Typology and Review of Measures of Human Aging, Longevity and Superlongevity, with Applications to U.S. Data and Some Implications for U.S. Public Programs

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Abstract

A multiway typology of measures of aging, longevity and superlongevity is presented, with measures classified as measures of aging and longevity, direct and indirect measures of aging and longevity, and measures based on population data, death statistics and life table functions. More specifically, the typology distinguishes measures of individual aging, population aging and biological aging; measures based on observed populations, observed deaths and life table functions; cohort and period measures; and measures based on time from birth and time to death. Measurement of time to death serves as a new way of looking at aging and longevity, and use of it could provide a degree of control over the fiscal consequences of increasing longevity on public programs. A simplified measure of the slope of the distribution of the population from age 22 to age 84 is tested as a measure of the aging of the population. The ratio of life expectancy at birth to complete life expectancy at age 100 provides a new measure of the compression of mortality and of the direction and extent of the rectangularization of the survival curve. The data suggest that a substantial increase in life expectation at the highest ages, e.g., age 100, not currently envisaged, will be required to achieve a turnaround in the increasing rectangularization of the survival curve. The trend of the longevity dividend (i.e., the combination of the difference between conventional life expectancy and complete life expectancy, and the difference between period and cohort life expectancy) by age is analyzed. It is found that the potential gains over life expectancy at birth recorded in each period life table, from survival to later ages and from the secular reductions in death rates, have been dramatic since 1900, but with the secular rise in life expectancy the potential gains have fallen off sharply.

The trends of the measures are compared using data for the United States from 1900 to 2050, and their implications for selected U.S. public programs are briefly discussed. The data are taken from NCHS, Census and SSA reports, principally census data, official population estimates, death registration statistics and official life tables.

1. Introduction

This paper aims to set forth in a systematic fashion the many measures that have been used to describe and analyze aging and longevity, including those used to measure superlongevity, to present historical and prospective data for many of the measures for the United States, and to consider some applications to U.S. public programs. This review of the measures leads to a suggested typology for them. I discuss and illustrate the measures with data for the United States, from 1900 on, but mainly for the century centering on the year 2000. The basic data are taken mainly from the records of the National Center for Health Statistics, the Census Bureau and the Office of the Actuary, Social Security Administration.

The measures describe in different ways the degree to which the U.S. population is aging, and reveal any shifts in population at the highest ages that may suggest whether human life span is rising and has an upper limit. While the logical endpoint is the change in population age structure, mortality data in the form of death statistics and life table functions provide an indirect way of making determinations about aging and a direct way of examining longevity. Hence, the measures described include some based on population data, some based on observed deaths, and some based on life table functions, including mortality rates, survivors, life table deaths and life expectancy. The scope of these measures reflects the more complex and refined analyses now being made of the upper segments of the age distribution.

1.1 Concepts of Aging and Longevity

It is useful at the start to define the two principal terms with which this paper is concerned—aging and longevity. Aging has at least three meanings, and different measures of aging are associated with each concept of aging. We may distinguish individual aging, biological aging and population aging, and some variants of them. Individual aging refers to the chronological aging of individuals or groups of individuals such as birth cohorts. Biological aging gives a biological focus to individual aging. It is a term often used by molecular biologists and biodemographers. It refers to the increasing vulnerability of a human to deleterious influences both from within the body and from the environment as the individual grows older. The term is also used to refer to the accumulated damage to the cells, tissues, and organs that occurs as an individual gets older, particularly after the start of the reproductive period. In the latter meaning, biological aging is also called senescence. Like the demographer's concept of individual aging, biological aging is a characteristic of individuals and includes the concept of chronological aging, but more importantly it encompasses the age-related somatic changes besetting the individual as she/he gets older. In contrast to individual aging and biological aging, population aging, the third concept of aging, is a characteristic only of a population, and measures of population aging inform us directly whether the population as a unit is getting older or younger. Measures of population aging are strictly measures of aging and not longevity, but they can provide insights into longevity indirectly.

Longevity is a general term for the length of life and is a characteristic of individuals. Measures of individual longevity can be aggregated to describe groups of individuals and populations. We are familiar with such longevity concepts for individuals as age at death and life span, and the aggregation of these measures in the form of life expectancy and probability of surviving to specified ages.

1.2 Direct and Indirect Measures of Population Aging and Longevity

Several measures have conventionally been used to describe and analyze population aging. The most common measure is simply the proportion of the population aged 65 years and over but variations of this proportion are common. The average age of the population has also been used. In addition to these common measures, the slope of the proportionate age distribution of the population has also been proposed as a measure of the aging of the population. These serve as direct measures of population aging, but they can also serve as indirect measures of longevity. Many measures of longevity based on death statistics and life table functions have as their primary function the measurement of longevity but they can serve indirectly as measures of population aging. They typically aggregate data based on individual events of death or survival to describe longevity and population aging. The most common measure is life expectancy at birth, of course, but there are several extensions of this type of measure, including life expectancy at various ages, complete life expectancy at various ages, and age until expected death. Finally, at a different level of analysis, I describe various measures that reflect still more indirectly the progress in longevity incorporated into the tools we now use to describe longevity—mortality compression, longevity dividends and the biological rate of aging. For example, the relation between two measures of life expectancy (e_o and total life expectancy at age 100) is proposed here as a useful measure of the compression of mortality and of the direction and extent of the rectangularization of the survival curve.

1.3 Typology of Aging and Longevity

This general orientation toward the measures of aging and longevity form the basis of a typology relating the varied measures (Exhibit 1). The typology of measures of aging and longevity is constructed in terms of three levels, reflecting the different degrees of directness of the measures in relation to population aging and longevity and the different sources of the data. Measures at the primary level include the shares of elderly, advanced-aged, and super-aged persons in the population, the average age of the general population and of the aged population, and various ratios of them, and measures of the slope of the age distribution. These measures directly inform us about the aging of the population and indirectly inform us about the longevity of members of the population.

EXHIBIT 1

Typology of Measures of Population Aging, Longevity and Superlongevity

	Population	Vital statistics	Life tables
Level I. Population aging based on population data			
Percents elderly for different ages	X		
Ratio of elderly to younger age groups	X		
Average ages (mean, median)	X		
For total population, for ages 25+	X		
Slope of age distribution	X		
Average maximum observed life span	X		
Percent 100+ in total population	X		
Percent 100+ of 85+	X		
Level II. Direct measures of longevity; indirect measures of aging; measures of individual aging based on deaths and survivors			
Average age at death and percents over specified ages		X	X
Life expectancy at birth, at age 25			X
Age corresponding to specified years until death			X
Life endurancy			X
Average maximum life span			
Decedents		X	X
Survivors			X
Maximum annual age at death		X	
Level III. Indirect measures of longevity: Compression of mortality; survival dividends; biological rate of aging			
Compression of mortality: Relative interquartile range; coefficient of variation; percent life expectancy at birth ÷ total expectation at age 100			
For total population, for ages 25+		X	X
Longevity dividends			
Survival dividend			X
Cohort dividend			X
Combination of dividends			X
Biological rate of aging			X

Measures at the second level are indirect measures of population aging, but are direct measures of longevity. They include the average age of deaths, average maximum life span, life expectation, the age with specified years until death, the maximum annual age at death and complete life expectation. These measures may be based on observed death statistics or life table functions.

At the third level is a group of measures encompassing mainly the measures of mortality compression (or rectangularization of the survival curve) and the so-called longevity dividends. Longevity dividends are defined here as the gains in life expectancy achieved by success in survival. Illustrations are complete or total life expectation at each age as compared with the conventional expectation of life at birth, and cohort life expectancy as compared with period life expectancy. The combination of these two longevity dividends reflects a tremendous gain over period life expectation at birth. In this third category it is convenient to locate also the measure of aging of the population based on the age-progression of mortality rates and known among biologists as the rate of aging.

2. Direct Measures of Population Aging

2.1 Aging of the General Population

Proportions of the elderly. The U.S. population has been aging steadily ever since its founding and is expected to age very rapidly in the next few decades as the baby-boom cohorts reach age 65. (The first of the baby-boom cohort members reach age 65 in 2011; they are now 42-61 years old and the front-runners reach age 62 in 2008.) For this general characterization of the population, I am, as is commonly done, defining aging in terms of changes in the proportion of the population 65 years of age or over. Population aging can also be defined in terms of other population ratios, such as changes in the proportion under 18 years of age and changes in the ratio of the population 65 years and over to the population under 18 years or under 65 years. The United Nations uses 60 and over for the elderly population because the Less Developed Countries have such small proportions of their populations over age 65.

Table 1 presents values for some of the measures of aging for the United States at decennial intervals from 1900 to 2000, estimates for 2004 and middle-series projections from 2010 to 2050, based on U.S. Census Bureau reports. All of these measures indicate the same general aging trend over the last century and the first half of this century, although the slope measure displays a major irregularity in one vicennium.

