimodal, with one peak at birth and a second peak late in life. He investigates the use of the upper mode, M , to study changes in old-age mortality. After summarizing related research, by Wilhelm Lexis and others, Kannisto introduces two measures of the "dispersion of the length of life." The first measure is the standard deviation of life durations above the mode, $SD(M+)$, and the other is the expectation of life at the mode $e(M)$. For all the countries and time periods studied, these two measures are highly correlated, with correlation coefficients around 0.99. Furthermore,

the ratio of $SD(M+)$ to $e(M)$ is close to 1.24, ranging from 1.215 (for Polish males in 1990-5) to 1.257 (for French females in the same period). Kannisto concludes that this regularity is evidence for "the existence of a fairly universal mortality pattern in old age which is consistent with the observation of Lexis that the distribution of deaths above the mode approximates the normal curve".

Kannisto also investigates whether mortality at older ages "is being compressed into a shorter age span". Using long time-series of data for females in four countries as well as shorter series on females in 13 countries, Kannisto concludes that the decline "in old-age mortality, as evidenced by an increase in life expectancy at age 80, has been accompanied by an equally steady advance of the mode but that at the same time the dispersion of the length of life as well as life expectancy at mode have been declining." Because of innate and acquired heterogeneity among people in their chances of death, this process of compression cannot continue indefinitely. Monitoring the process, Kannisto argues, may provide "clues as to any limits to human life and to the length-of-life distribution...".

Thatcher's article in this special issue of *Population* focuses on the demography of centenarians in England and Wales. In the first part of the article, he dissects the causes of the "explosion" in the numbers of centenarians. For both males and females, "by far the largest single cause" has been improved survival from age 80 to age 100. As, however, Thatcher bemoans, the reasons for improved octogenarian and nonagenarian survival are still not well understood.

A third article in this issue also sheds some new light on reductions in mortality at advanced ages. Michel Poulain, Dany Chambre and Michel Foulon study more than 4,000 centenarians who were born in Belgium between 1870 and 1895. They find, among other interesting results discussed below, that remaining life spans increased for centenarians born in 1885-1894 compared with those born in 1870-1884. At exact age 101, for instance, female centenarians born in the later period lived almost 700 days on average whereas female centenarians born in the earlier period lived just over 600 days.

Finally, Jean-Marie Robine's contribution to this volume, like Kannisto's, considers the dispersion of the length of life and the question of whether mortality is being compressed into a shorter span of ages. As discussed above, Kannisto focuses on two highly-correlated measures of dispersion and uses data from many countries. In contrast, Robine reviews 15 measures but uses data from a single country, France. He concludes that all the measures show a long-term compression of mortality if the entire life span is considered. If, however, attention is focused on older ages, then some of the measures suggest that further compression has been slow in recent decades and other measures suggest that there has been an expansion of the period at the end of life when deaths occur. Because none of the measures is clearly superior to the other measures, the truth in this

case is like a piece of sculpture that reveals different aspects when viewed from different perspectives.

Robine relates his findings to the stages of the epidemiological transition. He finds support for the first two stages proposed by Omran (1971), the "Age of Pestilence and Famine" and the "Age of Receding Pandemics." He concludes, however, that Omran's third stage and the additional, fourth, stage proposed by Olshansky and Ault (1986) can best be viewed as a single stage. He labels this the "Age of the Conquest of the Extent of Life". This Age, which started around 1950 or 1960 in most developed countries, is characterized by remarkable improvements in survival at older ages and substantial increases in life spans. In particular, this Age saw the emergence of supercentenarians, those pioneers on the frontier of survival who have lived 110 years or more.

II. Growth of Oldest-Old Populations

In most countries, both developed and developing, the population above age 80 is rapidly growing, in part because of mortality reductions after age 80. Consider, for example, England and Wales, where the remaining life expectancy of 80-year-old females around 1950 was approximately 6 years. In the late 1990s, the corresponding figure was 9 years and the population of female octogenarians in England and Wales was roughly half again as big as it would have been if mortality after age 80 had remained at 1950 levels. More than a half million females age 80+ were alive in England and Wales who would have been dead if mortality after age 80 had not been reduced (Vaupel, 1997).

