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Mortality of Supercentenarians: Does It Grow with Age?

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1. Introduction

Accurate estimates of mortality at advanced ages are essential for forecasts of population aging, and 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 data with poor quality compared to data with 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 2014). On the other hand, existing studies of mortality after age 110 years demonstrated 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 sufficiently large sample 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 estimation) applying standard method implemented in the Stata package. Methods of mortality trajectory analysis are based on comparing alternative models of mortality using a standard goodness-of-fit procedure.

Data and Methods

Data

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 more from 15 countries with good quality of 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.

We used a portion of IDL records for persons belonging to extinct birth cohorts (born before 1893) since the last deaths in IDL were observed in 2007. Also we used data for birth cohorts that did not contain censored observations. Our earlier study of mortality at advanced ages based on Social Security Administration death Master File (DMF) showed that data for older birth cohorts have generally lower quality compared to younger 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 1885-1893) birth cohorts. Taking into account very small number of male records, we used data for both sexess in our analyses.

Statistical Methods

Age-specific death rates were calculated using Stata command ‘ltable’. Age-specific death rate is also called an actuarial estimate of hazard rate (Kimball 1960) and is calculated in the following way:

$$\mu_x = \frac{2q_x}{\Delta x\,(2 - q_x)} = \frac{2}{\Delta x}\,\frac{l_{x-\Delta x} - l_x}{l_{x-\Delta x} + l_x} \qquad (1)$$

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

Mortality data were fitted by the most frequently used models of adult mortality: the Gompertz model (Beard 1971; Gavrilov and Gavrilova 1991; Gompertz 1825) and the alternative ‘logistic’ Kannisto model (Thatcher et al. 1998).

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

Kannisto: $$\mu_x = \frac{a e^{bx}}{1 + a e^{bx}} \qquad (3)$$

Data for older and younger birth cohorts were studied separately.

Goodness-of-fit for the Gompertz and the Kannisto models was evaluated using the Akaike Information criterion, AIC (Akaike 1974).

All calculations were conducted using the Stata statistical software, release 13.

Results

Figure 1 shows age-specific death rates in semi-log scale for younger cohort of centenarians using yearly estimates of hazard rates. Note that mortality trajectory follows the Gompertz law fairly well with no visible sign of mortality deceleration (straight line in semi-log scale). In order to make the sample more homogeneous, we analyzed data of younger cohorts 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 very well. We also restricted our sample to records with particularly good quality (group A in the IDL). This restriction did not change the trajectory presented in Figure 1 (data not shown). Finally, we used quarterly instead of yearly estimates of hazard rates (see Figure 3). As expected, use of quarterly estimates of hazard rates increased the statistical noise but did not affect the mortality trajectory (see Figure 3). It is also interesting to note that at very old ages (114-115 years) hazard rates grow in fact steeper than predicted by the Gompertz law. In the case of older cohort, we still observe growth of mortality with age, but the trajectory shows higher scatter of data points (Figure 4).

In order to quantify this finding, we compared Gompertz and Kannisto 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 the Gompertz model demonstrates better fit than the ‘mortality deceleration’ Kannisto model.

It is also interesting to check if the Gompertz model at very advanced ages has the same slope as observed at younger ages. Table 2 shows parameters of the Gompertz model for all studied groups. For all groups belonging to the younger cohorts the slope parameter is higher compared to the slope parameter obtained in the interval 85-106 years (0.0946 $year^{-1}$, 95%CI: 0.0945-0.0946). For older birth cohort the slope parameter is lower (Table 2). We should note that in most cases the slope parameter is not significantly different from the slope parameter observed for middle age mortality. This observation does not support the suggestion about two-stage Gompertz model of mortality with two different slopes at different ages (Curtsinger et al. 1992; Curtsinger, Gavrilova and Gavrilov 2006).