TABLE 1

Comparison of Various Measures of Population Aging: United States, 1900 to 2050

(Census figures as of census date, April 1, unless shown otherwise. Figures refer to U.S. resident population. Census Bureau estimates and projections as of July 1)

Year	Percent 65 and over	Median Age	Mean Age	65+ [a] * 100 / 0-17	65+ [b] * 100 / 0-64	Slope of Age distribution[c]
Census						
1900 (June 1)	4.1	22.9	26.3	10.0	4.2	8.0
1910 (April 10)	4.3	24.1	27.2	11.6	4.5	7.9
1920 (Jan. 1)	4.7	25.3	28.1	12.4	4.9	8.7
1930	5.4	26.4	29.4	15.6	5.7	8.9
1940	6.8	39.0	31.6	22.4	7.4	9.2
1950	8.1	30.2	32.1	26.2	8.9	10.6
1960	9.2	29.5	31.7	25.8	10.2	14.3
1970	9.9	28.1	32.0	28.7	10.9	10.9
1980	11.3	30.0	34.0	40.1	12.7	9.2
1990	12.6	32.8	35.3	48.6	14.3	12.3
2000	12.4	35.3	36.3	48.4	14.2	15.1
Estimate						
2004	12.4	36.0	37.1	50.0	14.1	13.7
Projections[d] (Middle Series)						
2010	13.0	36.0	37.8	54.1	15.0	14.4
2020	16.3	37.0	39.1	68.0	19.4	16.6
2030	19.6	38.0	40.2	83.4	24.5	19.6
2040	20.4	38.1	40.8	87.3	25.7	23.0
2050	20.7	38.1	41.0	88.0	26.0	22.1
Change in Selected Periods						
1900-1950	4.0	7.3	5.8	16.2	4.7	2.6
1950-2000	4.3	5.1	4.2	22.2	5.3	4.5
2000-2030	7.2	2.7	3.9	35.0	10.3	4.5
2030-2050	1.1	0.1	0.8	4.6	1.5	2.5

[a] Ratio of the population 65 years and over to the population under 18 years per 100.
[b] Ratio of the population 65 years and over to the population under 65 years of age per 100.
[c] Number of ages corresponding to one-quarter of one percent change in the percent of the population at an age from average percent aged 22–24 to average percent aged 82–84.

Formula: .0025 / (Ave. P22..P24 - Ave. P82..P84) * 60

[d] Base date of projections is July 1, 2004.

Source: B**ased on** U.S. Census Bureau reports. *www.census.gov*.

It is possible for a population to grow younger although this has been very uncommon in the history of the United States or the western industrialized nations. Population younging is indicated by a decline in the proportion of persons 65 years and over, the median or mean age of the population, or the ratio of persons 65 years and over to persons under 18 years or under 65 years, or by a rise in the proportion of persons under 18 years. With these measures, it is possible for a population to grow older and younger at the same time, as when the proportion of persons 65 and over and the proportion of persons under 18 both increase and the proportion in the intermediate ages decreases (e.g., United States, 1950-1960).

Population aging as shown by these measures is affected by all three factors of population change—fertility, mortality and migration—but a country's fertility history largely explains the general contour of the age distribution and hence the aging class in which it falls. Among the countries of the world the United States is currently "middle-aged," with 12.4 percent aged 65 and over, but in the next several decades it will rapidly become "old" and then "very old," however measured. By 2050 the percent 65 and over is expected to be about 21.

<u>Average age of the general population</u>. Some measures of population aging focus on the shifts in the "average" age of the population (Table 1). They are the mean age and the median age of the population. These two measures generally move in tandem but the mean is a few years higher than the median because of the right skewness of the population age distribution. The record of the median age for three dates a half-century apart gives the general progression—30 in 1950, 35 in 2000 and 38 in 2050. The reader will notice that I did not include the modal age of the population among the averages. The modal age of the population is not useful since it is always likely to be near or at the youngest ages, as is the modal age of the life table survival population. It is not informative as a measure of aging or longevity.

<u>Demographic rate of aging.</u> The proposal was made a few decades ago to measure the aging of the population by fitting a straight-line curve to the age distribution of the

population and by obtaining the slope of the fitted line as the measure of aging (Kii, 1982). This procedure was not then subjected to close scrutiny and little attention was given to it. I apply this idea again here but in a simplified form. My simplified measure is the average number of ages required for the percent of the total population in single ages to fall by 0.025 (one-quarter) percent over the age range 22-24 to 82-84. Table 1 shows some illustrative figures using this measure for the population of the United States from 1900 to 2050. If this measure is to inform us about aging, the number of ages should rise as the population aged between 1900 and 2050, as suggested by several more conventional measures in Table 1.

My results show the number of ages very generally rising, but fluctuations around 1960-1980 are out of line. The arrival of the first members of the baby-boom cohorts at their early 20s appears to have “artificially” raised the share of the population at these ages and caused the number of ages reflecting the slope of the age distribution to fall over the 1960-1980 period. Perhaps for such a reason this measure can serve only as a rough indicator of population aging over short periods. The slope estimates over half-century periods, however, give a consistent picture; they are 8.0 years in 1900, 10.6 years in 1950, 15.1 years in 2000 and an expected figure of 22 years in 2050.

Comparison of the trend of the measures. In general, the various measures provide the same indication of the direction of the trend of the aging process—a generally increasing one and rapid increases over much of the 1900-2050 period. I pointed out the few exceptions earlier. However, they differ greatly in the rate of aging indicated. The ratio of the number of elderly to children is very sensitive to changes in population structure and rises very rapidly; the rate of change in the proportion of 65+ persons in the total population and the ratio of the 65+ population to the < 65 population are intermediate; and the mean and median ages and the slope of the regression curve move upward slowly. The trends of the latter three measures are highly correlated with one another but not with the other three measures. Yet, some studies have used the mean age in lieu of the percent 65 and over in the analysis of population dynamics because of the greater ease of mathematically manipulating the former (Preston et al., 1998).

2.2 Direct Measures of Aging of the Aged Population

Proportions of the aged population. Some measures of population aging focus on changes in the upper and even extreme parts of the age distribution. These measures of superlongevity have been used to identify changes at the highest ages to ascertain what they suggest as to changes in the life span of members of the population, the compression of mortality and the rectangularization of the survival curve. Analysis of changes in the number and share of persons at the very highest ages has become the new, second, front in the analysis of population aging in the western countries. Popularly persons 85 years and over are considered as advanced aged. The analysts of superlongevity are focusing on those 95 and over, centenarians—persons 100 years and over, and supercentenarians—persons 110 years or more. The new measures of the extreme aged are structured in terms of these age ranges. Typical measures are the percent of persons aged 100 and over among persons aged 85 and over, and the percent of persons 95 and over among persons 85 and over, but there are many variations depending on the interests of the analyst, such as,

85+ as percent of total population
85+ as percent of 65+
100+ as percent of 85+
95+ as percent of 85+
105+ as percent of 100+

In 2000 the reported number of centenarians in the U.S. population was 51,000 but its percent in the total population was only 0.02 (Table 2). Before the year 1980 the reported percent of persons 100+ in the total population was too small and shaky to be displayed; so I have omitted any data before that date. The percent of persons 100+ among persons 85+ apparently did not reach as much as 1 percent until 1980. The uncertain and tiny percentages before 1980 have been omitted from Table 2.

TABLE 2

Various Measures of Extreme Population Aging
Based on Population Data: 1900 to 2000 and
Projections, 2010 to 2050
(Month of reference same as in Table 1)

Year	Percent 85+ of total pop.	Percent 85+ of 65+	Percent 100+ of total pop.	Percent 100+ of 85+
1900	0.2	4.0	NA	NA
1910	0.2	4.2		
1920	0.2	4.3	|	|
1930	0.2	4.1		
1940	0.3	4.0		
1950	0.4	4.7	|	|
1960	0.5	5.6		
1970	0.7	7.5		
1980	1.0	8.8	0.01	1.0
1990	1.2	9.9	0.01	1.2
2000	1.5	12.1	0.02	1.2
2005	1.7	13.8	0.02	1.3
2010	2.0	15.2	0.04	1.9
2020	2.2	13.3	0.07	3.3
2030	2.3	13.4	0.11	4.2
2040	3.9	19.2	0.15	3.8
2050	5.0	24.1	0.27	5.5

NA: Reliable figures not available for years from 1900 to 1970.

Source: U.S. Census Bureau reports, www.census.gov.

