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Mortality Trajectories at Exceptionally High Ages: A Study of Supercentenarians

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Abstract

The growing number of persons surviving to age 100 years and beyond raises questions about the shape of mortality trajectories at exceptionally high ages, and this problem may become significant for actuaries in the near future. However, such studies are scarce because of the difficulties in obtaining reliable age estimates at exceptionally high ages. The current view about mortality beyond age 110 years suggests that death rates do not grow with age and are virtually flat. The same assumption is made in the new actuarial VBT tables. In this paper, we test the hypothesis that the mortality of supercentenarians (persons living 110+ years) is constant and does not grow with age, and we analyze mortality trajectories at these exceptionally high ages.

Death records of supercentenarians were taken from the International Database on Longevity (IDL). All ages of supercentenarians in the database were subjected to careful validation. We used IDL records for persons belonging to extinct birth cohorts (born before 1895) since the last deaths in IDL were observed in 2007. We also compared our results based on IDL data with a more contemporary database maintained by the Gerontology Research Group (GRG).

First we attempted to replicate findings by Gampe (2010), who analyzed IDL data and came to the conclusion that “human mortality after age 110 is flat.” We split IDL data into two groups: cohorts born before 1885 and cohorts born in 1885 and later. Hazard rate estimates were conducted using the standard procedure available in Stata software. We found that mortality in both groups grows with age, although in older cohorts, growth was slower compared with more recent cohorts and not statistically significant. Mortality analysis of more numerous 1884–1894 birth cohort with the Akaike goodness-of-fit criterion showed better fit for the Gompertz model than for the exponential model (flat mortality). Mortality analyses with GRG data produced similar results.

The remaining life expectancy for the 1884–1894 birth cohort demonstrates rapid decline with age. This decline is similar to the computer-simulated trajectory expected for the Gompertz model, rather than the extremely slow decline in the case of the exponential model.

These results demonstrate that hazard rates after age 110 years do not stay constant and suggest that mortality deceleration at older ages is not a universal phenomenon. These findings may represent a challenge to the existing theories of aging and longevity, which predict constant mortality in the late stages of life. One possibility for reconciliation of the observed phenomenon and the existing theoretical consideration is a possibility of mortality deceleration and mortality plateau at very high yet unobservable ages.

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Introduction

Accurate estimates of mortality at advanced ages are essential for forecasts of population aging and for testing the predictions of competing theories of aging. They also contribute to more reliable forecasts of future longevity (Gavrilov et al. 2014).

Earlier studies suggest that exponential growth of mortality (Gompertz law) is followed by a period of deceleration, with slower rates of mortality increase at extreme old ages (Greenwood and Irwin 1939; Horiuchi and Wilmoth 1998; Thatcher 1999; Thatcher, Kannisto and Vaupel 1998). This mortality deceleration eventually produces the “late-life mortality leveling-off” and “late-life mortality plateaus” at extreme old ages. Greenwood and Irwin (1939) provided a detailed description of this phenomenon in humans and even made the first estimates for the asymptotic value of the upper limit to human mortality (see review by Olshansky 1998). The same phenomenon of “almost non-aging” survival dynamics at extreme old ages is detected in other biological species, and in some species the mortality plateau can occupy a sizable part of their life (Carey et al. 1992; Gavrilov and Gavrilova 2006).

Studies of mortality after age 110 years are scarce because of difficulties in obtaining reliable age estimates. It was demonstrated that the age misreporting at older ages results in mortality underestimation (Preston, Elo and Stewart 1999). Also, it was found that mortality deceleration is more expressed in the case of poor-quality data than with data of better quality (Gavrilov and Gavrilova 2011). Recent analysis of detailed records from the U.S. Social Security Administration Death Master File for several single-year extinct birth cohorts demonstrated that the Gompertz law fits mortality data better than the logistic (Kannisto) model up to ages 105–106 years (Gavrilov and Gavrilova 2011; Gavrilova and Gavrilov 2015). However, existing studies of mortality after age 110 years reported flat mortality, which does not grow with age (Gampe 2010; Robine and Vaupel 2001).

In this paper, we analyze mortality trajectories for supercentenarians, using data on a sufficiently large sample of supercentenarians (aged 110 and older) available in the International Database on Longevity (IDL) (Cournil et al. 2010). All ages of supercentenarians in the database were subjected to careful validation. Hazard rates of supercentenarians were measured using an actuarial estimate (equivalent to mortality rate or death rate estimation), applying the standard method implemented in the Stata package (release 13). Methods of mortality trajectory analysis are based on comparing alternative models of mortality, using a standard goodness-of-fit procedure.

Data and Methods

Data

International Database on Longevity

We used records of supercentenarians available in the International Database on Longevity (www.supercentenarians.org). This database contains validated records of persons aged 110 years and older from 15 countries with good-quality vital records. The records were deidentified to remove personal information. The contributors to IDL performed data collection in a way that avoided age-ascertainment bias, which is essential for demographic analysis. The database was last updated in March 2010.

To avoid data truncation, we used a portion of IDL records for persons belonging to extinct birth cohorts (born before 1895), since the last deaths in IDL were observed in 2007. Our earlier study of mortality at advanced ages based on the Social Security Administration Death Master File (DMF) showed that data for older birth cohorts have generally lower quality than for more recent birth cohorts and show more expressed mortality deceleration (Gavrilov and Gavrilova 2011). To compare different birth cohorts, data were divided into older (born before 1885) and younger (born in 1885 and later) birth cohorts. The same division into older and younger birth cohorts was conducted in the earlier study of mortality after age 110 years (Gampe 2010). Taking into account the very small number of male records, we used data for both sexes in our analyses. For more detailed analysis of mortality trajectories, we used cohorts born in 1884–1894, because these cohorts have the largest number of cases in IDL (401 cases) and hence are likely to be more complete.