If we compare monthly mortality estimates for supercentenarians with similar estimates for mortality at younger ages it turns out that the data for supercentenarians lie on the same trajectory as the data for younger ages (Figure 5). This figure also shows very high variation of hazard rate after age 110 years. Taking into account this high variation in hazard rate estimates after age 110 we decided to use more robust ways to test assumptions about mortality distribution at advanced ages. First of all, we tested the assumption that "human mortality after age 110 is flat" (Gampe, 2010). This assumption means that mortality after age 110 years follows simple exponential distribution. This distribution has at least two general properties. First property is that life expectancy should be flat (does not change with age) if survival follows the exponential distribution. The second property is that coefficient of variation for life expectancy should be equal to one. To test this assumption, we studied survival data for younger cohort of supercentenarians born in 1885-1892 and calculated life expectancies for each quarter of age from age 110 to age 115. At age 115 years there are less than 10 persons left so we did not attempt to calculate life expectancy for this small sample. The results of our estimates are presented in Figure 6. Note that life expectancy is declining with age and this decline does not agree with the assumption about constant life expectancy. The regression coefficient for linear regression model of life expectancy on age is negative (-0.24) and significantly different from zero ($p<0.001$). Changes of the coefficient of variation for life expectancy (CV) on age are presented in Figure 7. Note that CV has a tendency to decline rather than increase with age and is lower than one in all cases but one at the very end of age scale when variation is particularly high. The regression coefficient is negative (-0.041) and not significantly different from zero (0.066) although close to statistical significance.

Discussion

We found that hazard rate estimates based on age-specific death rates taken from the publicly available International Database on Longevity, continue to grow after age 110 years and follow well the Gompertz law. Younger birth cohort of supercentenarians demonstrates straight mortality trajectory in semi-log coordinates while mortality of older birth cohort grows slower with age. Similar results were obtained earlier using mortality data from the Social Security Death Master File or DMF (Gavrilov and Gavrilova 2011). One possible explanation of this observation is lower quality of birth recording in older data. Another explanation is a real more rapid increase of mortality with age in younger birth cohorts. As a result, we may expect mortality acceleration rather than deceleration at older ages. In our earlier study we observed that old-age mortality in the studied U.S. birth cohorts followed the Gompertz model despite substantial improvement of mortality over time. One possible explanation of this puzzling observation may be an assumption of accelerating age pattern of individual mortality rates in excess of the Gompertz model (steeper than Gompertz mortality trajectory). 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. More robust way to test the assumption of flat hazard rate function (constant life expectancy and CV equal to one) failed to confirm the validity of this assumption. This result may be important, because hazard rate at very advanced age is subjected to very high variation and methods based on the hazard rate estimates may produce inaccurate results.

Our results do not agree with the 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 of death rather than trajectories of hazard rate. Estimates of one-year probability of death and hazard rate are numerically close at younger adult ages when death rates are relatively small. However, after age 80-85 years probability of death shows a tendency of deviation from the hazard rate and it has a theoretical upper limit equal to one. In order to get more accurate estimates of hazard rate after age 80 year, probability of death should be estimated for monthly rather than yearly age interval (Gavrilov and Gavrilova 2011). This problem is often overlooked by researchers. Gampe analyzed mortality after age 110 years for 224 supercentenarians from IDL and obtained almost flat age trajectory for hazard rate (Gampe 2010). We are not able to reproduce her results because the process of subsample selection for 224 supercentenarians was not described in her publication with sufficient detail. The result by Gampe can probably be explained by applying discrete duration model to hazard rate estimation where hazard rate is treated as probability and hence may be biased downward (Singer and Willett 2003). Gampe used her own program for hazard rate calculation rather than standard statistical package, so it is difficult at this time to reproduce her results. In our study we used standard program for hazard rate estimation available in Stata and publicly available dataset with clear subsample selection criteria.

Conclusion

We found that mortality after age 110 years continues to grow with age and follows well 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 possibility for reconciliation of the observed phenomenon and the existing theoretical consideration is a possibility of mortality deceleration at very high yet unobservable ages.