Average age of the extreme aged population. Another class of measures of extreme longevity focuses on shifts in the average ages of the extreme aged population. While there is serious concern about the accuracy of the U.S. reported data, we want to examine them for what they may suggest as to aging among the extreme aged and the superlongevity of the population. We could examine changes in the average age of the population 85 years and over, 95 years and over or 100 years and over, but I shall consider only one of these measures, the one I call the average maximum life span. It is the mean age of the survivors 100 years and over. The mean age of reported U.S.

centenarians was about 102 in the year 2000. The vast majority of persons 100 years and over in the United States are under 105. For example, in the 2000 census 90 percent of reported centenarians were under 105 years of age; 7 percent were between 105 and 110; and 3 percent were 110 or over. In 1980 the reported percent of centenarians under age 105 was about the same as in 2000—91 percent, and their mean age was also about 102.

The accuracy of this last type of measure depends greatly on the quality of reporting age at the very advanced ages in the census. Data are available on the extreme aged in the census, Medicare files and enrollments of Social Security beneficiaries. The Medicare data and the Social Security data are validated to some degree and are lower than the census figures. They are improving with time and are believed to be superior to the census data (Kestenbaum, 1992, 2005; Rosenwaike and Stone, 2003). The census data at the highest ages are notoriously in error or lacking, and so I do not present a historical series on average maximum life span in Table 2. No trend can be discerned in the census figures, but errors in the data may conceal a real change. These are probable maxima given the tendency for the ages to be overstated.

The super-aged front-runners. Up to the recent past, age 100 has often been used by demographers and epidemiologists to define human life span. This was considered to be the age to which a substantial number of humans as a species could survive under optimum conditions and beyond which only a few persons survived. This number was not based on any empirical investigation but on the indications of current censuses, life tables and conventional wisdom. Although human life span is essentially a theoretical concept for which no precise value can be given, it has been useful to have such a concept for tracking the gap between the longevity achieved by the average person in a given area (i.e., life expectancy at birth) and the longevity achievable by humans under the most favorable conditions. It has also served for comparative analysis of longevity with subhuman species.

The record for the maximum recorded life span, or the highest verified age of a member of the human species, living or deceased, is held by Jeanne Calment of France, who died in 1997 at the age of 122 years, 164 days. Often age 120 is now cited as the maximum life span for humans, but there is no validated record of anyone surviving to this age except Mme. Calment. While we still consider 100 as the maximum age to which any substantial number of persons may aspire to live under the most favorable circumstances, survival for many persons to age 100 is conjectural inasmuch as only a small fraction of 1 percent of any large population survives to this age. In 2005 the estimated percent of centenarians in the U.S. population was only 0.02.

The maximum observed life span is the highest verified age for a living member of the human species. The validated incumbent of this position changes frequently because of the high mortality rates at the very extreme ages. The incumbent in the United States and in the other industrialized countries has been 116 years of age or younger.

3. Direct Measures of Longevity Based on Deaths and Life Table Functions

3.1 Measures for the General Population

The measures of individual aging, or of groups of persons when the individual data are aggregated, based on mortality data and their extensions, inform us directly about longevity and indirectly about population aging. Some measures are based on observed deaths, such as the average age of deaths and the share of deaths 65 years and over and 85 years and over, and others are based on life table functions, such as life expectancy, average age of life table deaths and the age corresponding to a specified number of years until death. Measures based on life tables are limited by the strong assumptions underlying the construction of such tables, but have the advantage that they are independent of the actual population distribution and hence are standardized for differences in age distribution from population to population. In addition, life tables provide measures of lifetime survival experience and distributions of survivors of birth cohorts unaffected by migration. Probabilities of surviving and probabilities of dying in the life table "move" at different rates from one another and so give different indications of the rate of population aging. Cohort and period measures also provide different indications of the way the population is aging because they represent reality differently.

Measures based on time from birth (e.g., life expectancy at some age) and measures based on time to death (e.g., age with 15 years to live) also offer us alternative ways of measuring change in longevity.

3.2 Average Ages of Deaths

The various measures of central tendency of the age distribution of deaths—mean, median and mode—can be used to describe the longevity trend and the aging of the population. An extension of these measures can then be used to examine trends in the compression of mortality and the rectangularization of the survival curve. Different results are obtained from the observed death statistics and life table deaths, of course. All of the measures based on observed deaths are affected by the migration and fertility histories of the population as well as its mortality history. The life table measures are not affected by these factors, but they are bound by the assumptions that there is no migration and the birth rate and numbers of births are constant.

Although I have not done so here, some of the measures of aging and longevity could be based on the adult population (e.g., ages 25 years and over) since this analysis is concerned with aging and longevity. This would apply to the mean and median ages at death for the observed population, the median and mean ages of life table deaths and life expectancy. All the measures based on deaths would be raised and their relative magnitudes could be affected to some extent.

<u>Mean age at death, life expectancy and complete life expectancy</u>. A variety of measures using observed death statistics to examine the trend in longevity between 1950 and 2000 is displayed in Table 3. The measures of central tendency are consistent in reflecting a continuous upward trend in longevity but the picture is mixed with regard to the trend of longevity of the superaged. A larger and larger percent of the deaths has been occurring among the extreme aged but the average maximum life span is virtually stationary. The life-span figure was 102.3 years in 1970 and 102.1 years in 2004 while the percent of deaths 100 years and over among the deaths 85 years and over rose from 1.3 in 1950 to 2.8 in 2004. Trends could be distorted because of the defects in the age

reporting of deaths.

TABLE 3

Measures of Longevity Based on Observed Death Statistics, for the United States: 1950 to 2004

	Average Age			Average Maximum	Percent Deaths			
Year	Median	Mean	Mode[a]	Life Span[b]	100+	85+	65+	(100+) ÷ (85+)
1950	66.2	59.8	72.5	NA	0.1	8.0	52.6	1.3
1970	70.3	65.1	77.5	102.3	0.2	12.9	61.6	1.6
1980	72.6	68.3	77.5	102.3	0.3	18.0	67.5	1.7
1991	75.7	70.5	80.5	102.2	0.6	22.0	72.1	2.8
2000	77.3	72.9	81-83	102.2	0.8	27.4	74.9	2.8
2004	77.4	72.8	83.0	102.1	0.8	28.0	73.2	2.8

NA: Not available.
[a] Second mode, or mode at adult ages. Figures are approximate.
[b] Mean age of recorded deaths 100 years and over.

Source: Based on U.S. National Center for Health Statistics, various *Vital Statistics of the United States* and *National Vital Statistics Reports*.

The mean age at death in the life table corresponds to the life expectancy at birth, the most widely used measure of the longevity of populations. Increasing life expectancy at birth, and increasing life expectancy at the older ages particularly, are direct measures of longevity and have been closely associated with population aging. This association is not a necessary one. A population could get older, even if death rates rise and life expectation falls, if some other factors contributing to aging are strongly at play, such as low current fertility, past history of declining fertility, and the movement of large cohorts (e.g., baby-boom cohorts) into the elderly ages. This could be the outlook for the United States a few decades ahead under some mortality scenarios.

Life expectancy at birth has shown a steady progression in the United States, with few exceptions, for the more than 100 years since official life tables were first published. Its increase in the last century has been no less than phenomenal, from 48 years in 1900 to 68 years in 1950 to 77 years in 2000 (Table 4). As suggested by these three figures, however, the increases have generally been falling, from 20 years for 1900-1950 to 9 years for 1950 to 2000. In fact, the decadal increases have been irregular, with an increase of 4.5 years between 1940 and 1950, a notable pause in the '60s, and an increase of 1.5 years between 1990 and 2000.

TABLE 4

Measures of Central Tendency and Dispersion of the Age Distribution of Life Table Deaths: United States, 1900 To 2000

Year	Mode[a]	Mean[b]	Median[c]	1st quartile[c]	3rd quartile[c]	IQR[cd]	RIQR[cd]
2000	85.5	76.9	80.3	69.7	88.0	18.3	22.8
1989-91	83.5	75.4	79.0	67.9	87.2	19.3	24.4
1979-81	83.5	73.9	77.6	66.3	86.0	19.7	25.4
1969-71	80.5	70.8	74.9	63.1	83.5	20.4	27.2
1959-61	81.5	69.9	74.3	62.7	82.8	20.1	27.1
1949-51	78.5	68.1	72.8	60.6	81.5	20.9	28.7
1939-41	76.5	63.6	69.9	55.5	79.2	23.7	33.9
1900	72.5	47.7	56.4	20.2	73.1	52.9	93.8
Increase							
1970-2000	5.0	6.1	5.4	6.6	4.5	-2.1	-4.4
1940-1970	4.0	7.2	5.0	7.6	4.3	-3.3	-6.7
1900-1940	4.0	15.9	13.5	35.3	6.1	-29.2	-59.9

[a] Second mode. Approximation.
[b] Mean age of deaths, or life expectation at birth.
[c] Describes both the deaths and the survivors.
[d] Interquartile range (IQR) and interquartile range as percent of median age at death (RIQR).