Gerontology Research Group (GRG) Database on Supercentenarians
Steven Kaye, M.D., and Stephen Coles, M.D., Ph.D., cofounded the GRG during the spring of 1990. One of the continuing interests of the group is to authenticate cases of the oldest humans in history, the population of so-called supercentenarians (persons older than 110). The GRG publishes the most current validated list of living and deceased supercentenarians on a regular basis in the journal *Rejuvenation Research* (Young, Muir and Adams 2015). The GRG also maintains database on supercentenarians on the group's website, at http://www.grg.org/Adams/TableE.html. To be included in the GRG official database, a person needs to have at least three independent sources of documentation: a birth certificate, baptismal certificate, or marriage certificate; consistent US Census records dating back to 1900; and some other photo identification, such as an old driver's license. This is the most up-to-date list of supercentenarians available to the public. This database was last updated on January 27, 2016. We used records of supercentenarians born in 1885–1898. According to GRG, the 1898 birth cohort is the most recent cohort, which does not have living supercentenarians. This ensures that we analyzed only extinct birth cohorts in our study.

Statistical Methods

Hazard Rate Estimation

Hazard rate was estimated using the standard statistical package Stata (procedure *ltable*). The procedure *ltable* calculates hazard rate for discrete data in the following way. Let $f_j = d_j/n_j$ is the within-interval failure rate, where d_j is the number of deaths within interval j and n_j is the number alive at the beginning of interval j. Then the maximum-likelihood estimate of the hazard rate for interval j is:

$$\mu_j = \frac{1}{\Delta x} \frac{f_j}{1 - \frac{f_j}{2}} \qquad (1)$$

where Δx is the length of age interval j.

This estimate of hazard rate is also called an actuarial estimate of hazard rate (Kimball 1960). Its main assumption is uniform distribution of deaths over age interval.

This estimate provides nonbiased estimates of hazard rate at old ages, in contrast to the often-used one-year probability of death, which has a theoretical upper boundary equal to 1 (Gavrilov and Gavrilova 2011).

Fitting Mortality at Advanced Ages Using Two Competing Models

Mortality data were fitted by two competing models of mortality at advanced age: the Gompertz model (Beard 1971; Gavrilov and Gavrilova 1991; Gompertz 1825) and the alternative exponential model, or flat mortality model (Gampe 2010):

Gompertz: $$\mu_x = a e^{bx} \qquad (2)$$

Exponential model: μ_x = const (3)

Goodness-of-fit for the Gompertz and the exponential models was evaluated using the Akaike information criterion, or AIC (Akaike 1974). Parameters of the Gompertz and exponential models were calculated using weighted nonlinear regression. Age-specific exposure values (person-years) were used as weights (Muller, Wang and Capra 1997). All calculations were conducted using the Stata statistical software, release 13.

Testing the Assumption About Mortality Plateau After Age 110 Years

If the hazard rate is constant with age, then life span is distributed according to the exponential distribution (Marshall and Olkin 2007). This is the basic distribution in survival analysis. The survival function *S*, density *f*, and hazard rate μ of the exponential distribution are, respectively,

$$\mathrm{S}(x) = e^{-\lambda x}, \quad x \geq 0, \qquad (4)$$

$$\mathrm{f}(x) = \lambda e^{-\lambda x}, \quad x \geq 0, \qquad (5)$$

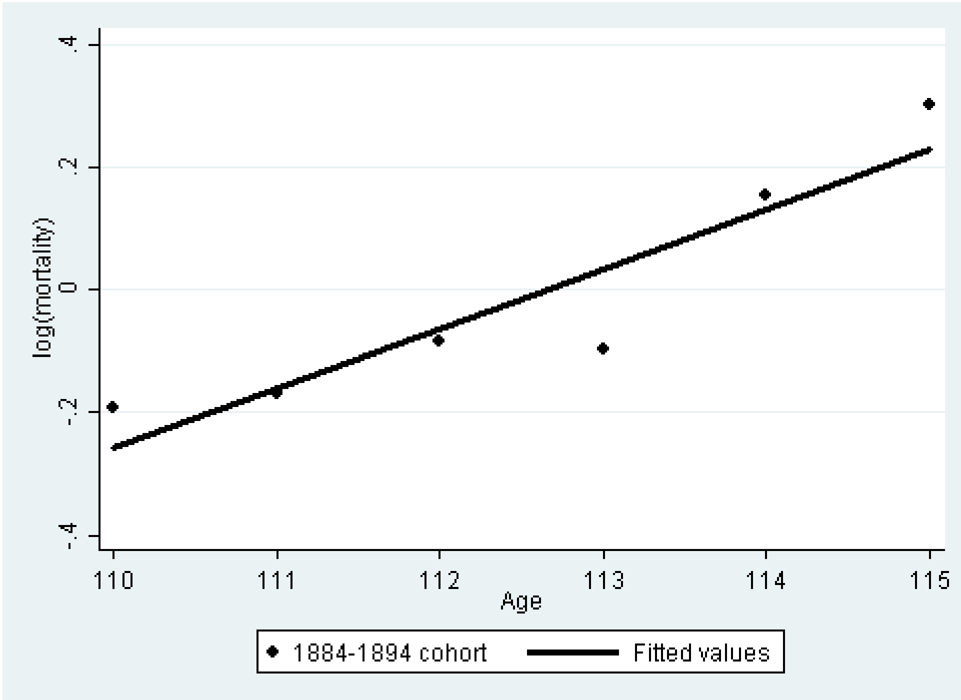
$$\mu(x) = \lambda, \quad x \geq 0, \qquad (6)$$

For exponential distributions, the mean remaining life (remaining life expectancy) is independent of the age *x* and is equal to 1/λ (Marshall and Olkin 2007). This property can be used to test whether mortality of supercentenarians is constant and does not depend on age. Declining mean remaining life expectancy with age would show that the life distribution is not exponential and hazard rate still growths with age. However, using computer simulations, we found that when sample sizes are small, then the remaining life expectancy may decline at the very end of the survival curve, even if the exponential distribution is valid. We used simulation to compare declining patterns for the remaining life expectancy in the case of the observed data, exponential model and the Gompertz model, taking the initial observed cohort size equal to 401 persons in each simulation. We assumed that in the case of the exponential model, the hazard rate remains flat and equal to 0.75 year^{-1}. In the case of the Gompertz model (equation 2), we assumed the following parameter values: *a* = 0.00000000017 and *b* = 0.2 year^{-1}.

Results

Figure 1 shows age-specific death rates in semi-log scale for 1884–1894 birth cohort of supercentenarians, using yearly estimates of hazard rates. Note that the mortality trajectory follows the Gompertz law fairly well, with no visible sign of mortality deceleration (straight line in semi-log scale).

