Lively Questions for Demographers about Death at Older Ages

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Research on aging is thriving. In particular, research on mortality is alive and well. Many interesting, important demographic analyses of survival are being undertaken by hundreds of researchers around the world. The Human Mortality Database («www.mortality.org»), supplemented by the Kannisto–Thatcher Database on Old-Age Mortality and the Human Lifetable Database (both available at «www.demogr.mpg.de»), have facilitated these analyses and are the source of most of the facts about deaths given below. I use these facts as a springboard to briefly discuss six questions about mortality at older ages that I think are especially significant and challenging.

1. Why is remaining life expectancy at older ages static for US females?

For Japanese women, remaining life expectancy at age 65 has been increasing, over the past three decades, by about 5 hours per day. For US women over the same time period, remaining life expectancy at age 65 has stagnated. This is not due to the changing ethnic or racial mix of the United States or to changing patterns of migration: since the late 1970s death rates after age 80 for native-born white Americans have remained roughly constant.

Women in several advanced countries, including France, Italy, and Spain, are doing about as well as women in Japan. For the Dutch, female mortality at older ages stagnated in the 1980s and 1990s. Since 2002, however, Dutch female life expectancy at age 65 has increased. The achievements of other countries—e.g., the Nordic countries, Canada, and Australia—fall between the successes of Japan and France and the dismal performance of the United States and (until recently) the Netherlands.

Male life expectancy is now lower than female life expectancy in every country of the world (Barford et al. 2006). In most of the countries with long life expectancy, however, the female/male gap is beginning to narrow. A notable example is the United States: female life expectancy at older ages is not improving, but male life expectancy is increasing at a pace comparable to that in other developed countries. One plausible explanation is cigarette smoking: in many developed countries the number of females who smoke has increased whereas the number of males who smoke has decreased (Pampel 2002, 2003, 2005). More generally, divergent trends in life expectancy across countries as well as between the sexes may reflect changing patterns of cigarette smoking a decade or two ago (Preston and Wang 2006). Other kinds of insalubrious behavior may also play a role, including the syndrome of obesity, lack of exercise, and unhealthy diet.

Populations are heterogeneous. One consequence is that people die at very different ages. The fact that the American population is very heterogeneous may underlie the stagnation of US female life expectancy, both for the population as a whole and for native-born whites. It may be that vanguard groups in the United States are enjoying life expectancies that are as high and rising as rapidly as those in Japan and France. Laggard groups in the United States may be suffering declining life chances, resulting in a stagnating average (Murray et al. 2006). The laggard groups may be smoking, drinking excessively, eating inappropriately, exercising too little, becoming obese, and so on, perhaps because of poor education or stress; they may also be getting inferior medical care, perhaps because they do not go to the doctor when they should. The puzzle remains that the United States is rich and spends enormous amounts on medical treatment, yet life expectancy at age 65 for women in the United States is not rising.

The poor performance of the Netherlands may be due to different causes. A major difference between the US and Dutch trends is that in the Netherlands both male and female life expectancy increased very slowly from 1980 to 2002. As noted earlier, old-age mortality for women started falling appreciably after 2002 and this is also the case for men. One possibility is that the Dutch enjoy long spans of healthy life but a relatively short span of unhealthy life at older ages. This may reflect lack of medical treatment at advanced ages, which may be consistent with the preferences of the Dutch population. Such speculation should be verified or refuted by careful research.

2. How should life expectancy be estimated when death rates are changing?

Suppose in some year mortality conditions improve. This means that some people's lives are saved, that is, their deaths are averted. The impact of the mortality reduction on life expectancy depends on how long the lives are saved. At the time the deaths are averted it is generally not known how long the lives will be extended; indeed, it is generally not known whose lives were saved. Hence, assumptions have to be made about the life chances of the new survivors. Demographers have traditionally assumed that the future age-specific death rates of those whose lives were saved by mortality improvements are the same as the corresponding death rates of those who were not about to die. In particular, demographers have assumed that the remaining life expectancy of a person escaping from imminent death is equal to the remaining life expectancy of a person who would have survived. This assumption is questionable.

Vaupel, Manton, and Stallard (1979) pointed this out in the context of their "frailty model." They argued that some people were frailer than others of the same age and that the frail were more likely to die. Consequently, improvements in mortality might tend to particularly benefit the frail, extending their lives but not for as long as the lives of their robust contemporaries. The authors showed how to calculate life tables for such heterogeneous populations and demonstrated that true life expectancy when progress was being made in reducing death rates was lower than life expectancy indicated by conventional calculations. Their research has, however, remained largely of theoretical interest because demographers have not yet developed powerful enough methods to estimate the nature and degree of heterogeneity in frailty. Some recent research on supercentenarians (i.e., people 110 years old and older) may lead to a breakthrough (Maier et al. 2009).