Source: Based on life tables published by U.S. National Center for Health Statistics or its predecessor agencies for 1939-41 to 2000, and by U.S. Office of the Chief Actuary for 1900.

In recent years criticisms of the accuracy of the conventional (period) measure of life expectancy as representing the average age at death have been made (Bongaarts and Feeney, 2002, 2005) and adjustments or alternatives have been proposed (Schoen and Canudas-Romo, 2005; Guillot, 2003). These proposals for changing the way period life expectancy is measured have not been widely accepted either because their basis is not readily understood or justified, or the proposed modification is too complex. I view them as additional measures of longevity at best, not replacements for the conventional period or cohort life expectancy.

A shift in the mean age of the life table distribution of deaths has direct implications for the longevity of the population and indirect implications for the rectangularization of the survival curve and mortality compression. The rise in life expectancy has been associated with increasing mortality compression/rectangularization of the survival curve, but this association is not a necessary one. To determine more closely if decreasing mortality is the “cause” of the increasing mortality compression, account must also be taken of the dispersion of the deaths, including any changes in the average maximum life span or the upper limits of the survival curve.

In the last few decades the rise in life expectation has maintained its association with mortality compression, but both the rate of increase in life expectation and the rate of mortality compression have been slowing down. While this close relation has been true in the past, an increase in life expectation can also be associated with mortality expansion, especially if maximum average life span rises substantially. On the basis of validated data for other industrialized countries, various analysts have observed a rising average maximum life span and a rise in the maximum annual age at death (Wilmoth et al., 2000; Wilmoth and Robine, 2003). A decrease in the rectangularization of the survival curve can theoretically be an outcome of such a change but it would require a sizeable rise in the average maximum life span, as will be shown later.

Another measure, total or complete life expectancy, is an additional direct indicator of longevity. Total life expectancy is defined as the sum of life expectation at some age plus the age itself. At birth, life expectancy and total life expectancy are equivalent, but at age 65, total life expectancy is considerably greater—65 years greater—than life expectancy at the same age. In the year 2003 total life expectancy of females at age 80 amounted to 90 years as compared to 10 years for life expectancy. Life expectancy falls with increasing age but total life expectancy steadily rises. At the higher ages total life expectancy diverges sharply from life expectancy because it incorporates the increasing gains won by survival to later and later ages.

Median age of deaths. The median, or middle value, of the distribution of deaths is widely used as an indicator of longevity because it is easy to calculate and interpret. It moves roughly *pari passu* with the mean age of deaths. It is higher than the mean, however, because the distribution of deaths is skewed to the left, especially now that the survival curve is so rectangular on the right.

Table 3 shows a historical series of median ages of observed deaths. The median age at death of the observed population is a function of both the age distribution of the population and the schedule of age-specific death rates. In low mortality/low fertility populations, such as the United States, the domination of the age pattern of mortality by the high age-specific death rates at the older ages, in combination with the relatively high proportion of elderly persons, means that most deaths occur at the old ages. As a result of the cumulative impact of the “aging” of both death rates and population over time, the median age of deaths has been sharply rising. The median age at death in 1950 was 66 years but by 2000 it had risen to 77 years. In 1950 only 8 percent of deaths occurred at 85 years of age or more, but in 2000 the figure was 28 percent. Now nearly three-quarters of all deaths occur over age 64.

The companion life-table measure, the median age of life-table deaths, is the 50 percent probability of survival for the life-table birth cohort. Like the life-table mean age at death, the life-table median age of deaths rose briskly between 1950 and 2000. The change for the life-table median was 7 years, from 73 years to 80 years (Table 4). However, the increase in the median age of life-table deaths was somewhat less than the increase in the mean age of life-table deaths, 9 years, and the median age of observed deaths, 11 years. The rise in the life-table median age, and the mortality compression/rectangularization of the survival curve, have been closely linked historically, but again, these two changes bear no necessary relation to one another or to the change in the maximum life span. A rising median age of deaths is quite consistent with either a rise or a fall in the average maximum life span or the maximum observed life span.

Modal age at death. Only the mode of the distribution of deaths at the adult ages, or the second mode, is directly relevant to this discussion unless we consider the first mode (typically infancy) and the second mode in combination, as described below. In the last few years the adult mode in the life table has been heralded as a particularly informative measure for analyzing the distribution of deaths and longevity (Cheung and Robine, 2007; Robine et al., 2006). Cheung and Robine have analyzed the trend of the mode for a few countries with highly accurate data, namely Japan and Sweden. It appears to have had a different course than the mean or median age of death in these countries. Data for the United States are less amenable to such analysis because the single-year-of-age data required are subject to substantial error. In addition, the data fluctuate in the area of the mode and the peak age may appear twice, reflecting a modal plateau rather than a specific point. Accordingly, it is difficult to pinpoint the precise modal age and measure changes over time.

In the case of the United States, the modal age of deaths was increasing until 1950 more slowly than the mean and median ages. After 1950 the exogenous causes of death (i.e., deaths due to external causes), which mainly occur at the younger ages and hardly affect the modal age at death, were largely replaced by the endogenous causes (i.e., deaths due to internal causes), which mainly occur at the higher ages. As a result, after 1950 the three measures of central tendency moved in more parallel fashion. Today the modal age at death in the life table is about 85-86 years, and the modal age of the observed deaths is about 83.

The relation of the two modal frequencies in a given distribution, the number of infant deaths and the frequency of the adult mode, whether in the observed data or life table, gives us a particularly sensitive measure of shifts in the age distribution of deaths and the progression of longevity. The ratio varies greatly depending on the development status of the country, the level of mortality and the aging of the population. Changes in the ratio of adult modal deaths to infant deaths from 1900 to 2000 for the United States illustrate the great mortality transition over that century, which saw the shift in mortality from mainly exogenous causes to mainly endogenous causes and from the young ages to the old ages. The ratio of the modal frequencies in the U.S. life tables for white females was 0.18 in 1900, rose sharply to 1.46 in 1950, and continued a rapid rise to 7.39 in 2000.

Time until death. Another measure of the longevity of a population is the age with a specified time until death. This age is determined by pre-setting life expectation at a given number of years (e.g., 10 or 15 years) and reading off the age in the life table to which this expectation corresponds. An historical series of ages corresponding to these two life expectations is shown in Table 5. These ages rose steadily over the last century. The ages with an expectation of 10 years were 72 in 1950 and 78 in 2003. The ages with a life expectation of 15 years were 63 years in 1950 and 70 years in 2003.

TABLE 5
Age Corresponding to Life Expectancies of 10 and 15 Years from 1940 to 2003 Based on Period Life Tables for the United States

Year	e_x = 10 years	e_x =15 years	e_0	e_{65}
1935			61.4[a]	12.5[a]
1939-41	70.0	61.4	63.2	
1949-51	71.7	63.1	68.1	
1959-61	72.5	64.0	69.9	
1965			70.4	14.6
1969-71	73.7	65.0	70.8	
1979-81	75.9	67.3	73.9	
1989-91	76.9	68.4	75.4	
2000	77.3	69.1	76.9	
2003	78.2	69.9	77.5	18.4
Increase,				
1965-2003			7.1	3.8
1935-2003			16.1	5.9

[a] Estimated.

Source: Based on U.S. decennial life tables, 1939-41 to 1989-91, and U.S. annual life tables for 1965, 2000 and 2003, published by NCHS.

The increases in this measure are in keeping with the declines in age-specific death rates at the higher ages. As long as the death rates at these ages fall, the age with “10 years to go” or “15 years to go” will continue to rise. These increases in the age for a fixed life expectancy suggest a possible mechanism for achieving a correspondence between increasing longevity and the age of normal retirement under Social Security, with the goal of improving the financial prospects of the Social Security retirement system, as explained further below. The later discussion also points to various problems in implementing the use of this measure, however.

The age representing the years-until-death measure can be used to ascertain the shifting proportion of the observed population that falls above this age. This proportion will tend to remain relatively stationary because the rise in the age with the same life expectation tends to be offset by the aging of the population.

4. Measures Relating to the Extreme Aged

Percents of totals and averages for the distribution of deaths. Several measures of longevity based on mortality data refer to aggregates of persons of extreme age. Depending on the interest of the analyst, either the observed death statistics or the data in a life table may be employed to compute the measures. The measures may be based on either survivors or decedents. One group of measures represents the percents of survivors of advanced ages of other survivor totals as indicated by current life tables, for example, the percent of survivors 100 years of age and over in the total population, or the percent of survivors 100 and over in the total 85 and over. Another group of measures computes average ages of deaths, for example, the average age of deaths 85 years and over and the average maximum life span (survivors or decedents). Table 6 shows a variety of measures of superlongevity based on life tables for the last half century. The measures give inconsistent indications of the trend in superlongevity during this period, with the average maximum life span remaining virtually unchanged and the percent of survivors suggesting an upward movement. This record does hint, however, that maximum life span is not a fixed number, as has so often been assumed in the past, but may vary, and that under optimal conditions members of a given population can live longer than in the past.