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Table 1. Testing two competing mortality models with human data. Akaike information criterion (AIC) for the Gompertz model and the 'mortality deceleration' Kannisto model. Data on supercentenarians taken from the International Database on Longevity

Subgroup	Gompertz model	Kannisto model	Best model(fit)
	Younger birth cohort (born in 1885-1895)		
All	-11.41	4.53	Gompertz
Born in the United States	-12.25	6.93	Gompertz
All in group A (better data quality)	-11.64	4.83	Gompertz
All, monthly estimates of hazard rate	-183.1456	-168.4173	Gompertz
	Older birth cohort (born before 1885)		
All	-12.91	6.67	Gompertz

Table 2. Parameters of the Gompertz model for different subgroups of supercentenarians*.

Subgroup	Slope parameter, year^{-1}	Intercept parameter, year^{-1}
	Younger birth cohort (born in 1885-1895)	
All	0.187 (0.070, 0.304)	6.65e-10 (-7.99e-09, 9.32e-09)
Born in the United States	0.259 (0.146, 0.371)	2.09e-13 (-2.42e-12, 2.84e-12)
All in group A (better data quality)	0.191 (0.076, 0.305)	4.49e-10 (-5.28e-09 6.18e-09)
All, monthly estimates of hazard rate	0.336 (0.187, 0.485)	3.56e-18 (-5.59e-17, 6.30e-17)
	Older birth cohort (born before 1885)	
All	0.025 (-0.053,0.105)	.03813 (-.29756, .37382)

* 95% confidence intervals are shown in parentheses.

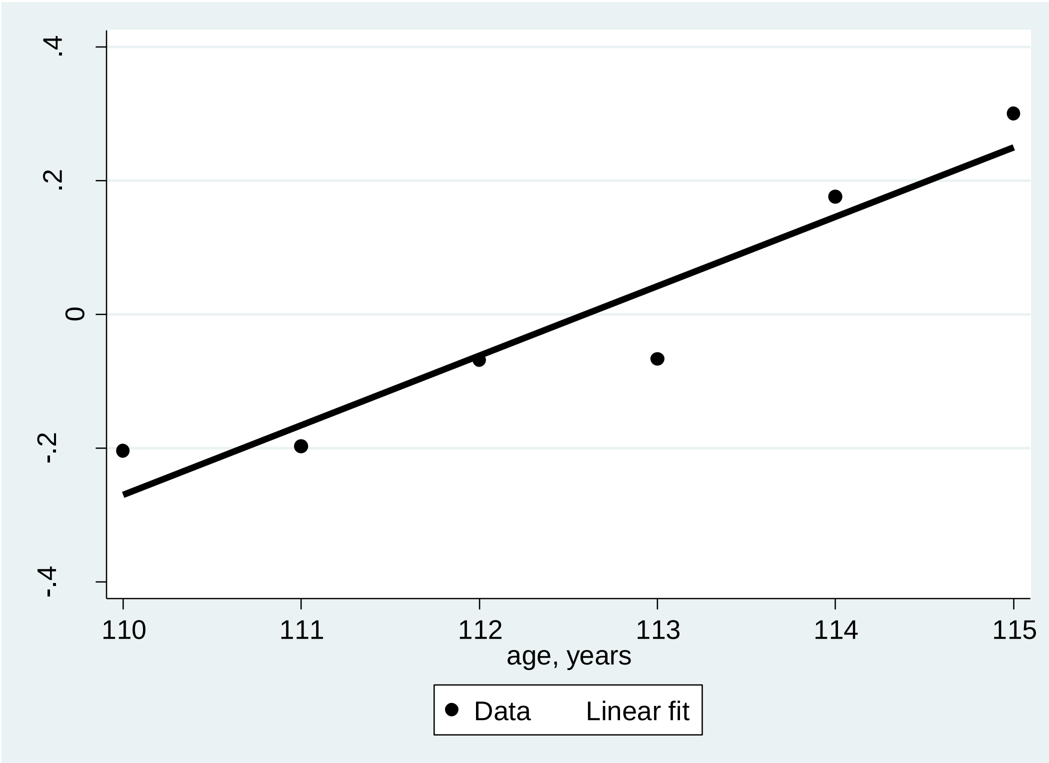

Figure 1. Age-specific hazard rates for supercentenarians born in 1885-1892 fitted by the Gompertz model. Note that the data fits well with the straight line in semi-log scale, as predicted by the Gompertz model, with no sign of mortality deceleration at extreme old ages

