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TRENDS IN SENESCENT LIFE EXPECTANCY

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Abstract

The distinction between senescent and non-senescent mortality has proven very valuable for describing and analyzing age patterns of death rates. Unfortunately, standard methods for estimating these mortality components are lacking. The first part of this study discusses alternative methods for estimating background and senescent mortality among adults and proposes a simple approach based on death rates by causes of death. The second part examines trends in senescent life expectancy (i.e. the life expectancy implied by senescent mortality) and compares them with trends in conventional longevity indicators between 1960 and 2000 in a group of 17 developed countries with low mortality. Senescent life expectancy for females rose at an average rate of 1.54 years per decade between 1960 and 2000 in these countries. The shape of the distribution of senescent deaths by age remained relatively invariant while the entire distribution shifted over time to higher ages as longevity rose.

Past projections of life expectancy at birth in the developed world were often too pessimistic, i.e. they underestimated subsequent improvements (Keilman, 1997; National Research Council, 2000). The main reason for this bias was the inclusion of an upper limit to future life expectancy in most projections made before the 1980s. These supposedly fixed limits to longevity were broken repeatedly in the years following the publication of the projections as mortality declines continued at an unanticipated rapid pace even in countries with the highest life expectancies (Oeppen and Vaupel, 2002). Most agencies that make these projections have now abandoned the practice of setting limits, but the debate over future trends in life expectancy in low mortality countries remains controversial. Some analysts believe that the deterioration of biological processes in the aging human body is inevitable and that further increases in longevity will be very small at best. (Fries 1980; Olshansky, Carnes and Cassel 1990; Olshansky and Carnes 2001; Carnes and Olshansky 2007). In contrast, others note that best-practices life expectancy has increased at a very rapid pace (about 2.5 years per decade) since the middle of the 19th century and that this trend can and will continue (Oeppen and Vaupel, 2002).

To shed light on this debate this study will examine recent trends in the two main components of mortality: 1) Senescent mortality, which is the result of biological aging; it can be postponed through medical intervention, but it cannot be avoided because death is inevitable; 2) non-senescent deaths unrelated to aging (e.g. accidents, certain infections) which can be avoided by effective public health and safety measures and by medical intervention. Much of the large historical increases in life expectancy have been due to declines in non-senescent mortality, in particular among the young, but this source of rising life expectancy has now largely disappeared in contemporary developed countries. Non-senescent mortality has reached very low levels and nearly all deaths are now due to senescence. The key question for forecasters therefore is whether and how rapidly senescent mortality is changing and how these trends affect future life expectancy. There is no doubt that old age mortality rates are still declining (Kannisto et al 1994, Rau et al. 2006; Wilmoth, 1997), but it is unclear what these trends imply for longevity.

The distinction between senescent and non-senescent mortality stems from the work of Makeham (1860,1867). He proposed dividing the total force of mortality for adults into "two distinct and independent forces", one caused by "diseases depending for their intensity solely upon the gradual diminution of the vital power" and the other by factors that "operate (in the aggregate) with equal intensity at all ages"(Makeham 1867). He also demonstrated that the addition of a constant to the original exponential Gompertz model for adult mortality provided a better fit to observed age specific mortality rates than to the Gompertz model alone. The recent demographic literature often uses the terms "senescent" and "background" mortality to refer to the two components introduced by Makeham. The distinction between senescent and non-senescent or background mortality among adults has also proven very valuable for describing and analyzing contemporary age patterns of death rates (Carnes and Olshansky, 1996; Gavrilov and Gavrilova, 1991; Horiuchi and Wilmoth, 1998)[1]. Logistic models using these two components provide an extremely good fit to empirical data (Thatcher 1999, Bongaarts 2005).

It is important to emphasize that the terms "senescent" and "background" used in this study overlap with, but are different from, the terms "intrinsic" and "extrinsic" mortality used by biologists to refer to similar mortality components (Carnes et al. 2006). Intrinsic mortality is due to causes of death that arise primarily within an organism while extrinsic mortality originates from outside. Unfortunately, the distinction between intrinsic and extrinsic is not always clear even if detailed cause of death information is available (Carnes et al. 2006). In contrast, the two Makeham components can be identified empirically from demographic data: any cause of death resulting in mortality that rises steeply with age among adults is considered senescent while any cause that doesn't change or changes little with age is considered "background" regardless whether the origin is inside or outside the organism. For many causes of death the labels assigned by these two decomposition approaches are the same. For example, cancer and heart disease are considered both intrinsic and senescent, and accidents are considered both extrinsic and background. But there are notable exceptions in which the labels differ between the decompositions. For example, mortality from most infectious and parasitic diseases rises rapidly with age among adults and will therefore be considered senescent, but biologists call this mortality extrinsic because it originates outside the body.

Conversely, mortality related to pregnancy and childbirth would be considered intrinsic, even though it plays no role senescence.

The first part of this study discusses alternative methods for estimating background and senescent mortality among adults and proposes a simple method based on death rates by cause of death. The second part examines trends in senescent life expectancy (i.e. the life expectancy implied by senescent mortality) and compares them with trends in conventional longevity indicators between 1960 and 2000 in a group of 17 developed countries with low mortality.