TABLE 6

Selected Measures of Superlongevity of Males and Females Based on Period Life Tables for the U.S. Social Security Area, for Selected Dates

Measure	Males 1950	Males 1980	Males 2000
Average maximum life span—survivors[a]	101.7	101.9	101.9
Average maximum life span—decedents[a]	101.9	102.2	102.1
Percent survivors 100 years and over	0.14	0.38	0.49
Percent survivors 100 and over of survivors 85 and over	0.5	0.9	0.8
Life expectation at age 100	1.92	2.20	2.06
Total life expectation at age 100[b]	101.9	102.2	102.1
Life endurancy (Pr = 0.01)[c]	95.1	97.4	98.3
Life endurancy (Pr = 0.001)[c]	100.7	103.0	103.3

Measure	Females 1950	Females 1980	Females 2000
Average maximum life span—survivors[a]	102.1	102.1	102.1
Average maximum life span—decedents[a]	101.6	102.5	102.3
Percent survivors 100 years and over	0.33	1.72	1.96
Percent survivors 100 and over of survivors 85 and over	0.6	1.8	1.7
Life expectation at age 100	1.92	2.42	2.35
Total life expectation at age 100[b]	101.9	102.4	102.4
Life endurancy (Pr = 0.01)[c]	97.5	101.5	101.8
Life endurancy (Pr = 0.001)[c]	102.4	106.4	106.4

[a] Mean age of life table survivors or decedents 100 years of age and over.
[b] Life expectation at age 100 plus 100.
[c] Age to which the proportion shown of the original birth cohort survives.

Source: Based on Office of the Chief Actuary, U.S. Social Security Administration, *Actuarial Study* No. 116 (August 2002).

The various measures of maximum life span discussed so far are to be distinguished from life expectancy at birth, which, as we have seen, represents, in effect, the average of the ages at death for a particular population, as indicated by its life table. While we speak at times of the life span of an individual and that figure may resemble the life expectation of the population, more commonly the term applies to some measure of the maximum number of years lived by members of the population. There is currently a gap of about 24 years between life expectancy at birth in the United States and the average maximum life span in the United States. This is the difference between the life expectancy at birth of 78 years in the year 2004 and the average maximum life span of survivors of about 102 years in the year 2004. This difference suggests how much progress in mortality reduction must be made at this time for the average person in the United States to reach the maximum average longevity achieved by a few super-aged persons. It is also approximately the amount of progress that the country must make to achieve the projected life expectancy of 100 for 2060 made by some analysts (Oeppen and Vaupel, 2002). The age-specific death rates of the year 2000 would have to be reduced by about 82 percent to achieve a life expectancy of 100 years under the assumption of uniform reductions in the death rates.

Maximum age of observed deaths. Several studies have been made of the trend of the annual maximum age at death in various industrialized countries. The maximum age at death in a population in a given year is the age of the oldest decedent in that year. Tracking this series over time for several industrialized countries with carefully evaluated data, particularly Sweden, has been used to support the argument that maximum human life span has been increasing and has no specifiable limit (Wilmoth et al., 2000; Wilmoth and Robine, 2003). According to the Wilmoth/Robine analysis of data on deaths for Sweden and several other countries of Northern and Western Europe, this age has been rising irregularly for a century and a half. Moreover, the pace of the increase, as measured by the slope of regression lines fitted to the data, has quickened in the last half century, almost tripling in the case of Sweden. They speculate on the basis of their data that the maximum age at death in a calendar year was around 108 years in the 1860s and about 115 or 116 years in the 1990s. This record is consistent with the view that maximum life span is not fixed and has no specifiable limit at this time. It is notable that data for the United States were not included in this analysis; they are too inaccurate to be probative on this question.

Life endurancy. Life endurancy is a measure of extreme longevity based on the survival function of the life table. It appears in the reports presenting historical series of life tables published by the U.S. Office of the Chief Actuary (2002). Life endurancy refers to the age to which 1.00 percent, 0.10 percent, 0.01 percent or other specified percent of the initial cohort in a life table survives. Thus, the male population would reach 98 years, and the female population 102 years, with a .01 probability according to the SSA life table for 2000 (Table 6). The corresponding ages for the 0.001 probability are ages 103 and ca. 106. A half century earlier the ages with these probabilities were several years lower. Given the assumption of continuing reductions in death rates at all ages, these ages are still higher in the SSA life table for 2050, but the relative increase over time is lower. The shifts in the age for a given survival probability from birth provides evidence of the changing survival of the members of the cohort to extreme ages.

5. Indirect Measures of Longevity: Compression of Mortality, the Longevity Dividend and the Biological Rate of Aging

In this third and final category, I include a miscellaneous group of measures of aging and longevity that represent extensions of the measures discussed earlier. For the most part, they indirectly reflect longevity. These are measures of the compression of mortality, a group of measures of the longevity dividend arising from survivors' success at survival over the ages and in time and the biologist's measure of aging in animal species.

5.1 Measures of Mortality Compression

Numerous measures of the compression of mortality/rectangularization of the life table survival curve have been described and evaluated. Among these are the relative interquartile range (RIQR), defined as the ratio of the "age" distance from the first quartile to the third quartile of the age distribution of deaths to the second quartile (median age at death). Another is the coefficient of variation (CV) of the age distribution of deaths, defined as the ratio of the standard deviation of the age of deaths to the mean age at death. These measures show a continuing compression of mortality since 1900, with a sharp slowing of the process in the second half of the 20th century (Table 4). This historical narrowing of the RIQR and the CV has been associated with the aging of the population, which has also been proceeding apace but slowing in recent decades. Once again, the changes in the RIQR and CV are associated with the declines in the death rates at the higher ages, consistent with a possible rise in the maximum average age at death, but the two types of changes bear no necessary relation to one another.

Kannisto (2000) and Wilmoth and Horiuchi (1999) have described several additional measures of mortality compression. Kannisto has proposed the standard deviation of the age at death above the mode, the standard deviation of the age at death in the highest quartile and the shortest interval in which a given proportion (say, 90 percent) of deaths take place, as well as the interquartile range. Wilmoth and Horiuchi have enumerated some of the same measures and added several of their own. I have proposed another measure of mortality compression that I described previously in a presentation at the SOA Symposium in 2005 (Siegel, 2005). It takes direct account of the shifts in the very upper limits of the distribution of deaths. The formula, expressed as a percentage, is:

$$\frac{\text{Life expectation at birth}}{\text{Total life expectation at age 100}} * 100 \qquad (5)$$

(An alternative version is the ratio of life expectation at age 25 to total life expectation at age 100.)

As stated earlier, total life expectation at age 100 is defined as life expectation at age 100 plus 100, 100 being the age already achieved by survival. Table 7 sets forth an historical and projected series for this measure from 1900 to 2100. The rise in the percentage from 48.2 in 1900 to 77.6 in 2000 indicates that life-table deaths were being increasingly compressed and that the survival curve was becoming increasingly rectangular over the past century. However, as the measure indicates, mortality compression was much greater in the first half of the 20th century than in the second half. By this measure 71 percent of the compression over the whole century occurred in the first half of the century. This finding is consistent with those shown by other measures of the mortality-compression phenomenon (Table 4).

TABLE 7

Life Expectancy at Birth as Percentage of Total Life Expectancy at age 100, for Females in the Social Security Area: 1900 to 2100

Year	Life expectancy (e_0)	Total life expectancy at age 100 (e_{100}+ 100)	Percentage (e_0) ÷ (e_{x100} + 100)	Change over prior date
1900	48.96	101.61	48.2	--
1950	71.13	101.92	69.8	21.0
1980	77.52	102.42	75.7	5.9
2000	79.38	102.35	77.6	1.9
2050	83.54	103.08	81.0	3.4
2100	86.87	104.01	83.5	2.5

Source: Based on period life tables for the U.S. Social Security Area. Office of the Chief Actuary, U.S. Social Security Administration, *Actuarial Study* No. 116 (August 2002).

If, for this discussion, we accept the projections of mortality rates at the ages over 100 made by the Actuary's Office, as well as its projections for earlier ages, it is evident that further mortality compression, based on the agency's assumptions of continuing increases in life expectation, can be consistent with a continuation of increases in maximum average life span. The percentages for future years show a continuing compression of mortality from 2000 to 2050, and from 2050 and 2100, albeit at a progressively slower pace, even while life expectancy at age 100 is assumed to rise (Table 7). Trial computations suggest that a considerable increase in maximum average life span or a fall in life expectation would be required before mortality compression would come to a halt. For now and many years to come, given reasonable reductions in late life death rates, the compression of mortality will continue even as the rise of life expectancy at age 100 continues. Note that mortality expansion is ipso facto consistent with a continuation in the rise of maximum average life span and maximum life span.