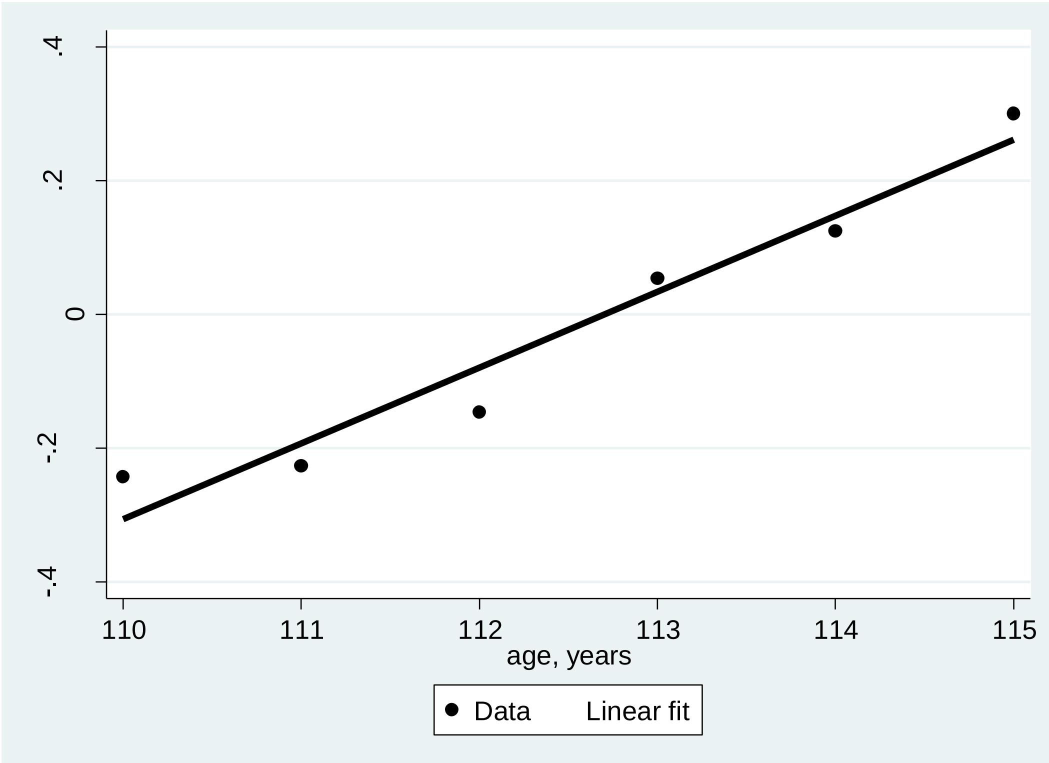

Figure 2. Hazard rate (measured at yearly age interval) as a function of age. Supercentenarians born in the United States in 1885-1892. Note that the data fits well with the straight line in semi-log scale, as predicted by the Gompertz model