Data

The empirical results presented below on overall mortality are drawn from the Human Mortality Database (2008). Death rates by single age from 25 to 109 and for every year from 1958 to 2002 were downloaded for males and females in the following seventeen countries: Australia, Austria, Canada, Denmark, England and Wales, Finland, France, Italy, Japan, Netherlands, New Zealand , Norway, Portugal, Spain, Sweden, Switzerland, and the USA. Single age and single year death rates often contain significant seemingly random variation, particularly at younger ages, and in a few instances death rates are even zero. To avoid these undesirable fluctuations five year moving averages were calculated with the smoothed age specific death rates for year *t* equal to the averages for years *t-2, t-1, t, t+1* and *t+2*. Mortality indicators derived from these rates are therefore available for all 17 countries from 1960 to 2000. The age pattern was not smoothed[1].

In addition, estimates of death rates by cause were taken from the WHO Mortality Data base databank (WHO 2009). This database contains the number of deaths by country, year, sex, age group and cause of death (coded according to the International Classification of Diseases (ICD)) from 1958 to 2002 for the seventeen countries included in this study. Age specific death rates were calculated by dividing numbers of deaths in each category by the corresponding population which is also provided in the database. Five year moving averages of these rates were calculated as described above.

Alternative methods for estimating senescent mortality

Let $m(a,t)$ denote the death rate at age a in year t. Makeham, divided this rate for adults into two components: $m_b(t)$ for background and $m_s(a,t)$ for senescent mortality so that

$$m(a,t)=m_b(t)+m_s(a,t) \qquad for\ a>25 \qquad (1)$$

Background mortality can changes with time but was assumed constant above age 25, and all mortality under age 25 was considered non-senescent. Makeham examined mortality above age 20, but a slightly higher age limit is used here to avoid the "accident hump" around age 20 in many contemporary societies.

Two methods for estimating the senescent and background components among adults are discussed below. Both methods first estimate background mortality and then calculate senescent mortality by subtracting estimated background mortality from the observed mortality of all causes combined. In the first method background mortality can vary with age while the second method assumes it to be age invariant.

1) From cause of death information

Figure 1 plots the death rates (log) for the 15 leading causes of death for age groups <1,1-4,5-15…75-85 in the United States in 2005 (Kung et.al. 2008). These results confirm that Makeham's idea of two classes of causes of death among adults is roughly correct. For three leading causes (accidents, suicides and homicides) the death rates are approximately constant or slightly declining with age for adults, while the rates for the remaining causes rise steeply with age. The one cause that does not fit this pattern clearly is chronic liver disease and cirrhosis which rises steeply to around 60 and then rises at a much slower pace at higher ages.

Figure 2 plots the total death rate of all causes combined (upper solid line) as well as the estimated background and senescent components (dotted and dashed lines respectively) by age. Background mortality is estimates by summing the death rates from accidents, suicides and homicides. It is nearly constant until around age 70 and then turns somewhat higher. The senescent component is estimated as the sum of the remaining causes. It follows a Gompertzian pattern for adults i.e. an approximately exponential rise

which becomes a straight line on the logarithmic scale plotted in Figure 2. In age group 15-25 overall mortality is largely attributable to background causes while at the highest ages nearly all mortality is senescent.

The flatness of the background mortality pattern does not extend to the youngest ages. Background mortality for children is lower than among adults. Presumably this lower incidence of accidents, suicides and homicides among children is attributable to the protective environment of the family in which most of them live. As individuals make the transition to adulthood, leave home and enter the labor force, background mortality rises for age group 15-25 but then remains relatively stable at higher ages.

These estimates of senescent and background mortality in the US are relatively crude because they rely on data for the 15 leading causes of death. They slightly underestimate the true background mortality because there are other less important causes of deaths that are not related to senescence. In the application that follow deaths from AIDS and maternal deaths related to pregnancy and childbirth are added to deaths form accidents, suicide and homicide to obtain more accurate estimates of background mortality by age, year and sex for each country.

2) Fitting a parametric model

In the past, data on causes of death by age were not readily available for many countries and trends over time were even rarer. This is why demographers often relied on a different approach to obtain a Makeham decomposition. The most widely used past method for estimating background mortality is to fit a parametric model for the age pattern of adult mortality to observed death rates. This approach involves three steps. First, a model for the force of mortality by age for adults at time t is specified. One of the parameters in this model should be the level of background mortality which is assumed age invariant. For example, Gravilova and Gravilova (1991) use a Makeham-Gompertz model. Horiuchi and Wilmoth (1998) , Thatcher (1999) and Bongaarts (2005) use logistic models which include a Makeham parameter for background mortality. Second, the model is fitted to the observed force of mortality (log) at time t using a suitable numerical procedure. In the final step, this fitting procedure is repeated for each year and separately for females and females for each population, yielding time series of

background mortality $m_b(t)$ by sex. Once estimates of background mortality are available senescent mortality is estimated by subtracting background from observed mortality.

This fitting procedure has the advantage that it can be applied to any population that has reliable age specific death rates. Unfortunately, the method sometimes yields implausible estimates. In particular, in some countries in some years the estimated value of background mortality is either negative (e.g. for Hungarian males from 1992-2001) or exceeds the observed mortality rate from all causes at age 25 (e.g. for Spanish females from 1991 to 2001). Such estimates are unacceptable, because background mortality has to be positive and less than observed rates of overall mortality, to insure that senescent death rates are positive at all ages. In practice, estimates of senescent life expectancy are not sensitive to errors in background mortality and this fitting procedure thus gives fairly accurate estimates of senescent life expectancy. Nevertheless the cause-of death method is clearly more accurate and more robust and will therefore be used below.