Bongaarts and Feeney (2002) launched a radically different attack on traditional life table calculations, based on their thinking about tempo effects. They argued that, at least for adults in developed countries today, the fundamental nature of mortality improvement was not to save a few people's lives for remaining general life expectancy, but to extend everyone's life span by a few weeks or months. For France, Sweden, and the United States in recent decades, this approach leads to estimates of life expectancy that are about two years lower than conventional estimates.

Some respected demographers more or less agree with Bongaarts and Feeney; others strongly disagree. (See Barbi, Bongaarts, and Vaupel 2008 for an anthology of perspectives.) Whether tempo effects on mortality exist in some age range, at some time periods, and in some countries is an open question that merits further research. Whether mortality change poses challenges for the calculation of life tables is, however, no longer a question. Some kinds of change may extend a few people's lives for an average period that may approach remaining general life expectancy. Other kinds of change may extend many people's lives for a short time. Still other kinds of change may slow the clock of aging. All populations are heterogeneous, so each of these kinds of change may affect individuals somewhat differently. Research is required to determine which model or mix of models is most helpful in understanding mortality change at various ages, various times, and as a result of various kinds of interventions.

In sum, demographers do not know how to calculate life tables when mortality is changing. To make progress, demographers need to develop a deeper understanding of the nature of lifesaving. If mortality conditions improve, then how many lives are saved and for how long? This is a fundamental question for mortality research.

3. What is the relative importance of in-utero vs. early-childhood vs. later-life vs. current conditions on health and survival at older ages?

Demographic research has shown that changes in age-specific death rates over time are largely determined by changes in period conditions rather than by changes in cohort conditions in early life. This is especially true in recent decades in countries with long life expectancies (Kannisto 1994, 1996; Vaupel et al. 1997). Because cohort effects are considered relatively unimportant in determining mortality change, forecasts of future death rates and life expectancy are generally based on models that are broken down by age and period (e.g., Lee and Carter 1992).

This emphasis on current conditions might be called the period perspective. It turns out that a cohort perspective is also useful. It is clear that a person's health—and chance of death—are influenced by the person's lifetime behavior and by the conditions the person has lived under and sailed or suffered through. The importance of cohort effects is emphasized by many medical researchers, biologists, and economists, as well as by some demographers. Barker and colleagues have demonstrated that conditions in utero can influence health in old age (e.g., Barker 1998). Finch (2007) explains why the cumulative burden of inflammation increases disease among the elderly and weakens survival chances. Cigarette smoking certainly has a long-term, cumulative effect on health. Explanations of the once widening and now narrowing gap between female and male life expectancy highlight the significance of cohort patterns of smoking among women vs. men (Pampel 2002, 2003, 2005; Preston and Wang 2006)

Hence, whereas (with a few notable exceptions) period effects dominate analyses of changes over time in age-specific mortality in a population, cohort effects become apparent in analyses of differences between populations or population subgroups, for example, males vs. females. The ultimate subgroup is a single individual, and cumulative lifetime experiences as well as genetic endowment determine the relative risk of death faced by one individual compared with another. Frailty models of heterogeneous populations (Vaupel, Manton, and Stallard 1979; Vaupel and Yashin 1985, 2006) are based on both cohort experiences and current conditions.

Do you die from your whole life? Or do you die from yesterday? Both present circumstances and past history surely play some role. Research is needed on the relative importance of these effects. How decisive are in-utero vs. early-childhood vs. later-life vs. current conditions on health and survival at older ages? How important is the past vs. the present for: (1) average levels of age-specific morbidity and mortality in a population, (2) the variance within a population, (3) changes over time in the levels, and (4) differences in the levels among populations?

4. Males are stronger than females and say they are healthier, but females live longer. Why are there frail females and dead males?

An editorial in the 8 April 2006 issue of the *British Medical Journal* announced: "Life expectancy: Women now on top everywhere." Even in the poorest countries, women can expect to outlive men (Barford et al. 2006). There is, however, a remarkable discrepancy between the health and survival of males and of females. As an example, grip strength is shown to predict disability, morbidity, and mortality in both sexes but still the mean grip strength of 80-year-old men corresponds to the mean grip strength of 45-year-old women (Frederiksen et al. 2006). Generally men are stronger, report fewer diseases, and have fewer limitations in the activities of daily living at older ages. Nonetheless, female death rates are substantially lower than male rates for all age groups. That is, in terms of mortality, women are healthier than men.