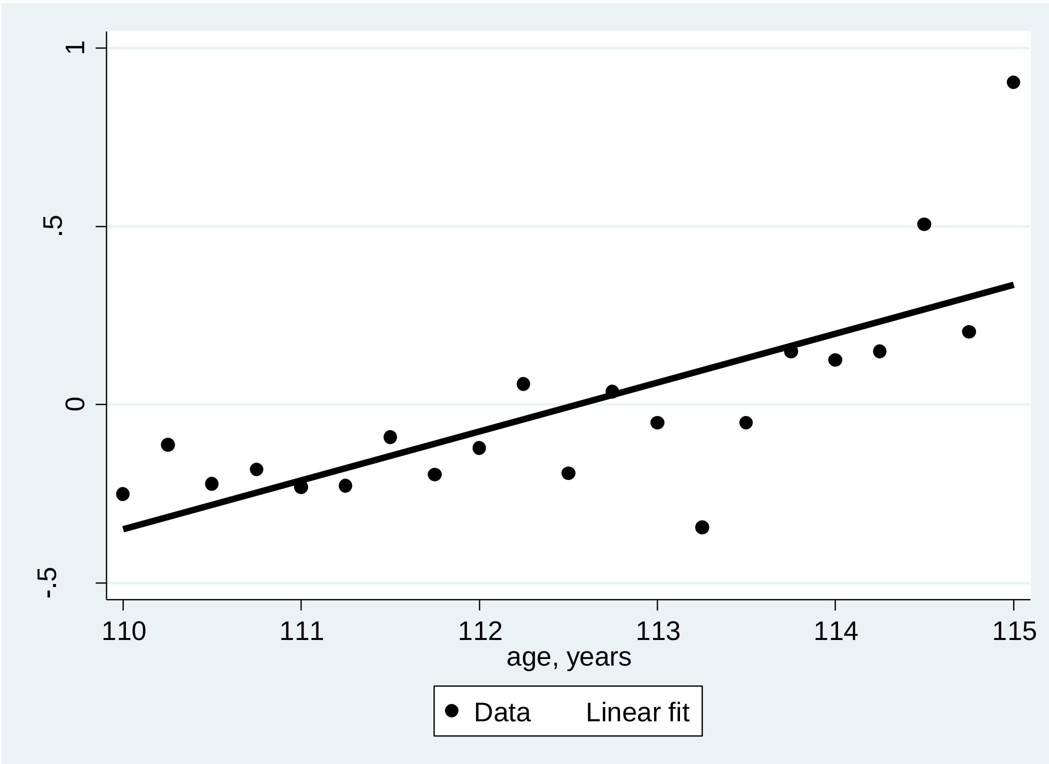

Figure 3. Hazard rate (measured at quarterly intervals) as a function of age. Supercentenarians born in 1885-1892. Note that the data fits well with the straight line in semi-log scale, as predicted by the Gompertz model

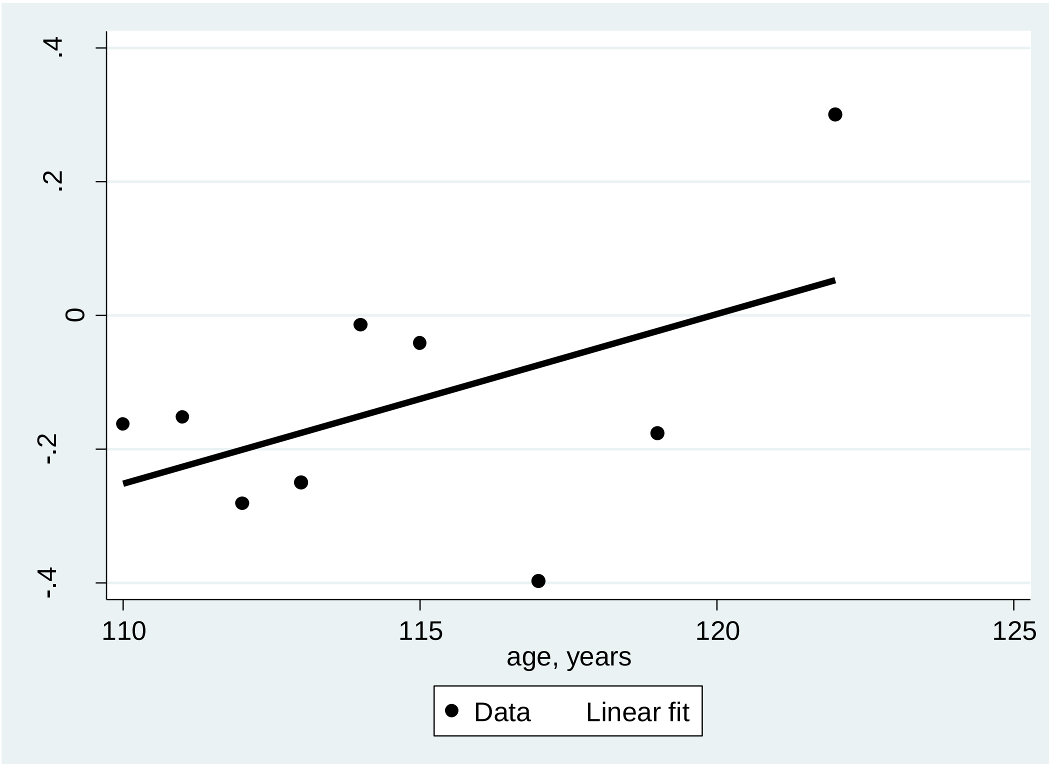

Figure 4. Age-specific hazard rates for supercentenarians born before 1885 fitted by the Gompertz model. Note that the hazard rate grows with age although data fit is not as good as for the younger birth cohort.