Fig. 1. Age-Specific Hazard Rates for Supercentenarians Born in 1884–1894, Fitted by the Gompertz Model



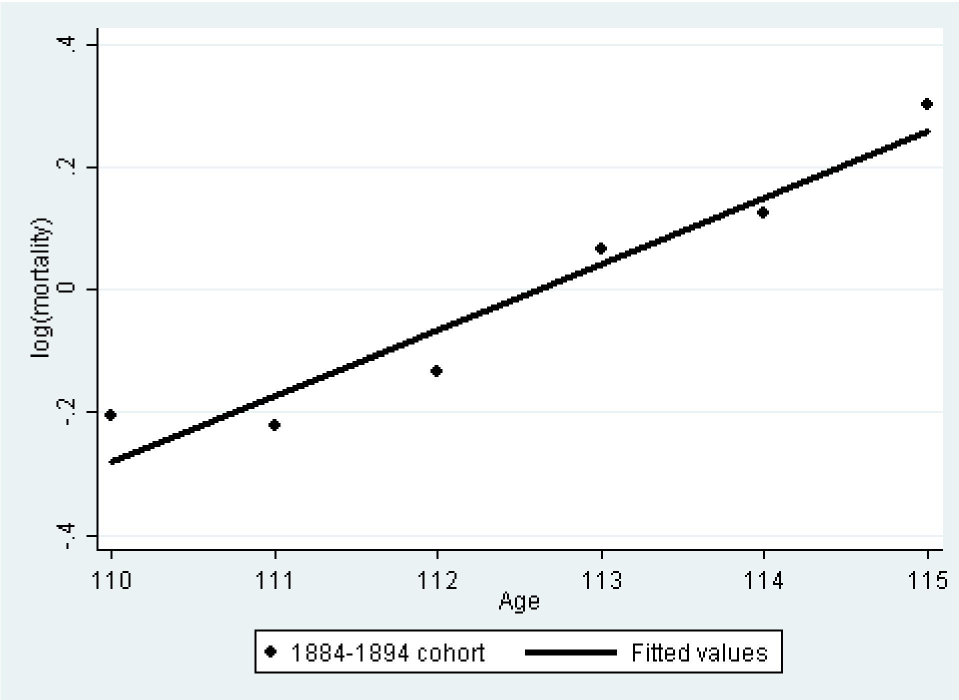
Note: Yearly age intervals. The data fits well with the straight line in semi-log scale, as predicted by the Gompertz model, with no sign of mortality deceleration at extreme old ages.

To make the sample more homogeneous, we analyzed data of the 1884–1894 cohort for persons born in the United States. The result of this analysis is presented in Figure 2. Note that as in the previous case, mortality follows the Gompertz law, and the trajectory is even straighter than in the previous case. We also restricted our sample to records with particularly good quality (group A in the IDL). This restriction did not change the overall linear trajectory in semi-log scale (Fig. 3).

Finally, we used quarterly instead of yearly estimates of hazard rates. As expected, the use of quarterly estimates increased the statistical noise but did not affect the mortality trajectory (see Fig. 4).

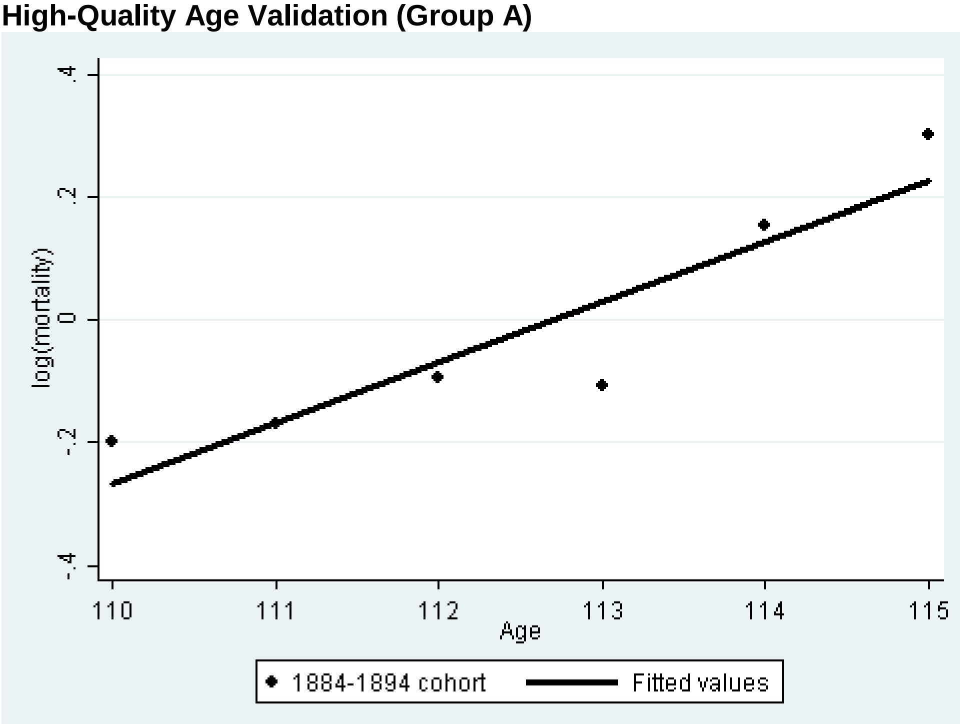
It is also interesting to note that at very old ages (114 to 115 years), hazard rates grow in fact more steeply than predicted by the Gompertz law. In the case of the older cohort, we still observe some growth of mortality with age, but the trajectory grows slower and shows greater scatter of data points (Fig. 5).