Results

To simplify the presentation results will only be given for females.

Background mortality

Annual estimates of background mortality by age from 1960 to 2000 for each of the 17 countries were obtained with the cause-of-death method. The estimates for age group 25-39 are plotted in Figure 3. In 2000 background mortality ranged from a high of 0.000329 in the US to a low of 0.000128 in England and Wales. The average background mortality for the 17 countries (solid line in Figure 4) declined by 27% from 0.000260 in 1960 to 0.000189 in 2000. This trend was not steady: a modest decline in the 1960s, then relatively little change until the early 1990s, followed by significant decline during the late 1990s. A full explanation for these trends and the substantial fluctuations in individual countries will not be attempted here, but it is noteworthy that transportation accidents generally rose during the 1960s and 1970s and declined subsequently, and AIDS deaths were very rare until the mid-1980s and peaked in the early 1990s. In addition there are no doubt errors in the reporting of causes of death.

Senescent age specific death rates

Estimates of senescent mortality for single ages from 25 to 109 were obtained by subtracting the estimated age specific background mortality from the observed age specific death rates. Figure 4 (solid lines) plots these rates for Sweden in 1960 and 2000 for ages 25 to 79. This figure also includes the observed death rates (dashed line). The difference between the dashed and solid lines measures the effect of background mortality. With rising age the proportion of all mortality that is background declines and above age 50 the lines are virtually indistinguishable. The 2000 age pattern of senescent mortality is very similar to the one in 1960 except for a shift to the right reflecting rising longevity.

Figure 4 includes the OLS regression lines fitted to the estimates of senescent mortality. The fit is excellent with R^2=0.994 in 1960 and R^2=0.996 for 2008. Similar results hold for other countries and for males as well as females with R^2 averages for 1960-2000 exceeding 0.99 in all cases except females in Portugal for which the R^2 averaged 0.989 (data not shown).

Senescent life expectancy

The life expectancy implied by the senescent death rates is obtained with a standard life table in which newborns are subjected only to the risk of senescent mortality. Senescent life expectancy at birth $e_s(t)$ is calculated from the senescent age specific mortality rates $m_s(a,t)$ with:

$$e_s(t) = 25 + \int_{25}^{\infty} e^{-\int_{25}^{x} m_s(a,t)\,da}\,dx \qquad (2)$$

This estimate of $e_s(t)$ equals the average number of years a new born would live in the life table for year t in the absence of non-senescent mortality. Estimates of senescent life expectancy for females plotted in Figure 5 show a steady rise from 1960 to 2000 in each of the 17 countries except for a pause in Denmark around 1990. On average $e_s(t)$ rose by 6.18 years between 1960 and 2000 (from 76.6 to 82.7 years). In 2000, 15 of the countries cluster around their average, but Japan (85.7) and Denmark (80.3) are outliers.

Distribution of senescent deaths by age

The period life table used to calculate senescent life expectancy also provides the corresponding distribution of senescent deaths by age. The mean of this distribution equals the senescent life expectancy. Figure 6 plots these distributions for 1960 and 2000 for females in Sweden. The shapes of the distributions are very similar in the two years, but the 2000 distribution is shifted to higher ages compared to the 1960 distribution. The amount of the shift (6.18 years) equals the rise in the senescent life expectancy between 1960 and 2000.

Standard deviation of the distribution of senescent deaths

Figure 7 plots the standard deviations of the age distribution of senescent deaths for all of the 17 countries from 1960 to 2000. Although there is some variation between countries, the trend for each country is nearly flat. The average standard deviation for the 17 countries is 12.2 years in 1960 and 11.6 years in 2000.

The main conclusion from these results is that senescent life expectancy has risen steadily at an average pace of 1.54 years per decade between 1960 and 2000 in this group of 17 countries. The shape of the distribution of senescent deaths by age remained relatively invariant while the entire distribution shifted over time to higher ages as longevity rises.

Comparison with standard life expectancy indicators

Levels and trends in senescent life expectancy will now be compared with the following four longevity indicators derived from conventional period life tables.

1) Life expectancy at birth, $e_0(t)$.

2) *Life expectancy at age 25 plus 25, $A_{25}(t)$.*This equals the mean age at death for survivors to age 25.

*3) Life expectancy at age 65 plus 65, $A_{65}(t)$.*This equals the mean age at death for survivors to age 65.

4) The adult mode of the distribution of deaths by age, M(t).

To simplify the discussion, estimates of these indicators from the 17 countries are averaged (unweighted) and the results for individual countries will not be examined. Figure 8 and Table 1 present the averages of senescent life expectancy and of each of the four conventional measures.