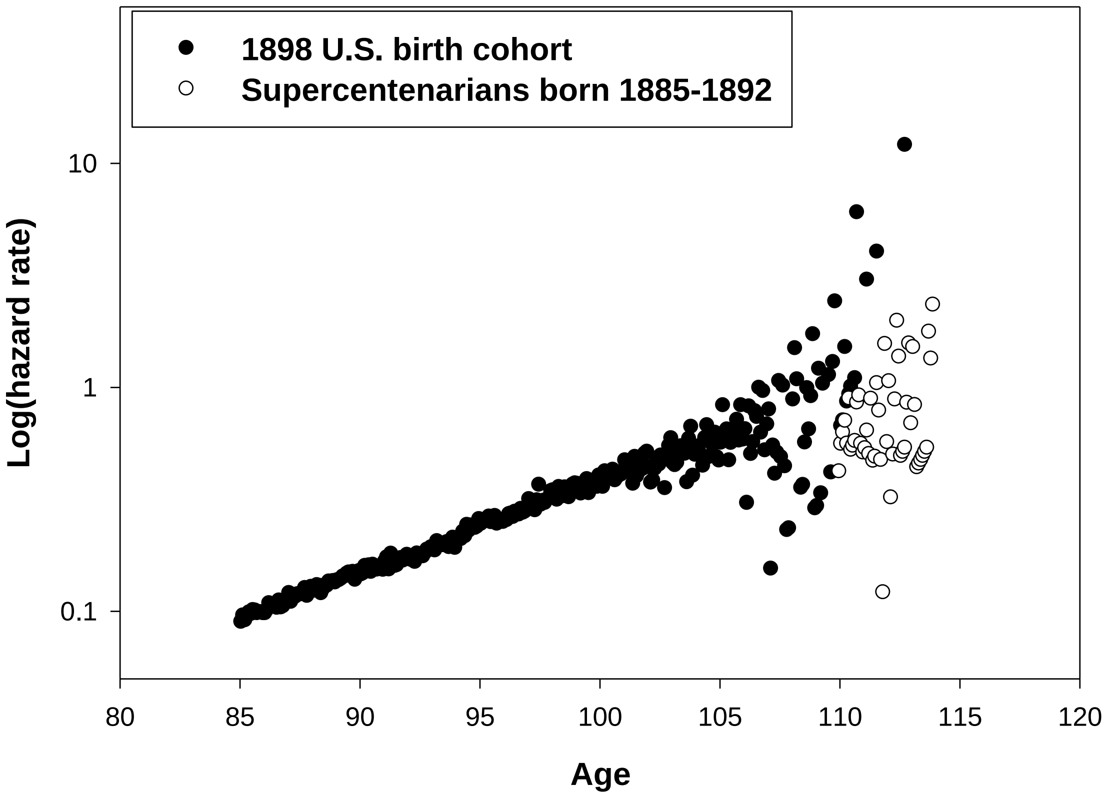

Figure 5. Mortality of supercentenarians (white circles) as compared to mortality of the 1898 U.S. birth cohort.