Interpretation of this apparent contradiction—that women live longer than men but experience worse health—is complicated by several factors, and a number of explanations have been proposed that are rooted in biological, social, and psychological theory. The most commonly proposed explanations involve biological risks, risks acquired through social roles and behaviors, illness behavior, health-reporting behavior, physicians' diagnostic patterns, and differential health care access, treatment, and use (Preston 1970; Waldron 1985; Nathanson 1995; Pampel 2002; Preston and Wang 2006). Austad (2006) concluded that although the health/survival paradox has been studied for decades, we still understand very little about the reasons for the paradox or its mechanisms. This lack of understanding is largely due to the complexity of the multiple factors that affect health and survival and that differentially affect males versus females.

A key reason that confusion envelops the health/survival paradox is that the paradox might not be true. What does "health" mean? Gaining a deeper appreciation of male versus female differences along various dimensions of health is an important research priority. Males may be healthier than females along some dimensions but not along others. Furthermore, seemingly better male health may be an artifact of differences between men and women in their willingness to participate in health surveys, in their interpretation of survey questions, or in their knowledge of their own health. Demographers deeply appreciate the problems that arise from "bad data," and it is vital that demographers help develop reliable, well-defined measures of health.

In addition to considering "what does 'health' mean?," attention should be given to "what does 'survival' mean?" At first thought, this may seem obvious but the question is actually a complicated one. "Survival" can be measured by life expectancy at birth or by remaining life expectancy at some age, such as 15 or 50. "Survival" can also be measured by the chance of living from some age, say 15, to another age, say 50. And "survival" can be measured by the probability of death at some specific age among those who reach that age—age 25, say, or age 80. For some populations females may suffer lower mortality than males at certain ages but not at others. A further complication is that it is sometimes difficult to get reliable estimates of mortality, especially in developing countries or in the past.

To advance knowledge about the health/survival paradox, it would be useful to study human populations in disparate countries today and also historically. Indeed, to put the paradox in deeper biological perspective, a key research endeavor would be to trace male versus female mortality and, if possible, some measures of health, back to prehistoric times. To the extent that male versus female differences stem from fundamental biological factors, the differences should also be found in other species. Hence it would be informative for demographers to study other primates, such as baboons or lemurs. More generally, studies of diverse vertebrates (mammals, birds, reptiles, amphibians, and fish) would shed light on the unity or diversity of sex differentials across the tree of life. Studies of animals can reveal deep conservation of mechanisms and processes across species and can lead to the formulation and testing of general principles that hold for humans as well as other species.

5. Life expectancy reached 40 and began to rise persistently starting in the second decade of the nineteenth century, this revolution being led by Sweden, Norway, and Denmark. Why the 1810s and why Scandinavia? And why persistently?

In 1814 Swedish female life expectancy was 40 years. It had exceeded 40 in a few scattered years before 1814 and it fell below 40 in four bad years afterward. But 1814 is a reasonable date for when the expectation of life for Swedish females decisively broached 40 and began a persistent rise. In five years before 1882 life expectancy exceeded 50, and after 1882 life expectancy never fell below 50. Norway and Denmark followed similar trajectories. England was also an exceptionally long-lived country in the early nineteenth century, with a life expectancy above 40 years for females—and in many years somewhat above Scandinavian levels—but the rise was slower than in Scandinavia: female life expectancy reached 50 some 20 years after it did so in Sweden. Other European countries lagged well behind, with female life expectancy persistently above 40 attained by France a quarter century after the Swedish breakthrough—and reached by the Netherlands, Germany, and Italy six, seven, and eight decades after Sweden.

For thousands of years human life expectancy appears to have fluctuated between a brutal level in the low 20s and a high level in the upper 30s enjoyed by favored populations in salubrious years (Jeune and Vaupel 1995; Hoppa and Vaupel 2002). Life expectancy rose and fell, with no steady upward trend. Then, in the first part of the nineteenth century, life expectancy in the national populations doing best reached 40 and began to increase to current levels of 80 or more. Oeppen and Vaupel (2002) show that record female life expectancy at birth rose by a steady 2.5 years per decade—3 months per year, 6 hours per day—from a level of 45 years in the Scandinavian countries in 1840 to a level of 86 in Japan in 2007.

Why did this life expectancy revolution begin in Scandinavia and why did it start in the first part of the nineteenth century? Sweden, Norway, and Denmark were poor countries at that time and were not leaders in science or technology. They were, however, largely rural—and life expectancy was especially short in the cities of the industrial revolution. Furthermore, their citizens were relatively well educated, and society was relatively well organized and cohesive. The Scandinavian countries were—and remain—egalitarian compared with the rest of Europe. These factors probably played a role, but it is not clear how important they are in explaining the start of the rise in the expectation of life. Human existence has been fundamentally transformed by the life expectancy revolution: understanding its origins is a clear research priority for demographers.