Table 1: Estimates of longevity measures for females in 1960 and 2000, average for 17 countries

	1960	2000	Gain 1960-2000	Pace Gain/yr
Senescent life expectancy $e_s(t)$	76.6	82.7	6.15	0.154
Life expectancy at birth $e_0(t)$	73.0	81.5	8.49	0.212
Life expectancy at age 25 plus 25, $A_{25}(t)$	76.0	82.2	6.18	0.155
Life expectancy at age 65 plus 65, $A_{65}(t)$	80.3	85.0	4.66	0.116
Mode, *M(t)*.	81.2	87.8	6.63	0.166

All indicator rise steadily over time but they differ significantly from one another. Life expectancy at birth is the lowest and the mode is the highest throughout the period. Explanations for the differences between the four conventional measures and senescent life expectancy are as follows:

- $e_0(t)$ is lower than $e_s(t)$, because it includes non-senescent mortality. The difference $e_s(t)$-$e_0(t)$ is a measure of the impact of non-senescent mortality on life expectancy.
- $A_{65}(t)$ is higher than $e_s(t)$ because it does not include mortality under age 65.
- $A_{25}(t)$ is lower than $e_s(t)$ because it includes background mortality. The difference between $e_s(t)$ and $A_{25}(t)$ is typically small in this group of countries because background mortality has reached very low levels.
- -*M(t)* is higher than $e_s(t)$, because the distribution of senescent deaths by age is skewed to younger ages.

The longevity indicators differ not only in level but also in trend. This is important because projections depend crucially on getting the trend right. Figure 9 and the next to last column of Table 1 present the average increases in the longevity indicators between 1960 and 2000. The largest increase of 8.49 years occurred in the life expectancy at birth, and the smallest in $A_{65}(t)$ (4.66 years). The order from highest to lowest pace is different from the order of longevity levels in Figure 8. For example, life expectancy at birth is lower than any of the other longevity measures throughout the period, but its pace of increase is highest. The explanations for the differences in trends are as follows:

- $e_0(t)$ rises at a faster pace than $e_s(t)$ because non-senescent mortality declines over time. Declines in non-senescent mortality have no effect on senescent life expectancy.
- $A_{25}(t)$ increases at a slightly faster pace than $e_s(t)$ because background mortality declines over time.
- $A_{65}(t)$, grows at a slower pace than $e_s(t)$ because the proportion of senescent deaths that occurs under age 65 declines over time as $e_s(t)$ rises
- $M(t)$ rises more rapidly than $e_s(t)$ because the distribution of senescent deaths has become slightly more skewed over time.

These results are summarized in Table 2 which lists the main advantages and disadvantages of each conventional measure as an indicator of senescent life expectancy. The last two columns of this table indicate whether observed levels and trends are higher (+) or lower(-) than for senescent life expectancy.

An interesting pattern is evident in Figure 8: $A_{25}(t)$, $A_{65}(t)$ and $e_0(t)$ converge over time to $e_s(t)$. This is as expected because the factors causing these indicators to differ from $e_s(t)$ are getting smaller over time. If juvenile and background mortality continue to decline in the future the difference between $e_s(t)$ and $e_0(t)$ and between $e_s(t)$ and $A_{25}(t)$ will approach zero. Similarly, as senescent life expectancy rises the proportion of

senescent mortality that occurs below age 65 will decline and the gap between $e_s(t)$ and $A_{65}(t)$ will eventually also approach zero.

Table 2: Advantages and disadvantages of five longevity measures as indicators of senescent life expectancy

	Advantage	Disadvantage	Relative to senescent life expectancy (1960-2000)	
			Level	Trend
Senescent life expectancy $e_s(t)$	Preferred indicator used as reference	Unconventional, requires estimate of background mortality	0 (reference)	0 (reference)
Life expectancy at birth $e_0(t)$	Widely known and available	Affected by trends in non-senescent mortality	--	++
Life expectancy at age 25 plus 25, $A_{25}(t)$.	Not affected by non-senescent mortality under age 25	Affected by background morality.	-	+
Life expectancy at age 65 plus 65, $A_{65}(t)$.	Not significantly affected by non-senescent mortality	Ignores senescent mortality under age 65 and trend is biased downward	++	--
Mode, $M(t)$	Simple to calculate	$M(t) > e_s(t)$ because age distribution of deaths is skewed. Mode is sensitive to small changes in distribution	++	+

Conclusion

The main objectives of this study are to estimate the background and senescent components of adult mortality and to analyze levels and trends in senescent life expectancy. In the 17 countries included in this study senescent life expectancy for females rose at an average rate of 1.54 years per decade between 1960 and 2000. The shape of the distribution of senescent deaths by age remained relatively invariant while the entire distribution shifted over time to higher ages as longevity rose.

The trend in e_s is close to linear between 1960 and 2000 and there is no obvious reason to believe that the pace will be significantly slower or faster in the future. This trend and the fact that e_0 converges on e_s in the long run makes senescent life expectancy the most suitable indicator for projecting future trends in life expectancy at birth.[2] The steady rise in senescent life expectancy between 1960 and 2000 suggests that, if there is a limit to life expectancy, it is much higher than current levels. However, the fact that the pace of improvement in e_s is lower than for e_0, also suggests that the pace of improvement in e_0 will be lower in the future than in the past. Increases in life expectancy at birth in the past were attributable to declines in both non-senescent and senescent mortality. Declines in non-senescent mortality have now largely run their course and will have little further impact on life expectancy in low mortality countries. Future improvements in life expectancy at birth will therefore have to come largely from continuing declines in senescent mortality. The pace of these declines will depend on the ability of science to keep developing new biomedical interventions to overcome or postpone biological aging and to treat diseases, and on the ability of economies to provide affordable access to new treatments.

Endnotes

1) The reason for not smoothing across ages is that in many countries observed mortality rates in the 20s are U-shaped, i.e. they decline from a low peak around age 20, reach a minimum in the mid 20s before starting to rise again in the late 20s. If smoothing were done by age this U-shaped pattern would also be smoothed and trend above age 25 would be distorted.