5.2 The Longevity Dividend

Gain from survival to older ages. While life expectation declines steadily with age from or just after infancy, total life expectation, the sum of life expectation at any age and the attained age, rises steadily with age. Moreover, as each higher age is reached, the survivor gains a larger and larger bonus for his/her success in surviving to the higher age. In 2003, for example, total expectation for females was 81.0 years at age 25 as compared with an expectation at birth of 80.1, representing a bonus of 0.9 year for survival to age 25; but at age 100, total expectation was 102.6, representing a bonus over expectation at birth of 22.5 years (Table 8). Such gains were greater in earlier calendar years, when life expectation at birth was lower. At age 100 in 1900 the bonus was 53 years for females and in 1950 it was 31 years. As life expectation at birth rises, the gain from survival to later ages is reduced. According to the SSA life table for females in 2050, the gain at age 100 is only 20 years. In sum, the longevity dividend from success at survival rises steadily with age, is not sizeable until the older ages, and as mortality levels fall over time, the dividend from this source decreases but remains substantial at the most advanced ages. This mortality dividend is independent of secular changes in death rates.

TABLE 8

Longevity Dividend from Survival to Selected Ages for Females in the U.S. Social Security Area, for Selected Dates, 1900 to 2100

(Columns are for total life expectancy, defined as life expectancy at the age shown plus the age itself, and gain from survival over life expectancy at birth)

	2000		1950		1900	
Age	Total e_x	Gain	Total e_x	Gain	Total e_x	Gain
0	79.4	0.0	71.1	0.0	49.0	0.0
25	80.3	0.9	74.1	3.0	64.3	15.3
50	81.7	2.3	76.5	5.4	71.5	22.5
75	87.0	7.6	84.0	12.9	82.2	33.2
80	89.0	9.6	86.8	15.7	85.3	36.3
85	91.5	12.1	90.0	18.9	89.0	40.0
90	94.6	15.2	93.6	22.5	92.9	43.9
95	98.2	18.8	97.6	26.5	97.1	48.1
100	102.4	23.0	101.9	30.8	101.6	52.6

	2003		2050		2100	
Age	Total e_x	Gain	Total e_x	Gain	Total e_x	Gain
0	80.1	0.0	83.5	0.0	86.9	0.0
25	81.0	0.9	84.0	0.5	87.2	0.3
50	82.4	2.3	85.0	1.5	87.9	1.0
75	87.6	7.5	89.3	5.8	91.4	4.5
80	89.6	9.5	90.9	7.4	92.8	5.9
85	92.2	12.1	92.9	9.4	94.5	7.6
90	95.2	15.1	95.7	12.2	97.0	10.1
95	98.7	18.6	99.1	15.6	100.2	13.3
100	102.6	22.5	103.1	19.6	104.0	17.1

Source: Based on period life tables of the Office of the Chief Actuary, U.S. Social Security Administration, *Actuarial Study* No. 116 (August 2002); data for 2003 based on U.S. NCHS, *National Vital Statistics Reports*, Vol. 54, No. 14.

Gain from secular decline in mortality, or gain from cohort changes. As is well known, period life expectation is a hypothetical measure of current longevity "prospects," calculated on the basis of the mortality rates of a single year or short group of years. The theoretical limitations of such a measure are overcome in part by constructing a cohort, or generation, life table, which describes the real longevity prospects for a single birth cohort. Comparison of the two types of life tables for the birth cohort of a given year indicates the longevity dividend gained by individuals who survive to later ages resulting from the secular reductions in mortality rates. This gain can be considerable, as shown by the data in Tables 9 and 10. Table 9 shows the differences in life expectancy at birth and later ages for the birth cohort of 1920. With each increase in age, the real birth cohort of 1920 experiences a longevity dividend over the "synthetic" birth cohort of 1920. These differences grow in relative size with increasing age. Of course, under a regime of increasing mortality rates, such as some anticipate for the United States, the reverse would occur. Historically, however, decreases have occurred on a regular basis and all available projections of population and mortality anticipate that this pattern will continue.

TABLE 9

Selected Life Expectancy Values from the SSA Generation Life Table for the Cohort of Females Born in the United States in 1920 and Comparison with Current Period Life Tables

Calendar year	Age	Average future lifetime		
		Cohort table	Period table	Difference
	(x)	(e_{x1})	(e_{x2})	(e_{x1} - e_{x2})
1920	0	69.3	56.3	13.0
1921	1	73.3	59.3	14.0
1925	5	71.5	57.6	13.9
1930	10	67.2	53.4	13.8
1935	15	62.6	48.9	13.7
1945	25	53.6	41.1	12.5
1955	35	44.4	33.8	10.6
1965	45	35.3	26.2	9.1
1975	55	26.8	18.9	7.9
1985	65	19.0	12.2	6.8
1995	75	12.1	7.3	4.8
2005	85[a]	6.6	4.1	2.5
2010	90[a]	4.7	3.0	1.7
2015	95[a]	3.4	2.2	1.2
2020	100[a]	2.6	1.7	0.9
2025	105[a]	1.9	1.2	0.7
2030	110[a]	1.4	0.9	0.5

[a] Projected.

Source: Based on U.S. Office of the Chief Actuary, Social Security Administration, *Actuarial Study* 116 (2002).

Historical and prospective changes in the comparison of life expectancies at birth are shown in Table 10, which is based on a series of SSA period and cohort life tables for the birth years from 1900 to 2000. For most of the cohort tables, projections of mortality are required to complete the table. Table 10 reflects the gains from actual or projected improvements in mortality after the year of birth. For example, the cohort life table for males for birth year 2000 anticipates a gain of six years over the period life table for males for that year. The gains in the cohort tables for males varied from 5.1 years to 8.2 years over this century, with no particular trend, and the gain for females varied from 5.2 years to 13.0 years, with all the larger gains occurring for the cohorts born in the pre-

1950 years.

TABLE 10

Comparison of Life Expectation at Birth for Males and Females in Period Tables for Specified Years and for Cohorts Born in These Years in Generation Life Tables: U.S. Social Security Area, 1900 to 2000

	Male			Female		
Year	Period table	Cohort table	Difference	Period table	Cohort table	Difference
	Years			Years		
1900	46.4	51.5	5.1	49.0	58.3	9.3
1910	50.1	56.2	6.1	53.6	63.7	10.1
1920	54.5	61.8	7.3	56.3	69.3	13.0
1930	58.0	66.0	8.0	61.3	73.0	11.7
1940	61.4	69.4	8.0	65.7	76.0	10.3
1950	65.6	72.2	6.6	71.1	78.7	7.6
1960	66.7	73.6	6.9	73.2	79.9	6.7
1970	67.2	75.4	8.2	74.9	81.2	6.3
1980	69.9	77.2	7.3	77.5	82.6	5.1
1990	71.8	78.5	6.7	78.9	83.7	4.8
2000	73.7	79.7	6.0	79.4	84.6	5.2

Source: U.S. Office of the Chief Actuary, Social Security Administration, *Actuarial Study* No. 116 (August 2002).

Combination of dividends. The combined bonus for success at survival to higher ages, both from eliminating risk at the ages already passed by and from surviving to later calendar years with lower mortality risks, can be tremendous. Consider an infant girl born in 1900 who succeeded in surviving to age 49 years. This age corresponds to her period life expectancy at birth. She won a dividend of 22 years for having survived to her 49th birthday and a dividend of 9 years for having survived over a 49-year period to 1949, a period when mortality rates were far lower than in 1900. Her combined longevity dividend is 31 years (Table 11). If she was born in 2000, her longevity dividends are expected to be much lower, but not trivial, yielding a total of 15 years over her expectation at birth.

TABLE 11

Longevity Dividend for Females Born in Selected Years from 1900 to 2100 Who Survive to Their Initial Life Expectancy at Birth, for the United States Social Security Area

Measure	1900	1950	2000	2050	2100
Life expectancy at birth	49.0	71.1	79.4	83.5	86.9
Longevity gain:					
From survival to age of life expectancy at birth	22.2	11.1	9.4	8.8	8.5
From secular reductions in death rates	9.3	7.6	5.2	(NA)	(NA)
Total longevity gain	31.5	18.7	14.6	(NA)	(NA)
Life expectancy achieved	80.5	89.8	94.0	(NA)	(NA)

NA: Not available.

Source: Based in part on Tables 8 and 10.