Fig. 2. Hazard Rates as a Function of Age for Supercentenarians Born in the United States, 1884–1894



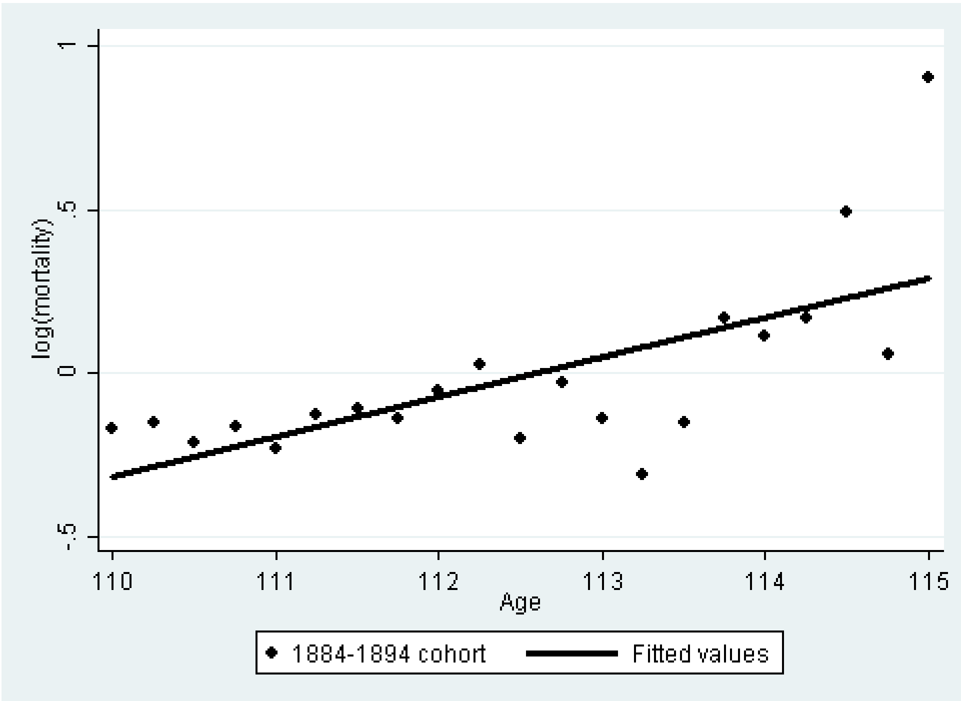
Note: Yearly age intervals. The data fits well with the straight line in semi-log scale, as predicted by the Gompertz model.

Fig. 3. Hazard Rates as a Function of Age for Supercentenarians Born in 1884–1894 with High-Quality Age Validation (Group A)



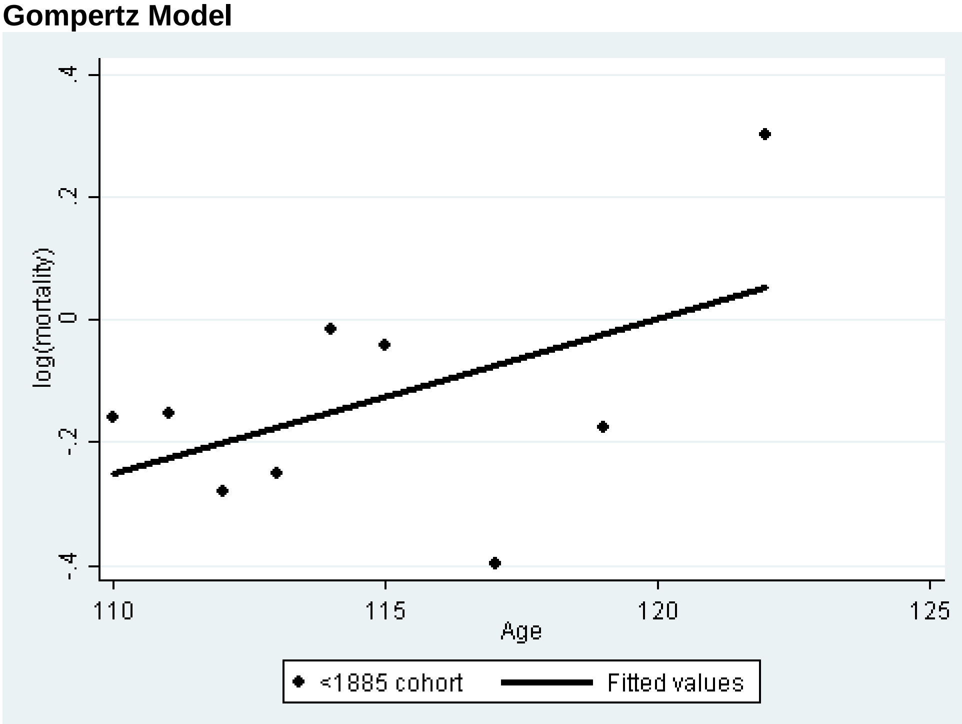
Note: Yearly age intervals. The data fits well with the straight line in semi-log scale, as predicted by the Gompertz model.

Fig. 4. Hazard Rates, Measured at Quarterly Intervals, as a Function of Age for Supercentenarians Born in 1884–1894



Note: The data fits well with the straight line in semi-log scale, as predicted by the Gompertz model.

Fig. 5. Age-Specific Hazard Rates for Supercentenarians Born Before 1885, Fitted by the Gompertz Model



Note: The hazard rate grows with age, although data fit is not as good as for more recent birth cohorts.

To quantify these findings, we compared Gompertz and exponential models using AIC as a goodness-of-fit measure. The results of this study for different studied groups are presented in

Table 1. Note that in all cases of the 1884–1894 birth cohort, the Gompertz model demonstrates better fit (lower AIC) than the exponential model, suggesting that mortality continues to grow with age. We also tested the possibility of a "data truncation" effect when the 1893 and 1894 birth cohorts are not fully extinct and hence contribute to mortality acceleration at older ages. To test this hypothesis, we conducted a sensitivity analysis when cohorts born in 1894, 1893 and 1892 were successfully eliminated from the analyses. This elimination did not change the conclusion of better mortality fit by the Gompertz model up to the 1884–1890 cohort. Thus, the conclusion about growing mortality after age 110 is valid for 1884–1894 birth cohorts and not affected by data truncation.

Table 1. Goodness of Fit for Two Mortality Models

	Akaike information criterion (AIC)		
Subgroup	**Gompertz Model**	**Exponential Model**	**Best Model (Fit)**
1884–1894 Birth Cohort			
All born in 1884–1894	–9.52	–3.53	Gompertz
Born in the United States	–10.08	–3.43	Gompertz
All in group A (better data quality)	–8.91	–3.31	Gompertz
All, quarterly estimates of hazard rate	8.93	15.13	Gompertz
Older Birth Cohort (Born Before 1885)			
All	–11.01	–12.80	Exponential

Source: Data on supercentenarians taken from the International Database on Longevity.