In Western Europe in the late 1990s there were between two and three times as many nonagenarians and about eight times as many centenarians as there would have been if mortality after age 80 had stayed at 1960 levels (Kannisto, 1992, 1994). In Western Europe, Japan and China, the population of centenarians has been doubling every decade in recent decades, largely because of mortality improvements after age 80 (Vaupel and Jeune, 1995). Concerns about age misreporting preclude reliable estimation of numbers of centenarians in most other parts of the world, including the United States (Jeune and Vaupel, 1995, 1999).

Long-term, highly reliable data for Denmark illustrate the trend. In the decade of the 1860s, a total of 19 Danish centenarians died. A hundred years later, in the decade of the 1960s, 226 Danish centenarians died. And between 1990 and 1998 the number had risen to 1931. These statistics are from Bernard Jeune and Axel Skytthe's article in this issue, an article that focuses on the growth in the number of centenarians in Denmark. A major contribution of the article is to document that most reported centenarians in Denmark before 1860 or so probably were not genuine centenarians.

The true number of centenarians historically was very small, with the first real Danish centenarian perhaps emerging around 1790. Furthermore, most and perhaps all of those reported to have attained the age of 105 before 1900 were probably younger. The very small number of centenarians a century or more ago makes the recent growth of the centenarian population look like an explosion.

Thatcher's article in this issue also considers the growth of the population of centenarians. He dissects the causes of this growth into different factors, including increases in births a century ago, improved survival from birth to age 80, improved survival between 80 and 100, improved survival after age 100, and net decrease due to war deaths, net migration, and other causes. As noted above, he concludes that by far the most important factor was mortality reductions for octogenarians and nonagenarians. Thatcher also looks to the future: projections suggest that the number of centenarians in England and Wales may increase from 102 in 1911 and 5,523 in 1996 to 95,000 in 2066.

Finally, the article by Poulain, Chambre and Foulon provides some new information about the growth of the centenarian population in Belgium. Of those born in Belgium in 1870, some 17 males and 50 females celebrated their 100th birthdays. Of those born in 1897, 75 males and 376 females endured to age 100. For men the proportion becoming centenarians nearly quadrupled, whereas for females the proportion was multiplied by a factor of nearly eight – over a period of only 27 years.

III. The Advancing Frontier of Longevity

Jeune and Skytthe's article also provides interesting information about record life spans. Increases in record life-spans are largely attributable to improvements in survival at the highest ages. In Sweden in the 30 years between 1860 and 1889, no one survived past age 105. The maximum attained life-span then gradually rose, reaching age 112 in 1994 (Wilmoth *et al.*, 2000). As Jeune has conjectured, it is possible in Denmark, Sweden and other countries with populations of a million or so that no one celebrated their 100th birthday before 1800 (Jeune and Vaupel, 1995). Many accounts exist of people living far longer at earlier times, but these accounts are generally fallacious, as are most accounts of centenarians today in most poor countries and some richer ones. A few scattered centenarians may have lived before the 19th century, perhaps a handful or less per century. This contrasts with the 100,000 or more centenarians who celebrated the dawn of the 21st century.

There were almost certainly no true supercentenarians (individuals aged 110 or above) prior to the mortality decline of the past two centuries (Jeune and Vaupel, 1995, 1999).

The first reasonably well documented case of a supercentenarian is Katherine Plunket, who died at the age of 111 in 1932 in Northern Ireland. Jeanne Calment was the first carefully verified instance of a person reaching age 120; she died at the age of 122 years and 5 months in 1997 in France (Robine and Allard, 1999).

In his article in this issue, Thatcher contributes some interesting information about likely future advances in record longevity. He argues that there is no sign of a fixed upper limit to the length of human life, but that given projected trends, increases in extreme life spans will be fairly slow. In recent years in England and Wales, the highest age attained has ranged between 109 and 115. Thatcher projects that in the decade of the 2080s, this range will shift upward to between 116 and 123 years.

IV. Age-Trajectories of Oldest-Old Mortality

Reliable data on mortality from age 80 to the highest age attained are available for Japan and 13 Western European countries. When these data are pooled, it is possible to accurately estimate the age-trajectory of human mortality up to age 105. Reasonable estimates can be made up to age 110 and shakier guesstimates can be boldly ventured up to age 122 by fitting curves to the data (Thatcher *et al.*, 1998; Vaupel *et al.*, 1998). Figure 2 shows that mortality does not increase exponentially after age 80. Mortality decelerates. Whether mortality is slowing increasing, level, slowly decreasing, or rapidly decreasing after age 110 is uncertain. A logistic curve that fits the data well from age 80 to 105 indicates that death rates may reach a plateau. A quadratic curve fit to the data at ages 105+ suggests a decline in mortality after age 110.