5.3 Biological Rate of Aging

Finally, in this group of measures, I consider the biological rate of aging and evaluate the concept with U.S. historical data. It is a concept that is used more in interspecies comparisons than in time series analysis for humans. A leading measure of biological aging is the number of ages that are required for the mortality rate to double with increasing age. Inasmuch as this measure is designed to reflect endogenous, or intrinsic mortality, and death rates at the very advanced ages are known to rise at a diminished rate, I have based my calculations on mortality rates in the age range from 30 to 80 years, a range excluding much of the exogenous mortality and excluding the advanced ages where mortality rates decelerate. Biologists now maintain that the rate of aging is distinctive for each species but does not vary over the age distribution and for subgroups in a given species (Austad, 1997). According to Austad, biologists believe that the mortality rate for humans doubles every eight ages.

Gompertz, the British actuary of the 19th century, posited an age model of human mortality that assumed a fixed rate of increase in mortality rates over the age scale (Gompertz, 1925). We can express this exponential curve simply as:

$$\mu_x = ae^{bx}$$

$$\ln \mu_x = \ln a + bx$$

$$Y_x = A + bx$$

where μ_x and ln μ_x (= Y_x) refer to the terminal mortality rate, *a* and *ln a* (=*A*) refer to the initial mortality rate, *b* is a constant representing the rate of increase in mortality, and *x* is the age band.

Analysis of the mortality data for the United States over the last century suggests that the rate of aging has been changing over time, varies over the age distribution, differs somewhat for males and females and varies for period data and cohort data. Table 12 gives results for several dates in the past century, two segments of the age distribution, males and females, and period and cohort schedules. The rate of aging has been speeding up. In 1900 it took about 12 ½ ages for the mortality rate to double; now it takes between 8 ½ and 9.0 ages. A major decline in aging time occurred during the first half of the last century, and the number of years has stabilized at 8.5–8.8 since mid-century. For all observation years from 1900 to 2003, the rate of aging was much slower at the younger ages than at the older ages, particularly in the early part of the last century. There is also a tendency for the rate of aging in the latter part of the age distribution to be more stable than the rate in the early part of the distribution. The male and female rates of aging tend to differ only in small degree, with the female figure being higher in the early years of the century and the male rate being higher in the later years of the century.

TABLE 12

Ages Required for the Age-Specific Mortality Rate to Double Over the Age Range 30 to 80 Years, for the United States: 1900 to 2003

Estimates based on NCHS data

Year	Average years			First doubling[a]			Last doubling[a]		
	Both Sexes	Male	Female	Both Sexes	Male	Female	Both Sexes	Male	Female
1900-02[b]	NA	12.3	12.6	NA	20.9	22.5	NA	8.4	8.5
1929-31[c]	NA	10.0	10.1	NA	13.0	16.0	NA	7.5	7.8
1949-51	8.6	8.8	8.4	9.7	9.7	9.7	8.3	9.1	7.5
1979-81	8.8	9.0	8.0	12.5	12.5	9.1	8.5	9.1	7.1
2003	8.6	8.9	8.0	10.0	10.9	8.3	7.6	7.7	6.9

Estimates based on SSA period data

Year	Average years		First doubling[a]		Last doubling[a]	
	Male	Female	Male	Female	Male	Female
1900	12.4	12.7	21.0	22.3	7.6	7.5
1930	10.7	10.7	14.4	16.8	8.7	8.1
1950	8.8	8.4	9.8	9.5	9.2	7.7
1950	8.9	8.0	12.5	9.2	9.1	7.2
2000	8.9	8.1	11.6	9.1	7.8	7.2

Estimates based on SSA cohort data

Birth Cohort	Average years		First doubling[a]		Last doubling[a]	
	Male	Female	Male	Female	Male	Female
1900	11.8	13.2	18.5	25.7	10.7	8.7
1930	9.5	9.1	8.7	8.6	8.6	7.8
1950	10.1	10.1	12.6	11.1	8.6	8.4

Note: NCHS= National Center for Health Statistics. SSA = Actuary’s Office, Social Security Administration.

NA: Not available.

[a] Earliest doubling years beginning at age 30 and latest doubling years ending at age 80.

[b] Whites in Original Death Registration States.

[c] Whites in continental United States.

Source: Based on various life tables of the U.S. National Center for Health

Statistics and the U.S. Social Security Administration, Office of the Chief Actuary, *Actuarial Study*, No. 116 (August 2002).

Gompertz' and modern biologists' generalizations are roughly correct about the human rate of aging today as far as U.S. data are concerned. They have overstated their cases, however, and are omitting many nuances in such a generalization. Further investigation would examine the rise in the mortality rates for intrinsic/endogenous causes of death only, instead of all deaths, in the same age range, 30 to 80 years.

6. Applications to U.S. Public Programs

The changes shown by these measures of aging and longevity have an important bearing on U.S. public programs. The reader is by now quite familiar with the impact of increased longevity on the size of the older population and on the share of the older population in the total population. Longevity does not act in a demographic vacuum, however, in affecting age distribution, and fertility trends and immigration have to be considered also. Historically, fertility trends have been as influential as, or more influential than, mortality trends in effecting the increase in the share of older persons. So, whether the population will continue to age very much depends on what happens to future fertility rates as well as future mortality rates and their past trends. There is little basis to expect any substantial rise in future fertility in the United States in the next several decades, however (Morgan, 2003). Immigration has been considered a partial solution to the aging problem as well, but studies have shown that our present massive immigration, including the illegal immigrants, is hardly making a dent in the problem. Even doubling the present volume will not change the balance of ages substantially (Center for Immigration Studies, 2007).

Fertility and mortality changes have also been responsible for a major shift in the relative numbers of persons of the "working" ages and persons of the older "dependent" ages. The increasing shares of older persons translate into rises in old-age dependency ratios—the ratios of persons of older age to persons of the main working ages. I do not want to appear to claim that "demography is destiny," however, since population dependency ratios in themselves have only limited impact in this connection and need to be translated further into ratios of retired persons to workers or SSA contributors to beneficiaries. And to avoid further being charged with demographic determinism, we have to figure in also the effect of changes in worker productivity, that is, output per hour of labor. There may be unexpected major increases in labor force participation at the older ages, or among women as well as men, but it seems unlikely now that increases in either the labor force, worker productivity, fertility or immigration will change the general outlook. With these observations, we will be able to consider more fruitfully the impact on public programs, including the Social Security program and the health care system, of the aging changes I have described.

6.1 Changes in Age and Social Structure and Health Characteristics

Before I do that, however, I want to make some comments on the effect of longevity changes on family structure and the health characteristics of families. The implications of the changes in longevity for family structures have not been widely noted. As a result of the combination of reduced fertility and increased longevity, the family is becoming more vertical and multigenerational and less horizontally extensive. The average number of generations in a family has been growing. Although parents have fewer children and children have fewer siblings, they are likely to have more relatives in a direct line of descendance and ascendance. The number of generations alive at any time depends mainly on longevity changes but it also depends on age at first parenthood. The latter factor has been "collaborating" with low fertility within marriage to keep fertility from "going anywhere." The mean age at marriage has been high and rising, and parenthood is often delayed to the point of being familially unproductive. In the meantime, longevity has "worked" forcefully to add to the number of generations. This change may have important implications for the insurance, homebuilding and other industries that cater to families.

Increased numbers and shares of long-lived persons provide challenges for public health administration. Issues are raised with respect to the management of the chronic diseases of later life. The measures and results presented here suggest that the management of the chronic diseases of later life will be a greater and greater problem for public and private agencies. Some consequences of the aging of the population include a shift in the types of chronic diseases that predominate (e.g., a diabetes "epidemic" and the emergence of Alzheimer's disease as a leading reported cause of death), an increase in the period of chronic illness and in the numbers of persons that are chronically ill or frail and a shift in the types and distribution of health services and personnel required. The main problem is how to allocate resources—money, facilities and personnel—so as to achieve a compression of mortality and morbidity while extending human life. Should funds be allocated primarily for biogerontological research or for specific chronic diseases or some combination of both?

6.2 Implications for Social Security Retirement

When the Social Security retirement program went into effect in 1935 naming age 65 as the normal retirement age, life expectation at birth was only 61 years and life expectation at age 65 was only 12 1/2 years (Table 5). Today, newborn babies have a life expectation 16 years greater than in 1935 and persons 65 years of age have a life expectation of about 18 years. Hence, an expectation of 10 or 15 years to death corresponds much more closely to the survival expectations of the U.S. population at age 65 when Social Security was introduced than the current survival expectation at age 65.