It is interesting that for the older cohort (born before 1885), we observe a different pattern. In this case, AIC shows that the Gompertz model and exponential model describe mortality almost equally well (with somewhat better description by the exponential model; see Table 1). Although Figure 5 shows slow growth of mortality for the older birth cohort, weighted regression gives more weight to mortality at earlier ages, discarding less reliable mortality estimates at older ages. Thus, mortality of supercentenarians for older birth cohorts may be considered as flat.

Table 2 shows parameters of the Gompertz model for all studied groups. For all groups belonging to 1884–1894 cohort, the slope parameter is higher compared with the slope parameter obtained in the interval 85–106 years for the 1898 U.S. birth cohort (0.0946 year^{-1}, with a 95% confidence interval of 0.0945–0.0946), although the accuracy of the parameter estimates for the supercentenarian cohort is relatively low (wider 95% confidence intervals). For the older birth cohort, the slope parameter is low and does not significantly differ from 0 (see Table 2).

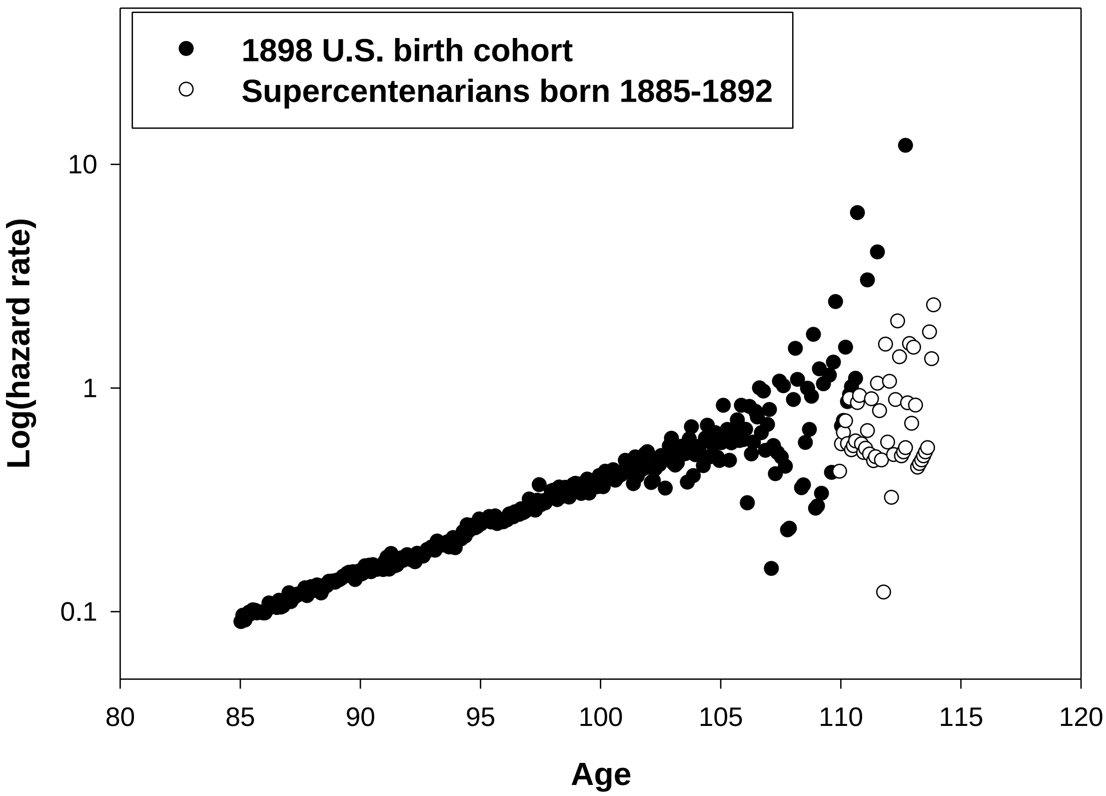
Table 2. Parameters of the Gompertz Model for Different Subgroups of Supercentenarians

Subgroup	**Slope Parameter, Year^{-1}**	**Intercept Parameter, Year^{-1}**
1884–1894 Birth Cohort		
All	0.163 (0.047, 0.279)	9.61x10^{-9} (–1.15x10^{-7}, 1.34x10^{-7})
Born in the United States	0.204 (0.071, 0.337)	9.76x10^{-11} (–1.35x10^{-9}, 1.54x10^{-9})
All in group A (better data quality)	0.165 (0.043, 0.287)	8.03x10^{-9} (–1.01x10^{-7}, 1.17x10^{-7})
All, quarterly age intervals	0.214 (0.073, 0.355)	3.22x10^{-11} (–4.76x10^{-10}, 5.40x10^{-10})
Older Birth Cohort (Born Before 1885)		
All	0.018 (–0.072, 0.108)	0.095 (–0.853, 1.043)

Note: 95% confidence intervals are shown in parentheses.

If we compare monthly mortality estimates for supercentenarians with similar estimates for mortality at younger ages, obtained using the Social Security Administration Death Master File (DMF), it turns out that the data for supercentenarians lie on the same trajectory as the data for younger ages (see Fig. 6). This figure also shows very high variation of the hazard rate after age 110 years.

Fig. 6. Mortality of Supercentenarians Compared With Mortality of the 1898 U.S. Birth Cohort



In addition to the study of 1884–1894 birth cohorts, we attempted to replicate analyses conducted by Gampe for older (born before 1885) and younger (born in 1885 or later) cohorts (Gampe 2010). Comparison of mortality for two birth cohorts in semi-log scale is presented in Figure 7. This figure shows much slower growth of mortality with age for the older cohort. Analyses presented in Tables 1 and 2 suggest that this growth is not statistically significant. In contrast, the growth of mortality for the more recent birth cohort is steep and statistically significant (Tables 1 and 2). This result underscores the importance of quantitative analyses in mortality study, in contrast to visual inspection. We also found similar mortality rates for men and women among supercentenarians (Fig. 8).