Studies of large populations of yeast, nematode worms, and several species of insects demonstrate that death rates rise at younger ages and level off and in some cases decline at older ages. This pattern also holds for various makes of automobiles (Vaupel *et al.*, 1998).

Although none of the articles in this issue concentrate on age-trajectories of oldest-old mortality, the articles by Thatcher and by Poulain, Chambre, and Foulon provide some information. Thatcher reports that for England and Wales the probability of dying within 12 months rises slowly from age 100 to 104 for males and from age 100 to 107 for females; his data do not permit estimates after these ages. From age 101 to 104 the rise is very slow for males: 41%, 41%, 42%, 43%. At the extreme ages of 104 to 107 the probabilities of death for females are 44%, 46%, 46%, 46%. Poulain, Chambre, and Foulon present similar findings for Belgium. For males at exact ages 101, 102, and 103, the annual probability of death fluctuates around 46%. For females at exact ages 103, 104, and 105, the probability fluctuates around 47%. Some higher probabilities of death are

reported at even older ages, but these estimates are based on fewer than 100 observations.

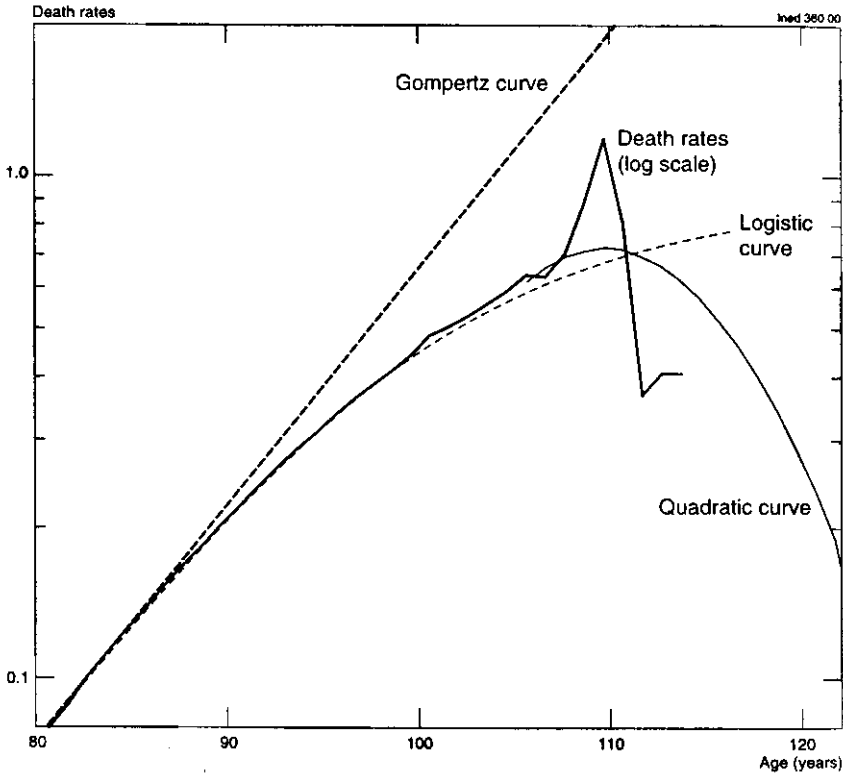


Figure 2.— Death rates in an aggregation of 14 countries (Japan plus 13 Western European countries)

Death rates, on a log scale, in an aggregation of 14 countries (Japan plus 13 Western European countries) with reliable data, over the period from 1950 to 1997 for ages 80 and above are shown by the bold line. The last observation is Jeanne Calment's death at age 122, but data are so sparse at the highest ages that the trajectory of mortality is too erratic to plot. Although the graph is based on massive data, some 287 million person-years at risk, reliable data were available on only 82 people who survived past age 110.

The exponential (Gompertz) curve that best fits the data at ages 80-84 is shown by the dashed line.

The logistic curve that best fits the data is shown by the dotted line.