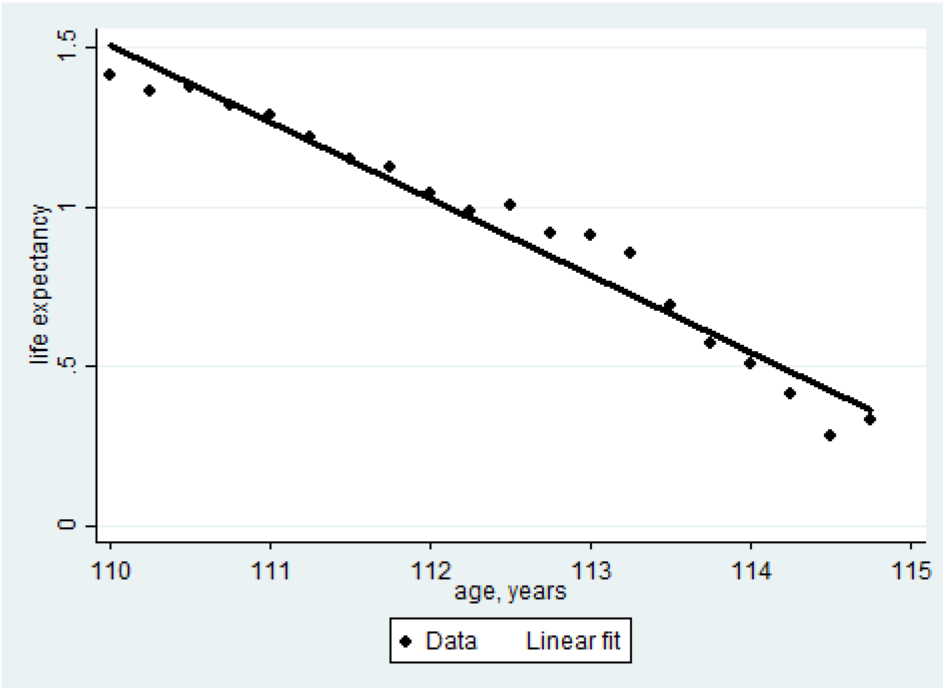

Figure 6. Changes of life expectancy after age 110. Supercentenarians born in 1885-1892. Note that life expectancy declines with age, which does not agree with the assumption about flat hazard rate (exponential model of survival).

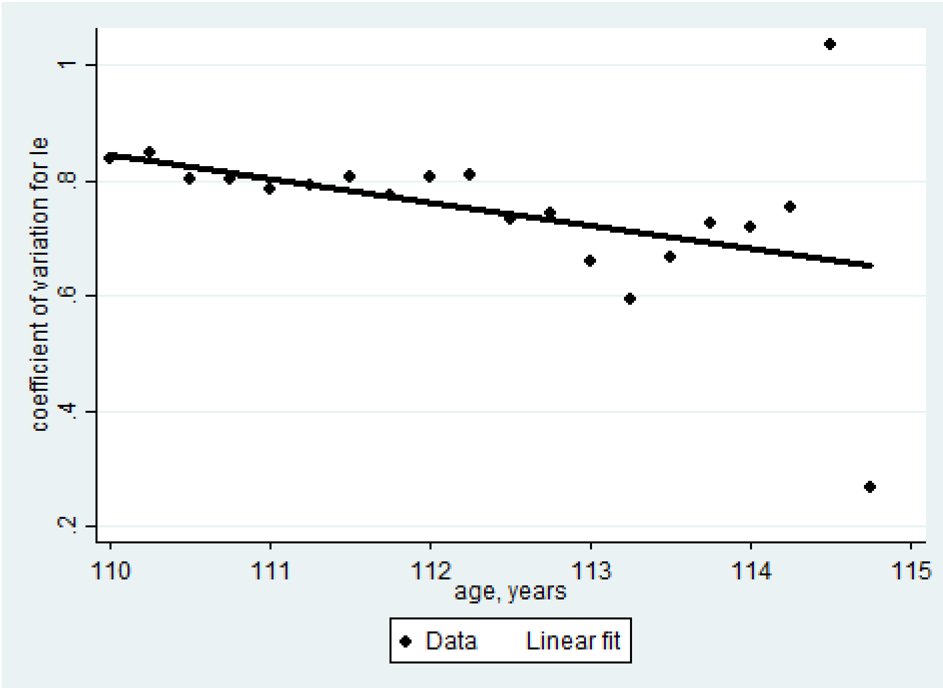

Figure 7. Changes of coefficient of variation (CV) for life expectancy after age 110. Supercentenarians born in 1885-1892. Note that CV is lower than one, which does not agree with the assumption about flat hazard rate (exponential model of survival).