Fig. 7. Age-Specific Hazard Rates for Supercentenarians Born Before 1885 and in 1885 and Later, Fitted by the Gompertz Model

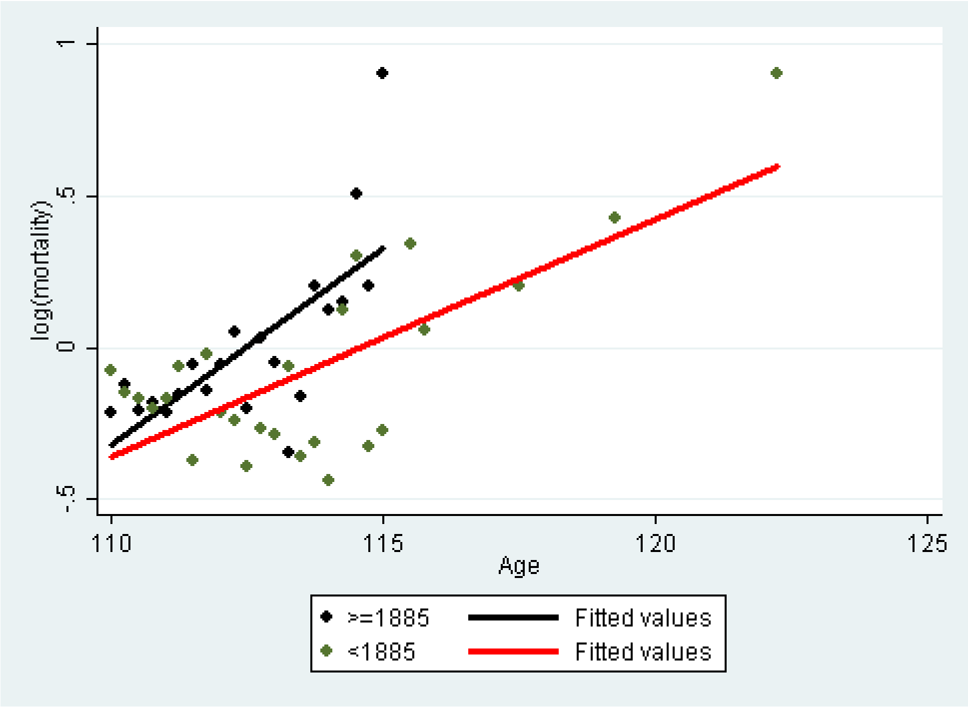
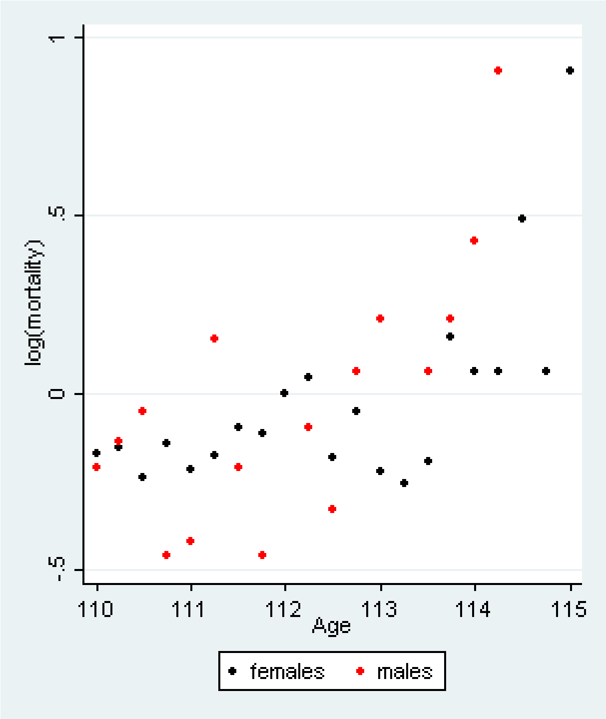
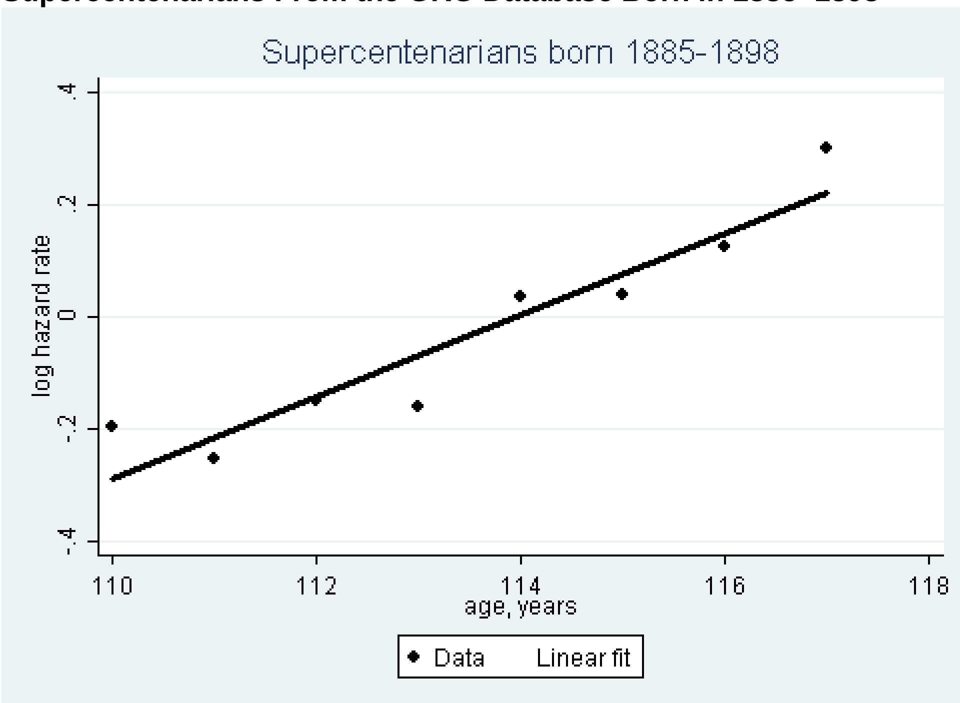


Fig. 8. Age-Specific Hazard Rates for Female and Male Supercentenarians Born in 1884–1894