A quadratic curve (that is, the logarithm of the death rate as a quadratic function of age) was fit to the data at ages 105 and higher; it is shown by the thin solid line.

Source: Vaupel *et al.*, 1998.

V. Theories about Longevity

The two main research findings in the 1990s concerning oldest-old mortality were: (1) death rates after age 80 declined substantially since 1950, at an accelerating pace, and (2) the increase in mortality with age decelerated at advanced ages for humans, various other species, and even automobiles. These two findings are perplexing. What biological charter permits us (or any other species) to live long post-reproductive lives? A canonical gerontological belief posits genetically determined maximum life-spans. Most sexually reproducing species show signs of senescence with age, and evolutionary biologists have developed theories to account for this. The post-reproductive span of life should be short because there is no selection against mutations that are not expressed until ages when reproduction and nurturing have ceased. It should be increasingly difficult to reduce death rates with advancing age and mortality should accelerate with age as reproductive activity declines. Because these hypotheses are wrong, theory has to be re-thought. (For further discussion of these points, see Wachter and Finch, 1997 and Vaupel *et al.*, 1998).

Vaguely related to the biological theory of aging are three widely-held notions:

(1) deaths at older ages are essentially due to old age, and nothing can be done about old age;

(2) the typical human organism is not constructed to survive much past age 80 or 90;

(3) causes of death at younger ages are largely extrinsic but causes of death at older ages are mostly intrinsic, and it is very difficult to reduce intrinsic causes of death.

These notions are dubious, ill-defined speculations that are inconsistent with available evidence.

In their stimulating, thought-provoking article on "Principles of Biodemography", James R. Carey and Debra S. Judge take a fresh look at concepts that could be used to develop a theory of longevity. Their article pulls together a broad array of ideas and findings in a highly original synthesis. About 150 references cover topics ranging from sex and death in protozoa, medfly mortality, and dietary restriction to the "third chimpanzee", technophysio evolution, and Danish twins. The reference to Keyfitz' *Applied Mathematical Demography* is followed by a reference to Kinzey's *New World Primates*. I will not attempt any summary of this contribution: anyone interested in biodemography or longevity should study the article by Carey and Judge carefully.

Carey and Judge include a short section entitled "Selection shapes mortality trajectories". Their brief review is accurate but perhaps does not provide the reader with full appreciation of the importance of the compositional change that occurs in a cohort as mortality differentially removes

the weakest. All populations are heterogeneous. Some individuals are frailer than others, innately or because of acquired weaknesses. The frail tend to suffer high mortality, leaving a select subset of survivors. This creates a fundamental problem for analyses of oldest-old mortality: as a result of compositional change, death rates increase more slowly with age than they would in a homogeneous population.

The leveling off and even decline in mortality can be entirely accounted for by frailty models in which the chance of death for all individuals in the population rises at a constant or increasing rate with age (Vaupel and Carey, 1993). On the other hand, mortality deceleration could also result from behavioral and physiological changes with age. Research is needed on the relative importance of compositional change vs. individual change in determining oldest-old mortality patterns.

Carey and Judge's overview touches on, but to my mind does not sufficiently emphasize, two biodemographic concepts – mortality correlation and induced demographic schedules – that point to promising directions for developing theory.

Demographers have long known that death rates at different ages are highly correlated across populations and over time. In addition to environmental correlations, there may be genetic correlations: mutations that raise mortality at older ages may do so at younger ages as well. Post-reproductive life-spans might be compared with post-warranty survival of equipment. Although living organisms are vastly more complex than manufactured products, they too are bound by engineering constraints that may impose mortality correlations. The trajectory of mortality for automobiles suggests the possibility that both mortality deceleration and mortality correlation are general properties of complicated systems. Carey and Judge correctly point out that "biological organisms die whereas mechanical systems fail". Nonetheless, despite the enormous differences between an automobile and a human, it may be possible to learn something about longevity by studying general properties of complicated systems.

