Science, Vol 291, Issue 5508, 1491-1492 , 23 February 2001
[DOI: 10.1126/science.291.5508.1491]

DEMOGRAPHY:

Prospects for Human Longevity

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The public-policy implications of an aging world are staggering--affecting the health status of billions of people, the financial integrity of age-based entitlement programs, and the economies of all nations (1, 2).

The dying of individuals and the aging of populations are linked, but there are important differences in their biological and statistical dynamics. Individuals have a specified life-span that is operationally defined by age at death. The documented longest-lived member of a species defines the maximum life-span. For populations, demographers and actuaries calculate a life expectancy based on the use of a life table. In heterogeneous populations, like humans, the maximum life-span is always greater than the life expectancy, by definition. Here, we examine the prospects for continued improvements in survival and increases in life expectancy for the human population.

In 1990, we demonstrated empirically that as life expectancy at birth rises, it becomes less sensitive to changes in death rates (3). This phenomenon is known as entropy in the life table (4-6). From demographic principles, we concluded that life expectancy at birth for males and females combined was unlikely to rise above 85 years (unless scientists can discover how to modify the aging process for a substantial portion of the population). Using age- and sex-specific death rates from 1985 to 1995 in Japan, France, and the United States, we have now examined whether recent trends in life expectancy at birth conform with our predictions.

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Methods

As before (3), we estimated the age schedules of conditional probabilities of death $q(x)$ required for the life table to yield life expectancies at birth of up to 100 years of age (in 5-year increments based on 1985 and 1995 death rates) by using two assumptions: (i) a proportional reduction p in age- and sex-specific death rates, $q(x)$, at every age x from 0 to 100 [that is, $q_r(x) = q_o(x)(1 - p)$, where q_r and q_o refer to the reduced and currently observed death rates respectively], and (ii) a proportional reduction in age- and sex-specific death rates for ages 50 and older. Infant mortality $q(0)$ was not permitted to decline below five deaths per 1000 live births, because we assumed that existing levels of lethal inherited diseases, accidents, and homicide represent a mortality barrier at about this level.

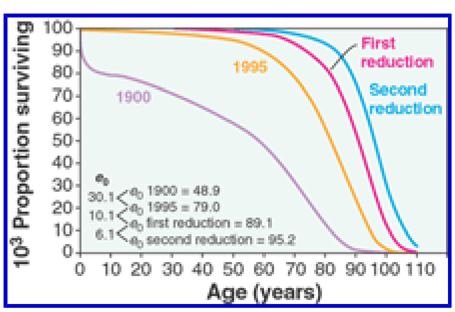
The mortality reductions from 1995 levels needed to yield life expectancies greater than 100 years require the near-total elimination of all mortality risks before age 85. Because that is unrealistic, we only dealt with mortality reductions that produce life expectancies no higher than 100 years. Limiting the analysis in this way avoids the technical problem of choosing how to close a life table for a sizable hypothetical population of supercentenarians surviving beyond the age of 120 (7).

Still in Search of Methuselah

Life expectancy at birth has continued to rise in low-mortality populations from 1985 to 1995. In order to rise to and beyond 85 years, however, extremely large reductions in current levels of total mortality for both males and females are required. For example, the 1995 death rates would have to decline by more than 50% at every age in order for life expectancy to reach 85 years in the United States (from 1995 levels of 79.0 for females and 72.4 years for males) [Web fig. 1 (8)]. Even among the longest-lived subgroup in the world (Japanese women), total mortality at every age would have to drop by 20% in order to raise life expectancy by 2 years from its current 83 years [Web fig. 2 (8)]. Although females in France have enjoyed a life expectancy at birth that has exceeded 80 years since 1987, their 1995 death rates would have to decline by more than 26% at every age in order to achieve a life expectancy of 85 years [Web fig. 3 (8)]. A decade after our initial calculations, 85% reductions in current levels of total mortality at every age are still required in order to reach a life expectancy at birth of 100 years in long-lived populations like those of Japan and France.