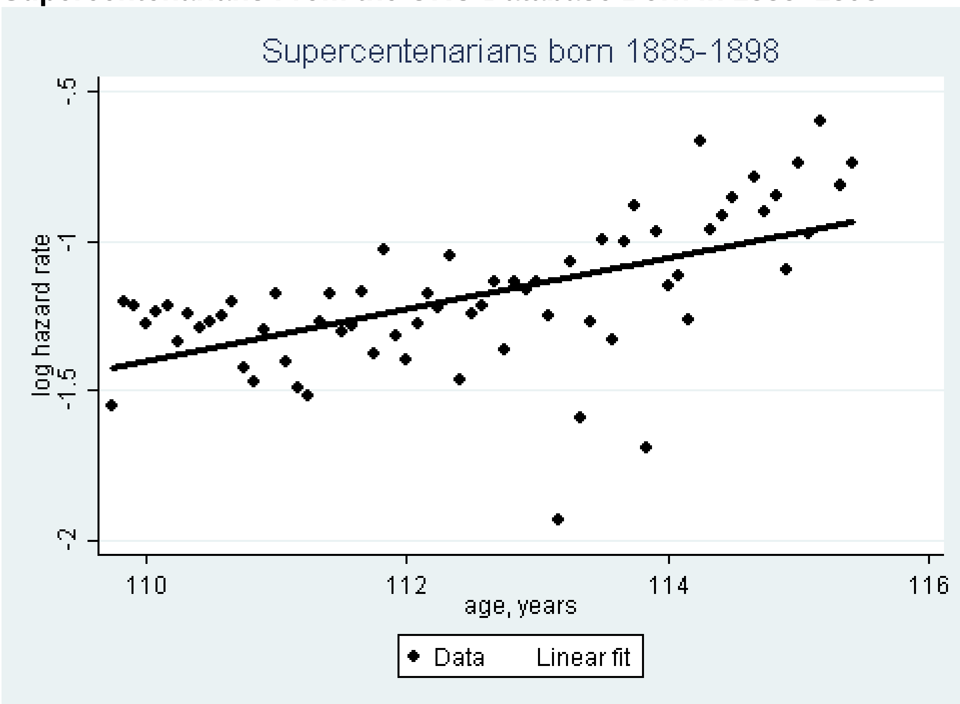
Use of more recent data from the GRG group demonstrated mortality growth with age. Figure 9 shows mortality trajectories for 1885–1898 extinct birth cohorts of supercentenarians with yearly estimates of hazard rates, and Figure 10 shows the same with monthly estimates. Note that mortality follows the Gompertz law with no sign of deceleration and even tends to accelerate at very advanced ages.

Fig. 9. Hazard Rate, Measured at Yearly Age Intervals, as a Function of Age for Supercentenarians From the GRG Database Born in 1885–1898



Note: The data fits well with the straight line in semi-log scale, as predicted by the Gompertz model.

Fig. 10. Hazard Rate, Measured at Monthly Age Intervals, as a Function of Age for Supercentenarians From the GRG Database Born in 1885–1898

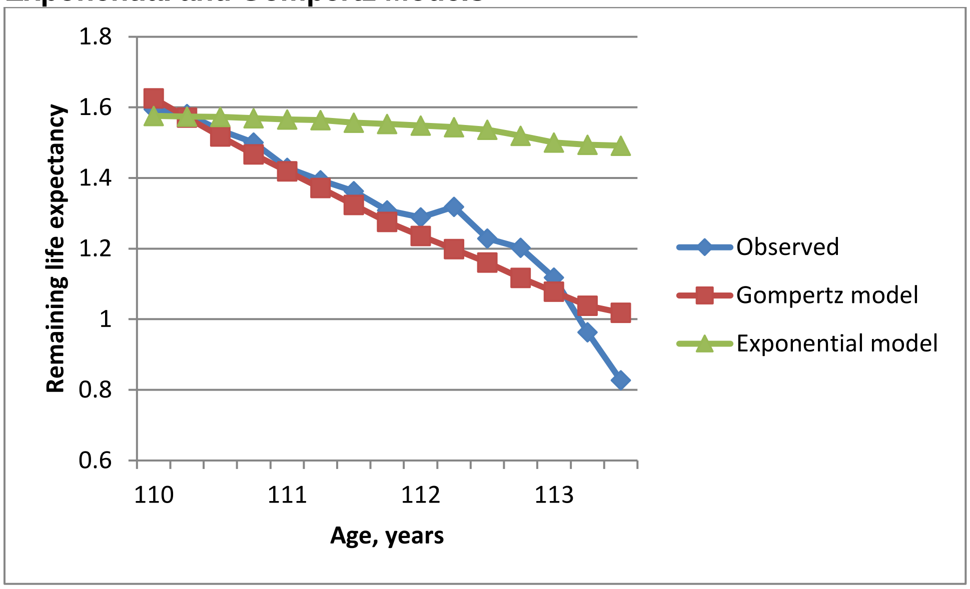


Note: The data fits well with the straight line in semi-log scale, as predicted by the Gompertz model.

Earlier study of mortality after age 110 years found very erratic behavior of hazard rates at these advanced ages (Gampe 2010), which indicates low accuracy of hazard rate estimates. Taking into account this high variation of hazard rate estimates after age 110, we tried to apply an alternative method of analysis using age trajectory of the remaining life expectancy. To this aim, we tested the assumption that "human mortality after age 110 is flat" (Gampe, 2010). This assumption means that mortality after age 110 years follows a simple exponential distribution. This distribution has a property that the remaining life expectancy is flat (does not change with age) if survival follows the exponential distribution. To test this assumption, we studied survival data for the 1884–1894 cohort of supercentenarians and calculated the remaining life expectancies for each quarter of age from age 110 onward. For comparison, we simulated trajectories of the remaining life expectancy in those cases when the Gompertz or exponential model is valid (assuming the same initial cohort number of 401 persons).

Age trajectories of the remaining life expectancy for the observed and simulated data are presented in Figure 11. Note that the remaining life expectancy in the case of exponential distribution is relatively flat until the sample size drops below 100 around the age of 112 years. Figure 11 also shows that the remaining life expectancy for the 1884–1894 birth cohort declines more rapidly than predicted by the exponential model, and the pattern of decline agrees better with the Gompertz model of mortality. These results confirm findings obtained when analyzing the shape of mortality trajectories.