A key construct underlying evolutionary theory is the Lotka equation, which determines the growth rate of a population (or the spread of an advantageous mutation). The simplistic assumption in the Lotka equation that fertility and survival schedules are fixed is surely wrong. Environments are uncertain and changing. An individual does not face fixed fertility and survival schedules, but dynamically adopts alternative schedules as the environment and the individual's capabilities change. Pathbreaking research by Carey and colleagues has kindled interest in this (*e.g.*, Carey *et al.*, 1998) and Carey and Judge provide some discussion of induced demographic schedules in their section on "Reproduction is a fundamental longevity determinant". I think the concept is even more important than Carey and Judge's discussion suggests, as the concept highlights the need to re-think Lotka-based theory. The Lotka equation, however, does capture a fundamental insight: it is reproductive success that is optimized by evol-

ution, not longevity. Deeper understanding of survival at older ages depends on intensified research into the interactions between fertility and survival.

VI. Determinants of Longevity

Oldest-old mortality is lower for women than men, people born in this century rather than earlier, and people born in rich countries rather than poor ones. Smoking is a health hazard at younger ages and probably at the oldest ages as well. Exercise may become increasingly important with age. Diet matters. The significance of medical treatment and other health-care interventions may grow with age. (For a lengthier review of risk factors for old-age mortality, see Christensen and Vaupel, 1996).

A key recent result is that about a quarter of the variation in adult life-spans appears to be attributable to genetic variation among individuals and that the importance of genetic factors may be of the same magnitude or even larger at advanced ages (Vaupel *et al.*, 1998). Several genes, including the ApoE gene, with polymorphisms that influence oldest-old mortality have been uncovered. There may be hundreds of genes with common polymorphisms that substantially affect oldest-old mortality.

Research in progress suggests that an additional quarter of the variation in life-spans after age 50 may be attributable to non-genetic characteristics that are more or less fixed by the time a person reaches age 50 (Vaupel *et al.*, 1998). In addition to educational achievement and socioeconomic status, month of birth influences oldest-old mortality (Doblhammer, 1999). Women and men who have a baby in their 40s suffer lower mortality at oldest-old ages. Nutrition and infections *in utero* and early in life have major effects on late-life mortality (Barker, 1992).

As the above paragraphs suggest, much is known about the determinants of longevity. Given the great interest among many people in the secrets of longevity, in recipes for long life, it might be expected, however, that even more would be known. Remarkably little systematic research has been done on the relative importance of different factors in determining longevity. Furthermore, almost no research has been done on longevity in developing countries. This makes the article in this issue by Zeng Yi *et al.* particularly important. The authors describe a major study of healthy longevity that was launched in 1998 in China. They assess the quality of the data, which turns out to be very good. Then they present some preliminary findings about active life expectancy at oldest-old ages. The major finding is that elderly Chinese can expect to spend the bulk of their remaining lifespans without either mild or severe disability.

Leonid and Natalia Gavrilov also contribute an article to this special issue that pertains to the determinants of longevity. The Gavrilovs' main interest is in two topics:

- (1) the effects of parental age at reproduction on offspring life span with particular emphasis on the consequences of late parenting; and
- (2) whether fathers or mothers pass their longevity on to their sons and daughters.

These are interesting questions, but the Gavrilovs' article is essentially a lengthy review of their published research to date on these two topics, with some new statistical calculations that support previous conclusions. They apparently plan to continue to do research on the two questions, because they label most of their findings "preliminary". In any case, one intriguing finding is that late paternal age at reproduction significantly lowers daughters' life spans, whereas paternal age at reproduction is much less important for sons and maternal age at reproduction is unimportant for both daughters and sons. A second finding that the Gavrilovs highlight is that there is a remarkable extension of the longevity of both sons and daughters if fathers live past age 70 or 80. In contrast, maternal life span appears to be less important for sons and probably for daughters as well.

Unfortunately, both these findings are indeed "preliminary", for the reasons the Gavrilovs give, including the need for larger sample sizes and more covariates, and also because the statistical tools they employ are elementary and perhaps not appropriate. Furthermore, their selective reporting of some findings and references but not of others raises doubts. For instance, the Gavrilovs make much of their finding that offspring life span tends to increase more and more rapidly as parental life span increases. They fail to report that a very simple model can account for this, a model in which children inherit their "frailty" from their parents and a person's frailty raises or lowers that person's mortality chances by the same factor at all ages (Vaupel, 1989).