A related priority is to understand why life expectancy steadily rose from 40 to more than 80 in the countries doing best. The life expectancy leader changed—from Sweden and Norway to New Zealand and then various other countries and now Japan. Progress was initially due to reductions in mortality at younger ages, especially from infectious diseases. The current rise in life expectancy is largely driven by improvements at older ages, especially regarding chronic diseases. For Swedish females in the 1840s, age-specific death rates were declining at an average pace of about 1 percent per year: that pace in Japan is now more than 2.5 percent per year. On the other hand, most deaths in Japan today occur among the elderly, so averting a death does not add as many years to life as it did when many deaths were among the young. The net outcome of these various shifting factors has been a remarkably linear increase in life expectancy in the best-performing countries. Determining how such simplicity resulted from such complexity is a puzzling challenge for demographers.

6. Why do some species (e.g., humans) suffer senescence whereas most species do not?

Hamilton (1966) forcefully argued that senescence, starting at sexual maturity, was inevitable for all species. He asserted (1996: 90) "that no life schedule, even under the most benign ecology imaginable, could escape from my spectrum of forces of senescence." Humans, at least today in modern societies, do indeed follow Hamilton's dictum, and other species undoubtedly do as well. But it appears that for extended periods after reproductive maturity many species enjoy constant or declining mortality and constant or increasing fertility. Demographers could help demonstrate this and could contribute to understanding why some species suffer senescence and others do not.

For humans, death rates are high in infancy, fall to low levels around puberty, and then start to increase with age. From age 35 or so to around age 90, the rise is exponential, following Gompertz's "law," with death rates increasing by about 8–14 percent per year depending on the time period and population. After age 90 mortality continues to rise but at a slower and slower pace. After age 110 death rates appear to level off at an annual age-specific chance of death of about 50 percent per year (Maier et al. 2009). The "increased inability to withstand destruction" (as Gompertz put it in

1825: see Smith and Keyfitz 1977) is accompanied by a rise in cognitive and physical impairment. After age 40, fertility declines sharply for women and more gradually for men. As we grow old, we suffer senescence, though with substantial differences among individuals.

A rise in mortality and morbidity and a decline in fertility with age are also observed in many other species, including all primates and nearly all mammals studied to date. In many instances, however, the process of progressive decrepitude appears to start at a later age than puberty: there is a long period of enhancement during which mortality falls and fertility rises with age (Nussey et al. 2008). This may even have been the case for humans for most of our existence as a species: Gurven and Kaplan (2007) review data on remote groups of hunters and gatherers that suggest that death rates may have declined at least up to age 30 or so.

For various species in other clades of life, mortality appears to fall and fertility appears to rise over most of the adult life span. It is not clear what happens at very old ages, but some species appear to enjoy enhancement up to ages when almost all adults have died. Suggestive data on extended periods of post-maturational enhancement are available for various species of birds, and Rebke et al. (2009) have conclusively demonstrated this for the common tern. Birds reach full adult size at the time of fledging, but many reptiles and fish continue to grow indeterminately—for many, and perhaps most of these species, mortality falls and fertility rises with size and hence age. This also appears to be the case for various plants that increase in size with age (Vaupel et al. 2004).

In her book *Inevitable Aging?*, Baudisch (2008) develops evolutionary-demographic models of why some species suffer senescence starting at maturity whereas other species enjoy extended periods of enhancement. She also considers maintenance, that is, constant mortality and fertility after maturity. Senescence can be considered the cumulative outcome of an imbalance between damage and repair. A species that can repair damage (or replace damaged organs) at the same pace damage occurs would enjoy sustenance. The chance of death would not be zero, but it would hover around a constant level as age progresses. Life expectancy would be finite but it would not decline with age. Baudisch presents some cogent theoretical arguments for the existence of such species. Martinez's (1998) research suggests that hydra may be an example.

Dobzhansky (1964) remarked that "nothing in biology can be understood except in the light of evolution" (p. 449). It can similarly be asserted that nothing in evolution can be understood except in the light of demography. Age schedules of fertility and mortality drive the growth or decline of populations and hence natural selection. Lotka's equation for the intrinsic rate of population increase serves as the foundation for much evolutionary analysis (Lotka 1922). Demographers can contribute to many topics related to evolution. In particular, they can shed light on why some species experience senescence and others do not. This research could fundamentally deepen our understanding of aging and might lead to breakthroughs that would help humans enjoy longer, healthier lives.

Conclusion

The study of death has been a focus of demographic analysis since the origin of the field when Graunt presented his *Bills of Mortality* to the Royal Society in 1662 (reprinted in Smith and Keyfitz 1977). Almost 350 years later, the endeavor shows no sign of senescence: mortality research is fecund and burgeoning with new ideas and findings. I have adumbrated six topics that fertile minds might find intriguing.

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