Fig. 11. Changes in Life Expectancy With Age After 110 Years: Remaining Life Expectancy of Supercentenarians Born in 1884–1894 Compared with Simulations Using the Exponential and Gompertz Models



Note: The observed life expectancy declines with age, and its trajectory is closer to the Gompertz model, which does not agree with the assumption about a flat hazard rate (exponential model of survival).

Discussion

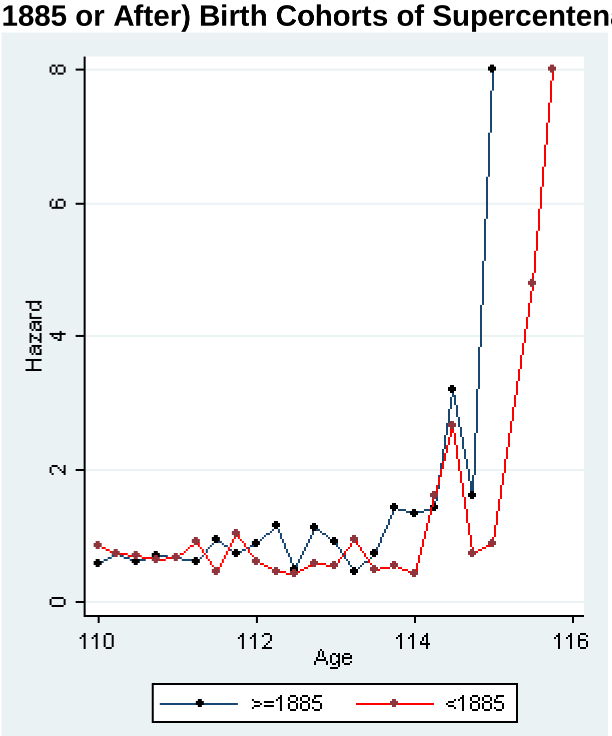
We found that hazard rate estimates based on supercentenarian data taken from the publicly available International Database on Longevity continue to grow after age 110 years and follow the Gompertz law. This conclusion holds for cohorts born after 1883. Similar results of mortality growth for more recent birth cohorts were obtained earlier, using data from the Social Security Death Master File (Gavrilov and Gavrilova 2011). Mortality of older birth cohorts (born before 1885) demonstrates slower growth with age, which is not significantly different from the constant mortality. One possible explanation of this observation is lower quality of birth recording in older data. Another explanation is a faster increase of mortality with age in more recent birth cohorts. As a result, we may expect mortality acceleration rather than deceleration at older ages in the future. Right now, accelerating mortality patterns are not observed in human populations, but such patterns may appear after significant improvement in age reporting at older ages. An alternative way to test the assumption of a flat hazard rate (constant remaining life expectancy) failed to confirm the validity of this assumption for the 1884–1894 birth cohort.

Our results do not agree with the conclusions of earlier studies of mortality of supercentenarians, which found no increase in mortality with age after age 110 (Gampe 2010; Robine and Vaupel 2001). Robine and Vaupel analyzed age trajectories of probability ofdying, rather than trajectories of hazard rate. Estimates of one-year probability of dying and hazard rate are numerically close at younger adult ages, when death rates are relatively small. However, after age 80–85 years, probability of dying shows a tendency of deviation from the hazard rate, and it has a theoretical upper limit equal to 1, which may result in an apparent flat trajectory for probability of dying at extreme old ages. Also, Robine and Vaupel (2001) analyzed data for older birth cohorts, which demonstrate a mortality plateau at advanced ages.

Gampe (2010) analyzed the hazard rate of supercentenarians, using the same IDL database as in this study, and came to a conclusion that mortality after age 110 years is flat and that there is no difference in mortality between the older (born before 1885) and more recent (born in 1885 and later) cohorts. We found that mortality is flat only for older birth cohorts, which are very heterogeneous with birth years varying from 1852 to 1884 (a 32-year interval). It is reasonable to expect flatter mortality trajectories in a more heterogeneous population. Also, the quality of age validation may be lower for persons who died in the 1960s and 1970s, compared with more recent cases, so some degree of age misreporting is possible for very old cases.

We believe that the main reason for differences between conclusion made by Gampe and our results lies in the manner of data analyses. Gampe based her conclusion on visual inspection of graphs presenting age trajectories of hazard (in plain scale) and the logarithm of survival function, rather than quantitative analyses. Visual inspection for both hazard and logarithm of survival function is not an accurate method of analysis and may lead to wrong conclusions. For example, comparison of hazard rates for older (born before 1885) and younger (born in 1885 and later) birth cohorts using a plain (non-logarithmic) scale does not catch the increasing trend of mortality for the 1885-and-later birth cohort (compare Figs. 12 and 7). Graphs for the logarithm of survival function are not able to discriminate between competing Gompertz and exponential distributions, based on a visual inspection. Although we initially applied this approach in our analyses (Gavrilov and Gavrilova 2003), we found later that this method is not sensitive enough to make conclusions about the shape of mortality distribution. Also, Gampe wrote her own program for hazard rate calculation, rather than using estimates provided by standard statistical packages, so it is difficult to test and reproduce her results. In our study, we used a standard program for hazard rate estimation available in the Stata package and a publicly available data set with clear criteria for subsample selection.

Fig. 12. Hazard Rate Change Over Age for Older (Born Before 1885) and Younger (Born 1885 or After) Birth Cohorts of Supercentenarians



Note: Quarterly estimates. The tendency of mortality growth with age (which is visible on a semi-log scale) is lost when data are analyzed using a plain scale.

It is possible that mortality at older ages was almost flat and did not grow with age in the past. In the case of more recent data, it is obvious that mortality continues to grow after age 110 years. And the most recent data based on GRG database (Fig. 9) confirm this conclusion.

Conclusion

We found that mortality after age 110 years continues to grow with age and can be fitted by the Gompertz law. This result suggests that mortality deceleration at older ages is not a universal phenomenon, and these findings may represent a challenge to existing theories of aging and longevity, which predict slowing down of mortality growth in the late stages of life (Gavrilov and Gavrilova 2001; Rose et al. 2006; Vaupel et al. 1998). One approach for reconciliation of the observed phenomenon and the existing theoretical considerations is a possibility of mortality deceleration and mortality plateau at very high yet unobservable ages.

Acknowledgments

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