To illustrate the phenomenon of entropy, consider the fact that when life expectancy at birth is 50, it takes an estimated 4.1% reduction in total mortality at every age to raise life expectancy 1 year [Web fig. 4 (8)], a mortality scenario similar to that experienced by French females at the beginning of the 20th century. By contrast, raising life expectancy from 80 to 81 years requires a 9.1% reduction in total mortality at every age. The mortality reductions at every age required to achieve a 1-year increase in life expectancy at birth today are more than twice those needed to achieve the same gain early in the 20th century. As life expectancy at birth reaches the 80s, entropy in the life table means that small but equal incremental gains in life expectancy require progressively larger reductions in mortality. So far, the empirical evidence is clear. Future gains in life expectancy will not only occur at a slower pace, but they will depend on a continuous stream of developments in the biomedical sciences that lead to treatments and cures for the diseases and disorders of aging itself. Achieving life expectancies of 100 years or more exclusively through life-style modification remains as unrealistic today as it was 10 years ago.

Throughout most of the 20th century, death rates declined dramatically at every age in developed nations, and life expectancy at birth rose rapidly (9). For example, life expectancy at birth for U.S. females increased from 48.9 years in 1900 to 79.0 in 1995. If these declines could be duplicated for the 1995 mortality levels, life expectancy would only rise by 10.1 years to 89.1, not the 30-year gain observed previously (see figure, below). A third repetition of the mortality reductions would yield an additional 6.1 years, another tangible example of entropy in the life table. In reality, the large mortality reductions of the 20th century cannot be repeated for the population under age 50 in the low mortality populations of the 21st century because infectious and parasitic diseases are no longer the primary causes of death at these ages. This means that much larger mortality reductions will be required at older ages for life expectancy to rise significantly.



Survival curves and life expectancy at birth for females in the United States (1900, 1995, and projected).

Among the longest-lived subgroups of the human population (Japanese females), recent mortality declines are steep enough to support our 1990 prediction that life expectancy at birth could rise to 85 years (88 years for females and 82 years for males) in some countries in the 21st century. Although death rates among long-lived populations continue to decline at middle and older ages, the chance of achieving a life expectancy at birth of 90 years and older has not changed appreciably over the last decade. Thus, despite predictions to the contrary, rapid increases in life expectancy, like those observed early in the 20th century, are no more plausible today than they were a decade ago.

If age- and sex-specific trends in death rates observed from 1985 to 1995 continue into the future, life expectancy at birth for males and females combined would reach 85 years in 2033 in France, 2035 in Japan, and 2182 in the United States (see table). If these trends continue, then life expectancy at birth of 100 years will not occur, if ever, until well after everyone alive today has died.

CHANGE IN DEATH RATES AND PROJECTED LIFE EXPECTANCY

	Annual average percentage change in $q(x)$ at ages						**Projected year for reaching life expectancy of**	
	0-19	**20-39**	**40-59**	**60-79**	**80-99**	**0-99**	**85**	**100**
France (F)	-2.7	-0.8	-1.3	-2.2	-1.6	-1.7	2014	2106
France (M)	-3.2	0.0	-1.6	-2.0	-1.3	-1.6	2052	2138
Japan (F)	-0.5	-1.4	-1.5	-2.2	-1.9	-1.5	2010	2118
Japan (M)	-1.5	-1.2	-1.8	-0.9	-0.7	-1.2	2060	2182
USA (F)	-1.1	+0.7	-0.7	-0.6	-0.3	-0.4	2125	2485
USA (M)	-1.1	+1.1	-0.5	-1.4	-0.1	-0.4	2239	2577

Observed change in death rates and projected life expectancy. The last two columns show the year in which life expectancy at birth would reach the exact ages of 85 and 100, as projected from the percentage change on the left; $q(x)$ is defined as age- and sex-specific death rates.

Conclusions

Entropy in the life tables of long-lived populations like France, Japan, and the United States is the primary reason that the measure of life expectancy is no longer a reliable barometer of the health of a nation.

Unless the aging process itself can be brought under control, the mortality trends observed from 1985 to 1995 remain consistent with the expectation that future gains in life expectancy will be measured in days or months rather than years. In an environment of optimism about modern medicine and human longevity, it is sobering to realize that life expectancy (at birth or at older ages) could actually decline for some populations because of the re-emergence of infectious diseases (10, 11), social and political unrest, or natural disasters.

There are no life-style changes, surgical procedures, vitamins, antioxidants, hormones, or techniques of genetic engineering available today with the capacity to repeat the gains in life expectancy that were achieved during the 20th century. If there is going to be another quantum leap in life expectancy at birth (20 to 30 years or more), these large gains will have to come from adding decades of life to the lives of people who reach the ages of 70 and older. Modifying endogenous biological processes to achieve this goal, although theoretically possible, will be much harder than reducing children's death rates from infectious and parasitic diseases (12).