Westendorp and Kirkwood's article in this special issue also focuses on how maternal and paternal life spans influence children's life spans. Their analysis is based on genealogical data on the British aristocracy; they used data on 6,415 males and 2,441 females for whom information was available on dates of birth and death of the individual and of both parents. Most of the individuals were born between 1700 and 1875, but some were born as early as the 8th century. The mean number of progeny per father and mother is reported as 1.83 and 1.69: it is not clear how these values were calculated, but they seem low. Furthermore, the number of males in the study is much higher than the number of females. Hence, while this is an interesting data set, there may be many missing children and females. Furthermore, Westendorp and Kirkwood, like the Gavrilovs, use simple statistical models that might not be appropriate for the data they are analyzing. For instance, "a person was classified as 'long-lived' if his or her age

of death was over 75 years." The chances of living this long, however, have increased greatly over time. Westendorp and Kirkwood try to control for secular trends in age-specific death rates by including a variable pertaining to year of birth in their regression analyses. Mortality fluctuations, however, including the enormous mortality improvements over the past century and a half, have largely proceeded by period rather than cohort. A better approach would be to estimate each person's survival fractile, i.e., the proportion of the person's sex-specific birth cohort that was alive when the person died. Then, the analysis could be based on these survival fractiles rather than on age *per se*.

Westendorp and Kirkwood report that the association between parental life spans and children's life spans changes depending on time period and sex. For instance, "between 700 and 1700, we found that the probability of longevity of men but not women was dependent on longevity of the parents, especially the father". Judicious demographers who are enticed by this kind of finding will want to do more careful studies using more cogent methods applied to less problematic data sets.

Finally the short article by Bertrand Desjardins in this volume investigates the heritability of longevity by replicating an earlier study by Robine and Allard (1998; 1999). Robine and Allard analyzed whether Jeanne Calment, who lived 122 years, had long-lived ancestors compared with a control population. She did. Desjardins reports a similar finding for a native of Quebec, Marie-Louise Meilleur, who lived almost 118 years. Although Meilleur's ancestors lived about 6 years longer on average than the members of the control group, about 22% of the individuals in both groups survived past age 80. This result contrasts with the finding of Robine and Allard that 24% of Calment's ancestors but only 2% of the controls lived past 80. As explained above, because the probability of surviving to age 80 differs for males and females and has changed radically over time, it might be worthwhile to re-do these analyses using survival fractiles rather than age *per se*.

VII. Forecasts of Longevity

Almost all population forecasts made by governmental organizations have assumed slow rates of mortality improvement. Because death rates over the past century have continued to fall at most ages and have been reduced at an accelerating pace at older ages, past forecasts have seriously underestimated progress in increasing survival.

In developed countries large increases in life expectancy depend on substantial reductions in oldest-old mortality. If slow progress is made, then period life expectancy at birth in 2050 may be less than 85 in most developed countries. On the other hand, if improvements in French morta-

lity continue in the future at the same pace as in recent decades, half of the baby girls born in France at the end of the 20th century may survive to celebrate the dawn of the 22nd century. Note the difference between these two statements. The first pertains to period life expectancy for both sexes combined. The second pertains to median cohort life-spans for French females. Much of the apparent disagreement among demographers about the duration of life in the future arises because different measures and populations are being compared. Real disagreements, however, exist about whether the pace of mortality improvement will persist, further accelerate, or decline over the coming century (Robine *et al.*, 1997, Wilmoth, 1998).

In their chapter in this issue Graziella Caselli and Jacques Vallin take a brave look at some radical future trajectories of mortality and fertility that might fundamentally alter population size and age structure. They are not too timid to explore life expectancies of 150 years or consequences all the way out to the year 2350. They do not make forecasts; rather they explore various "what if?" scenarios. Demographers are currently hotly debating whether life expectancy might increase to 100 and whether the global total fertility rate might fall to 1.8. Caselli and Vallin's willingness to explore much more extreme possibilities puts the current debate into perspective: the range of alternative forecasts currently in dispute is very small compared with the range of what could possibly happen. The truth is that we know very little about the future. So Caselli and Vallin's article is a stimulating corrective, a mind-opening revelation.