2) Methods for projecting mortality based on the extrapolation of senescent life expectancy are discussed in Bongaarts (2005, 2006)

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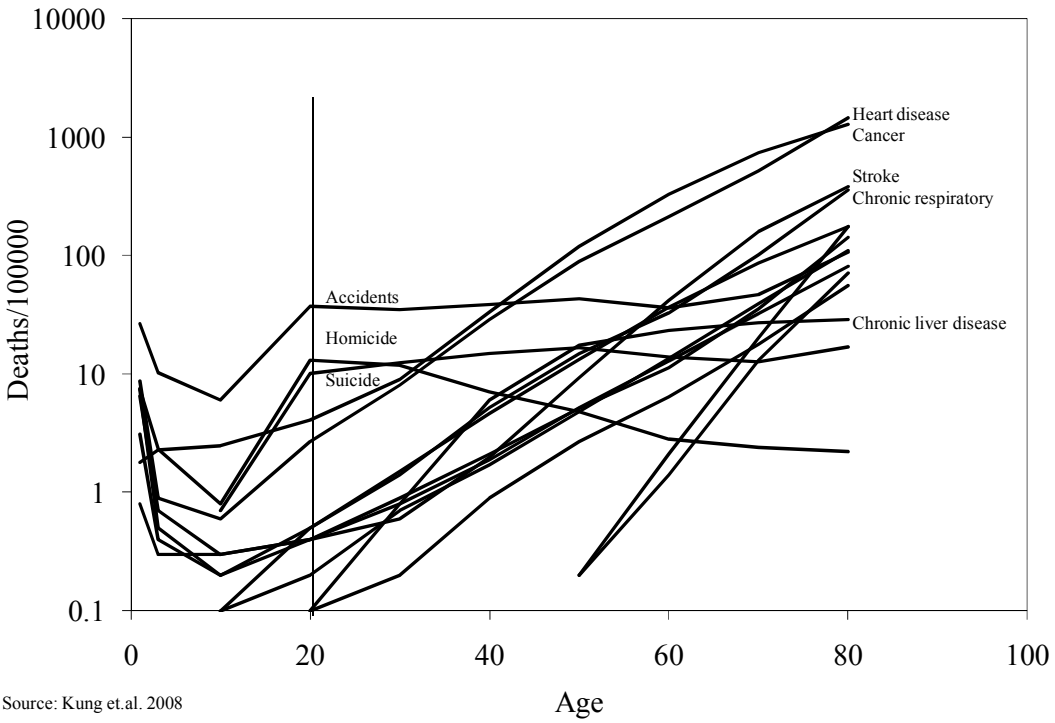
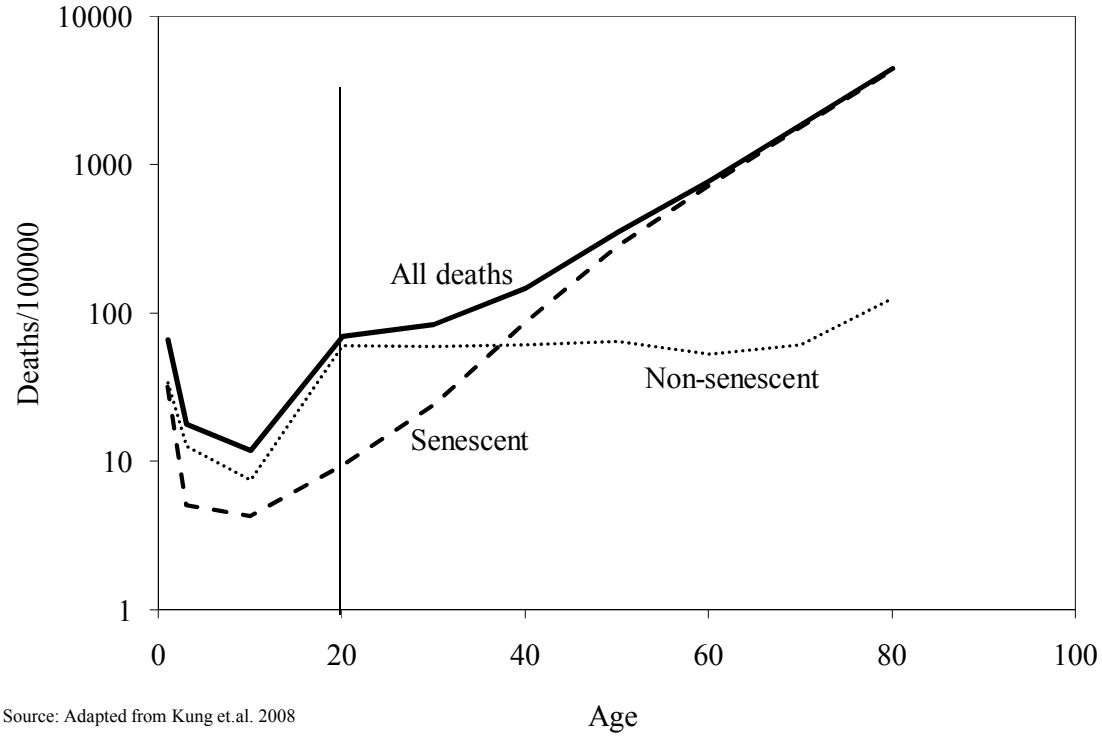
Figure 1: Death rates by age for the 15 leading causes of death, US 2005