Tables 13 and 14 set forth some of the relevant demographic data regarding the looming imbalance of workers and nonworkers, and contributors and beneficiaries, affecting the Social Security and Medicare systems. Since 1950 the balance of persons 65 years and over to persons 20 to 64 has increased by 50 percent, from a ratio of 14 to a ratio of 21 (Table 13). Little change occurred in this ratio between 1990 and 2005 or will occur in the next few years before 2010. However, in the two decades following 2010, as a result of the aging of the baby-boom cohorts, the ratio will climb steeply, reaching 35, or nearly 70 percent over its present level. The more pertinent indicators are the ratios that reflect the tendencies of these persons to work or retire, or to contribute to the entitlement programs or receive benefits from them. Using Bureau of Labor Statistics labor force projections, we see a little more favorable outlook—a 56 percent increase in the ratio of persons 65 and over not in the labor force to persons 16 years and over in the labor force, for the period 2004–2030 (Table 14). Projections from the Social Security Administration of the increase in the ratio of beneficiaries to contributors for the 2004–2030 period are slightly less problematic—52 percent.

TABLE 13

Historical and Projected Aged Dependency Ratios for the United States Social Security Area: 1950 to 2060

(U.S. Social Security Area includes outlying areas of the United States. Aged dependency ratios calculated as: Population 65+ / Population 20-64, per 100).

Historical series		Intermediate projections	
Year	Ratio	Year	Ratio
1950	13.8	2010	20.9
1960	17.3	2020	27.0
1970	18.5	2030	34.9
1980	19.5	2040	37.2
1990	20.9	2050	38.0
2000	20.8	2060	39.6
2004	20.7		

Source: U.S. Social Security Administration, *2006 Annual Report of the Board of Trustees of the Federal Old-Age and Survivors Insurance and Disability Insurance Trust Funds*, 2006, Table V.A.2.

TABLE 14

Elderly Economic Dependency Ratios and Beneficiaries/Contributors Ratios, for the United States: 1950 to 2004, and Projected, 2010 to 2050

Year	Not in labor force, 65+ per 100 in the labor force, 16+[a]	Beneficiaries per 100 contributors[b]	Contributors per 100 beneficiaries[b]
1950	14.0[c]	6.1	1639.3
1975	20.7	31.1	321.5
1990	22.1	29.5	339.0
2000	21.6	29.1	343.6
2004	21.2	30.2	331.1
2010	21.3	31.5	317.5
2020	25.9	38.8	257.7
2030	33.1	46.0	217.4
2040	35.9	48.5	206.2
2050	36.8	49.1	203.7
Percent change,			
1950 to 2004	+51	+395	-80
2004 to 2050	+74	+63	-39

[a] Labor force estimates from the Current Population Survey; intermediate series of projections from 2010 to 2050. Estimates are adjusted to include the institutional population in the "not in labor force, 65+" population and the Armed Forces in the "labor force, 16+."
[b] SSA beneficiaries include both recipients of OASI and DI.
[c] Estimated.
Source: M. Toossi, "Labor force projections to 2014: Retiring boomers." *Monthly Labor Review* 128(11):25-44, Nov 2005, Table 10; and M. Toossi, "A new look at long-term labor force projections to 2050," *Monthly Labor Review* 129 (11):19-39, November 2006, Table 6.
U.S. Social Security Administration, *The 2006 Annual Report of the Board of Trustees of the Federal Old-Age and Survivors Insurance and Disability Insurance Trust Funds,* Washington, DC: U.S. Government Printing Office.

The historical declines in mortality and fertility, and hence in the balance of beneficiaries to contributors, have laid the demographic foundation for the present issues regarding the solvency of the Social Security Old-Age Insurance program. The age for receiving full benefits under Social Security is being raised gradually from age 65 in 2003 to age 66 in 2009 and to age 67 in 2027 (in two-month increments, except that the age is frozen at age 66 for 11 years from 2009 to 2020). This increase in the age of retirement is consistent with the facts regarding past rises in longevity, but the changes being introduced may prove to be too little and too late. Furthermore, half of the workers retire well below the age for receiving full benefits—about age 62, just when they can receive partial benefits (Gendell and Siegel, 1996; Gendell, 2008). Some of these retire on disability, of course. Gendell (2008) reports, however, that in the last dozen years there has been a substantial increase in full-time labor force participation of workers over age 60 while the average age at retirement continues to fall. In the light of the changes in longevity that are occurring and may continue to occur, we can well expect a reconsideration of the dividing line defining old age in public and official thinking, and in fact official proposals have been made to raise the age for full benefits under Social Security to age 70.

The series of ages with 15 years remaining suggests one index by which the normal age of retirement could be gradually raised to accommodate rising life expectations and maintain a more manageable financial demand on the Social Security system. Among the problems arising in implementing such a plan are the differences among the racial and ethnic groups, the sexes, different socioeconomic groups and different geographic areas, in the ages at which their remaining lifetime is 15 years. Blacks have much shorter life expectancies at birth than whites, but the age at which they have 10 years of life remaining is now about the same as for the white population—78 years (Table 15). This means that they are less likely to survive to the age for receiving Social Security retirement income, but that those who do survive to age 65 will, on the average, receive benefits for nearly the same period as whites. Hispanics have greater life expectancies at birth and at age 65 than non-Hispanic whites, and have a higher age marking the point of 10 years "to go." Women live longer than men and have lower death rates above age 65, so that more women will reach age 65 to collect Social Security benefits and those who have arrived will collect Social Security benefits for more years than men.

TABLE 15

Age Corresponding to Life Expectancies of 10 and 15 Years Based on Period Life Tables for Whites and Blacks in the United States, 1950 to 2000

Year	e_x = 10 years		e_x = 15 years		e_0	
	White	Black	White	Black	White	Black
1949-51	71.7	73.6[a]	63.2	61.8[a]	69.0	60.7[a]
1959-61	72.4	73.9[a]	64.1	62.9[a]	70.7	63.9[a]
1969-71	73.6	74.6	65.1	63.4	71.6	64.1
1979-81	75.9	75.7	67.4	65.7	74.5	68.5
1989-91	76.9	76.1	68.5	66.0	76.1	69.2
2000	77.2	76.0	69.1	66.8	77.4	71.7
2003	78.0	78.0	69.8	68.7	78.0	72.7
Increase, 1950-2000	5.5	2.4	5.9	5.0	8.4	11.0

[a] For total nonwhite population.

Source: Based on U.S. decennial life tables, 1949-51 to 1989-91, and U.S. annual life tables for 2000 and 2003, published by NCHS.

A difficult question is whether the differences between the races and sexes should be recognized in entitlement programs. Since blacks are less likely to survive to collect full Social Security benefits, they may profit from opting for reduced benefits at age 62. Many secure full benefits at an earlier age through disability. On the other hand, survival of blacks to age 62 is an indicator that they will, on average, survive as long as whites beyond that age and are likely to receive retirement benefits as long as whites. Men and women now receive the same monthly benefits, though it is known that the women will receive them longer than men. In insurance programs, there are arguments for and against special treatment of the races and sexes. Here are some of the considerations. Distinctions on the basis of sex and race in premiums and benefits have generally been outlawed in public programs; and distinctions have been rejected for the races in most life insurance and retirement programs. Blacks in particular have higher rates of disability retirement, and disabled retirees can receive full retirement benefits long before normal retirement. Blacks who survive to very high ages have lower mortality rates than whites; that is, the rates cross (Kestenbaum, 1992). (Analysts disagree on the white/black crossover issue but I am going along with the preponderance of the evidence in the case.) The suggestion has been made that the lifetime benefits of all groups be equalized (Keyfitz, 1982). This proposal could mean that the monthly benefits for men and women, and blacks and whites, would be unequal.

Appendix Note

In addition to the various measures of population aging and longevity described in the main text, I should like to mention two hybrid measures, one essentially a measure of population aging and the other essentially a measure of longevity.

The first measure is based on a well-established method of estimating the extreme aged population known as the "method of extinct generations." It is the percent of extreme aged, using as numerator a reconstruction of the number of extreme aged persons from observed death statistics and as denominator the population from a census or survey. In this method, for example, deaths occurring to the cohort 85 years and over in 1990 and later years are accumulated so as to reconstruct the population 85 and over in 1990. Once the estimate of the number of extreme aged is derived in this way, the percent in the total population or in the population 65 years and over can be obtained by dividing by the population for the broader age group. The method was first described by P. Vincent in "La mortalité des vieillards, Population 6(2): 181-204, April-June 1951.

The second measure links the median age of the population with the life expectancy of the population. It is the expected number of years to be lived by a person at the median age of the population. If the median age rises, as is the common situation currently, this measure can rise or fall, depending on the changes in mortality rates. If the median age rises rapidly enough, in relation to declines in mortality rates, life expectancy at the median age may fall. I do not view this measure as a direct measure of aging, but rather as another measure of longevity and, hence, as analytically useful in interpreting population aging. The measure was described by W.C. Sanderson and S. Scherbov in "Average remaining lifetimes can increase as human populations age," Nature

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