The projected life expectancy of populations has important implications for public policy. For example, since 1935, actuaries at the U.S. Social Security Administration (SSA) have been required by law to make forecasts of the future size of the beneficiary population. In their latest official forecast, the SSA estimated that life expectancy at birth would rise to 79.3 years for males and 83.9 years for females by 2070 (13). Death rates in the age ranges 0 to 14, 15 to 64, and 65 and older would have to decline by 1.2%, 0.57%, and 0.50%, respectively, for each of the next 70 years for the SSA's forecast to be true (14). If this were to occur, however, the projected death rate would approach zero for the population aged 0 to 30 in the latter part of the 21st century. Given the inevitable presence of accidents, homicide, suicide, infectious and parasitic diseases, and inherited lethal disorders, such a projection is biologically implausible and overly optimistic. Despite these concerns, a 1999 advisory group to the SSA recommended that this prediction for the year 2070 was too pessimistic, and should be raised an additional 3.7 years, leading to a projected life expectancy at birth of 83.1 years for males and 87.5 years for females (15).

This revised assumption leads to the prediction that total mortality at every age for the next 70 years would decline at a rate that is twice as fast as the already favorable rate of mortality decline projected by the SSA. This point illustrates the public policy implications of ignoring the phenomenon of entropy in the life table and the underlying biology that influences age-specific death rates in populations.

Two methods have been used in recent years to predict that life expectancy at birth will reach 100 years in the 21st century: In the theoretical risk-factor model, all individuals are assumed to adopt optimum life-styles that promote health (16). In the second, demographic, approach, past declines in death rate are extrapolated to the future (17-19). Although the mathematics of the life table may not be violated by these methods, they ignore the biological forces that influence the length of life of individuals in genetically heterogeneous populations. Projections based on biodemographic principles that recognize the underlying biology within the life table would lead to more realistic forecasts of life expectancy that reflect the demographic reality of entropy in the life table, and the biological irony that biochemical mechanisms required to operate and sustain the machinery of life, also inevitably sow the seeds of its destruction.

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20. Funded by the National Institutes of Health/National Institute on Aging (AG13698-01 and AG00894-01 to S.J.O. and B.A.C.); the National Aeronautics and Space Administration (98-HEDS-02-257 to B.A.C.); and the Social Security Administration (10-P-98347-5-01 to S.J.O.). We thank S. Goss, R. Rogers, and L. Smith for comments on an earlier draft of this manuscript and L. Loziuk for preparation of figures.

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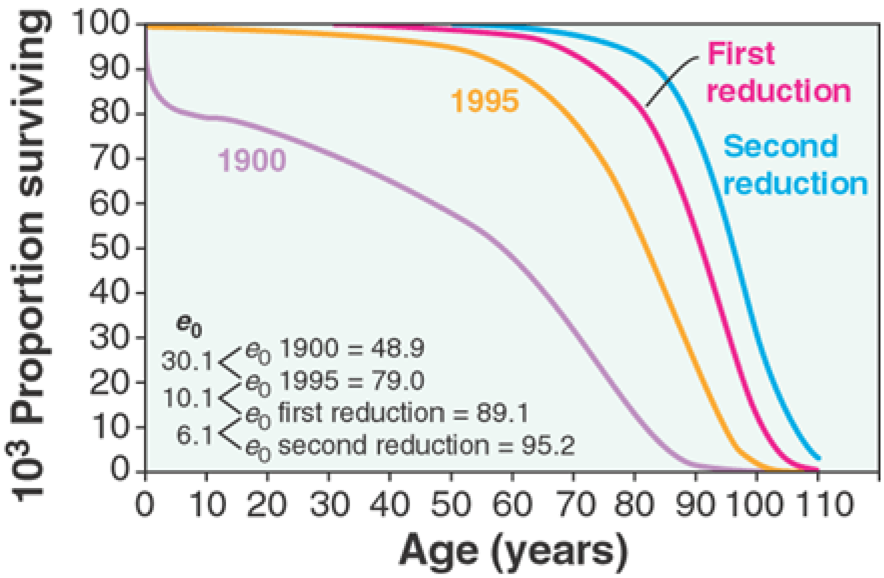

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