Source: Kung et.al. 2008

Figure 2: Estimated senecent and non-senecent death rates by age, US 2005



Source: Adapted from Kung et.al. 2008

Figure 3: Estimates of background mortality (ages 25-39) 17 countries 1960-2000

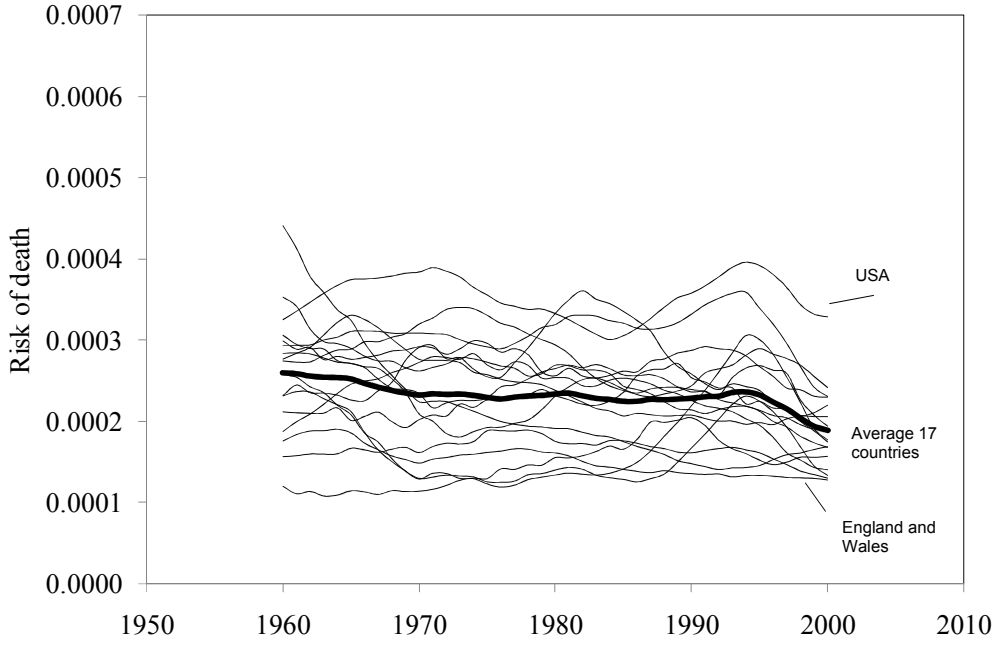


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Figure 4: Death rates by age, Swedish females, 1960 and 2000

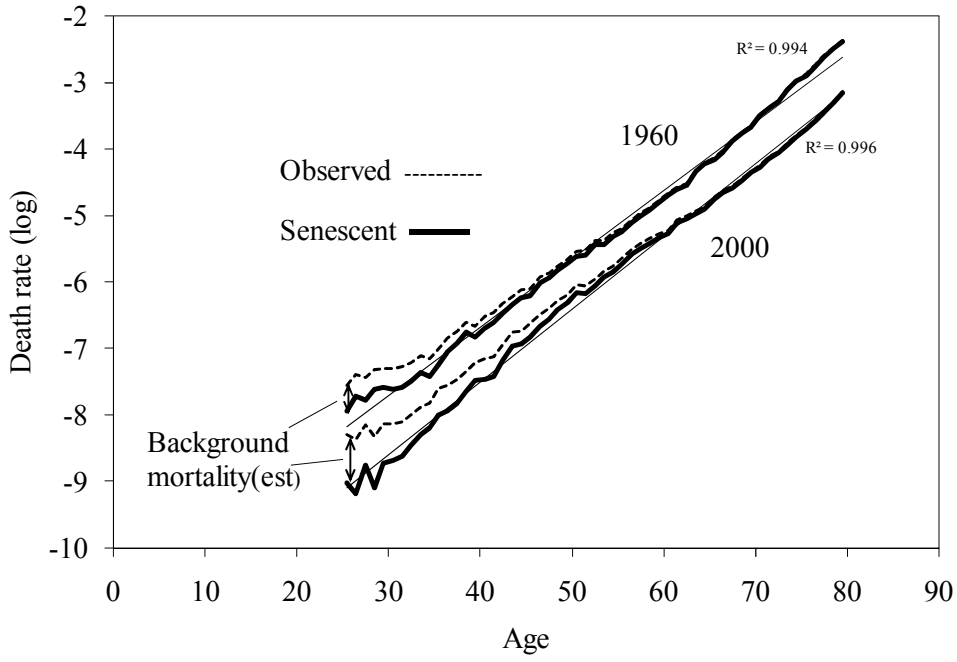

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Figure 5: Senescent life expectancy for 17 countries, 1960-2000