REFERENCES

- BARKER D.J.P., 1992, *Fetal and Infant Origins of Adult Disease*. BMJ Press, London.
- CAREY J.R., LIEDO P., MUELLER H.-G., WANG J.-L., VAUPEL J.W., 1998, "Dual modes of aging in Mediterranean fruit fly females", *Science*, 281, pp. 996-998.
- CHRISTENSEN K., VAUPEL J.W., 1996, "Determinants of longevity: Genetic, environmental, and medical factors", *Journal of Internal Medicine*, 240, pp. 333-341.
- DOBLHAMMER G., 1999, "Longevity and month of birth: Evidence from Austria and Denmark", *Demographic Research*, 1, 3 (text available at <http://www.demographic-research.org>).
- GJONCA A., BROCKMANN H., MAIER H., 2000, "Old-age mortality in Germany prior to and after reunification", *Demographic Research*, 2, 6 (text available at <http://www.demographic-research.org>).
- HILL M.E., PRESTON A.H., ROSENWAIKE I., 2000, "Age reporting among White Americans aged 85+", *Demography*, 37, pp. 175-186.
- JEUNE B., VAUPEL J.W. (eds.), 1995, *Exceptional Longevity: From Prehistory to the Present*, Odense University Press, Odense, Denmark (text available at <http://www.demogr.mpg.de>).
- JEUNE B., VAUPEL J.W. (eds.), 1999, *Validation of Exceptional Age*, Odense University Press, Odense, Denmark (text available at <http://www.demogr.mpg.de>).
- KANNISTO V., 1994, *Development of Oldest-Old Mortality. 1950-1990: Evidence from 28 Developed Countries*, Odense University Press, Odense, Denmark (text available at <http://www.demogr.mpg.de>).
- KANNISTO V., 1996, *The Advancing Frontier of Survival*, Odense University Press, Odense, Denmark (text available at <http://www.demogr.mpg.de>).
- MANTON K.G., VAUPEL J.W., 1995, "Survival after the age of 80 in the United States, Sweden, France, England and Japan", *New England Journal of Medicine*, 333, pp. 1232-1235.

- OMRAN A.R., 1971, "The epidemiologic transition", *Milbank Memorial Fund Quarterly*, 49, pp. 509-538.
- OLSHANSKY S.J., AULT B., 1986, "The fourth stage of the epidemiologic transition", *Milbank Quarterly*, 64, pp. 355-391.
- ROBINE J.-M., ALLARD M., 1998, "The oldest human", *Science*, 279.
- ROBINE J.-M., ALLARD M., 1999, "Jeanne Calment: Validation of the duration of her life", in Jeune and Vaupel, 1999.
- ROBINE J.-M., VAUPEL J.W., JEUNE B., ALLARD M., 1997, *Longevity: To the Limits and Beyond*, Springer Verlag, Berlin.
- THATCHER A.R., KANNISTO V., VAUPEL J.W., 1998, *The Force of Mortality at Ages 80 to 120*, Odense University Press, Odense, Denmark (text available at <http://www.demogr.mpg.de>).
- VAUPEL J.W., 1988, "Inherited frailty and longevity", *Demography*.
- VAUPEL J.W., 1997, "The remarkable improvements in survival at older ages", *Philosophical Transactions of the Royal Society London B*, 352, pp. 1799-1804.
- VAUPEL J.W., CAREY J.R., 1993, "Compositional interpretations of medfly mortality" *Science*, 260, pp. 1666-1667.
- VAUPEL J.W., CAREY J.R., CHRISTENSEN K., JOHNSON T.E., YASHIN A.I., HOLM N.V., IACHINE I.A., KANNISTO V., KHAZAEI A.A., LIEDO P., LONGO V.D., ZENG Y., MANTON K.G., CURTSINGER J.W., 1998, "Biodemographic trajectories of longevity" *Science*, 280, pp. 855-860.
- VAUPEL J.W., JEUNE B., 1995, "The emergence and proliferation of centenarians", in Jeune and Vaupel, 1995.
- WACHTER K.W., FINCH C. E., 1997, *Between Zeus and the Salmon: The Biodemography of Longevity*, National Academy Press, Washington DC.
- WILMOTH J.R., 1998, "The future of human longevity: A demographer's perspective", *Science*, 280, pp. 395-396.
- WILMOTH J.R., DEEGAN L.J., LUNDSTROEM H., HORIUCHI S., 2000, "Increase in maximum life-span in Sweden 1861-1999", *Science*, 289, pp. 2366-2369.
- ZENG Y., VAUPEL J.W., 2000, Mortality of centenarians in China. Submitted.