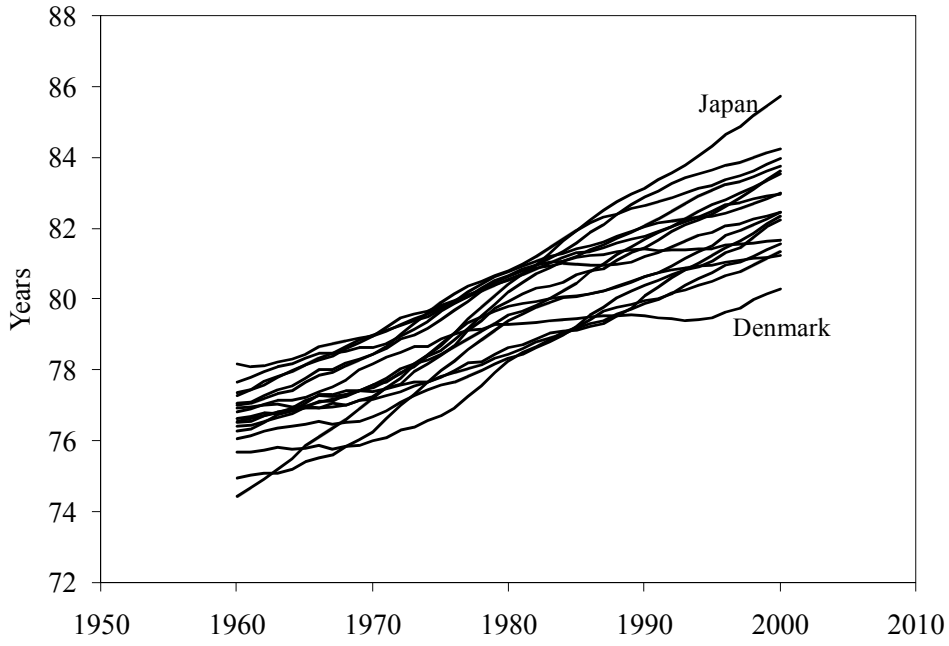

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Figure 6: Distribution of senescent deaths by age, Swedish females, 1960 and 2000

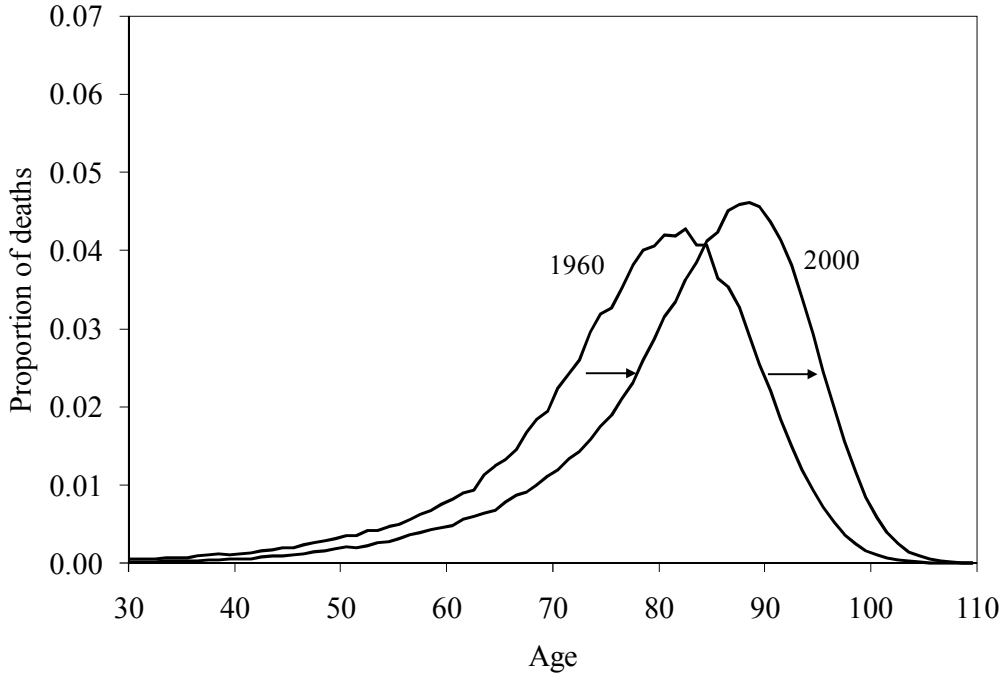

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Figure 7: Standard deviation of distribution of senescent deaths, 17 countries, 1960-2000

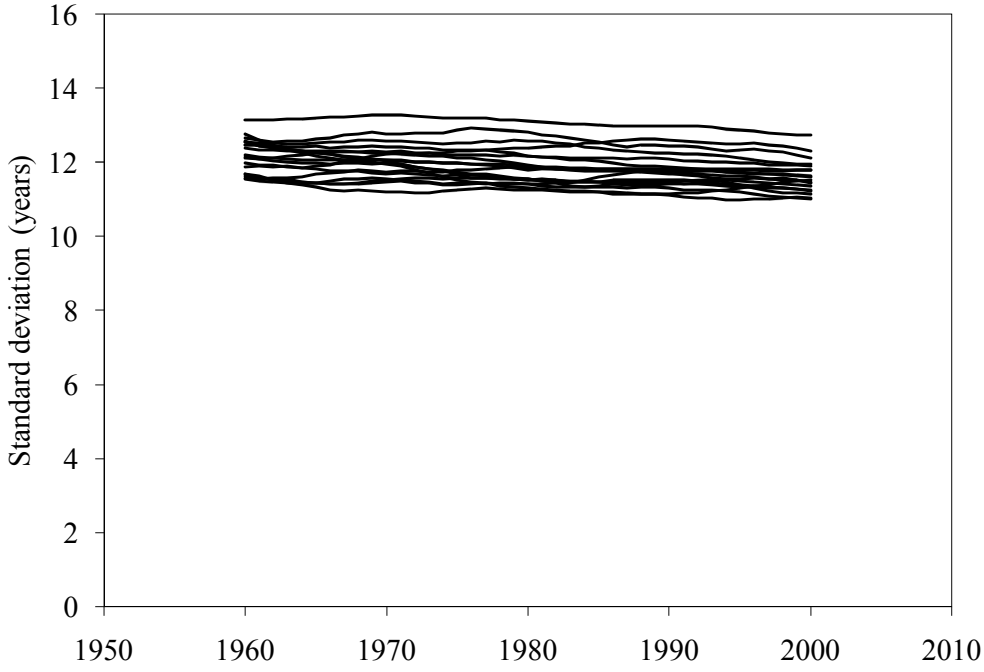

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Figure 8: Estimates of longevity measures for females, 1960 to 2000, averages for 17 countries

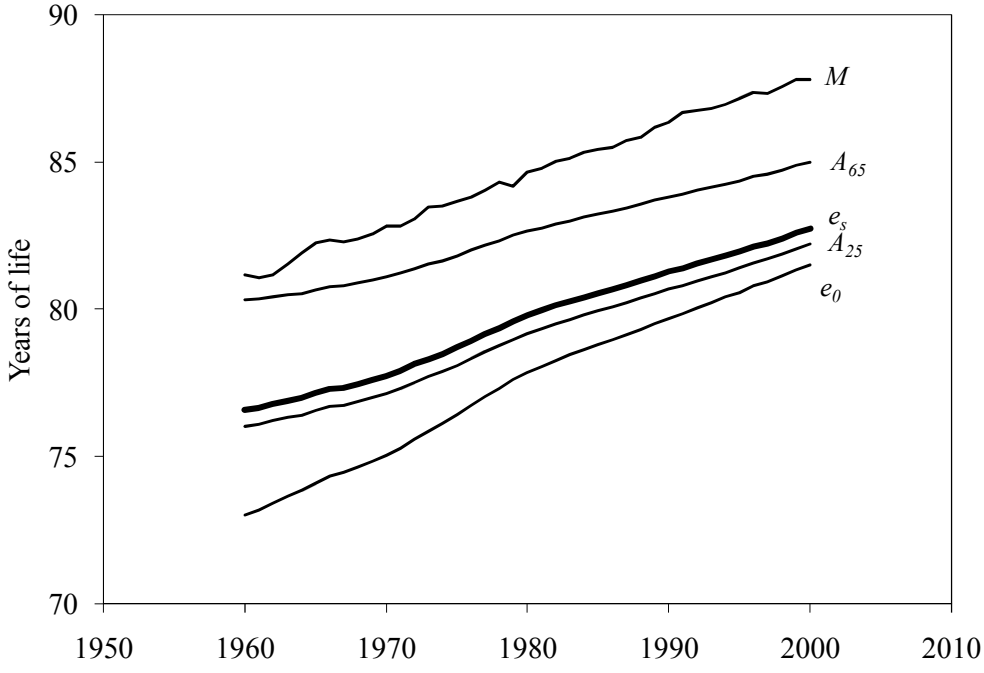

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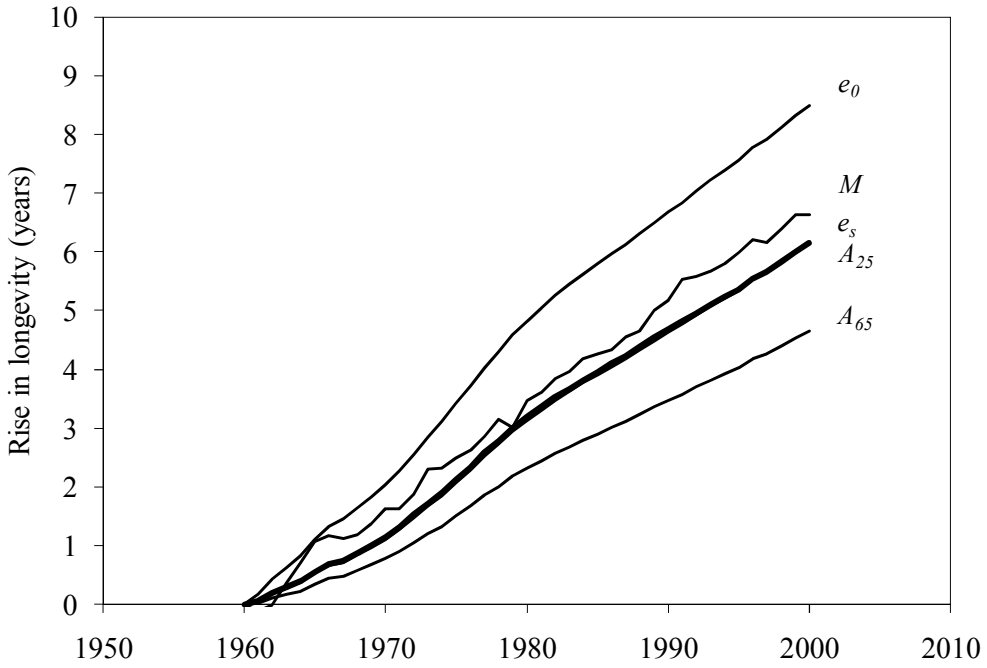
Figure 9: Rise in longevity measures from 1960 level for females, 1960 to 2000, averages for 17 countries



Source: See text