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The Plateau of Human Mortality: Demography of Longevity Pioneers

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Abstract

Theories about biological limits to lifespan and evolutionary shaping of human longevity depend on facts about mortality at extreme ages. The facts have remained in dispute. Do hazard curves typically ultimately level out into high plateaus, as seen in other species, or do exponential increases go on and on? Here we estimate hazard rates from data on all Italian inhabitants aged over 105 between 2009 and 2015 (born 1896-1910), 3836 carefully documented cases. We find level hazard curves, essentially constant beyond age 105. The estimates are free from artifacts of aggregation limiting earlier studies and provide the best evidence so far for the existence of extreme-age mortality plateaus in humans.

Summary

Above age 105 human mortality appears constant over age at levels that are slowly declining across cohorts.

Text

Survival to extreme ages tests the limits of evolutionary demographic potential. Here we report a curve of death rates by age for recent cohorts of Italians, a curve essentially level over 105. In so doing, we address what is at once nearly the oldest question and also the most current question in the formal study of human senescence: are there limits to the rise in risks of death by age?

In 1825, in proposing the first model for accelerating, exponential increases in mortality by age, Benjamin Gompertz (1) cautiously included an upper bound on ages of applicability. Whether to attribute apparent deviations at extreme ages to age misreporting or to structural processes long looked impossible to settle. After 1990, as data improved, studies (2-7) began to build a case for genuine deceleration from about age 80 onwards, contrasting with clearly exponential curves at lower adult ages. When a mortality curve levels out, it is said to reach a plateau. The new findings for humans accord with new discoveries of plateauing mortality at extreme ages in other species (8) and have stimulated a wave of biodemographic and evolutionary theory. Other studies, however, have reached an opposite conclusion: the better the data, the less the appearance of leveling (9-10). A recent work (11) reports exponential increases persisting even beyond 110 in sparse but high-quality data drawn from a collection of countries.

If claims of extreme-age plateaus in human mortality turned out to be generally illusory, much of the demographic modeling of the last two decades would have to be rethought. Here, to the contrary, we show a clean case where the plateau is real.

Accurate mortality data at advanced ages are difficult to obtain. In vital statistics, the very old are often aggregated in one age-group. Even in countries with reliable vital registration, age exaggeration is common among the oldest-old. These difficulties motivated the establishment of an international research team collecting, analysing, and meticulously checking data on people who reach ages of 110 years or more, supercentenarians, in fifteen countries including Italy. The International Database on Longevity (IDL) at the Max Planck Institute for Demographic Research is the result of this decade-long effort (www.supercentenarians.org), updated through 2010.

Thanks to this database, estimates of mortality after age 110 could be obtained (12). The hazard function, the usual continuous-age version of mor-

tality rates as a function of age, turned out to appear constant at least up to age 114, after which data become too sparse for reliable statements. For this result, data on supercentenarians had to be pooled from eleven countries to arrive at adequate sample sizes. Country-specific estimates were not feasible because individual countries do not provide enough observations to limit sampling variation. Within the limits of precision, supercentenarian hazards showed no improvement over time. These findings have been challenged (11) with analysis of the same IDL data by different methods. In the wake of limitations on precision and continuing controversy, the IDL project is now being extended to cover people who survive to age 105 or more.

In conjunction with the IDL extension, the Italian National Institute of Statistics (ISTAT) has recently collected and carefully validated the individual survival trajectories of all the Italian inhabitants aged 105 and over in the period from 1 January 2009 to 31 December 2015, the data for the present study. For several reasons, these data allow estimation of mortality at extreme ages with an accuracy and precision that were not possible before. First, individual trajectories provide information on survival in continuous time, therefore avoiding possibly misleading patterns of death rates that are computed on pre-specified age intervals and are often obtained by aggregating heterogeneous birth cohorts. Second, the validation procedure has been developed specifically for this population segment and meets the highest validation criteria provided by the IDL protocol. It is based on the resident population of the Italian municipalities that is yearly recorded on January 1st. Each municipality where individuals aged 105+ have been reported was contacted by ISTAT. A death certificate was required for each deceased subject. This certificate includes, among other information, the date of birth of the deceased certified by the Civil Status Officer. A certificate of survival was required for all the subjects who were expected to be still alive at the end of the study period. For supercentenarians, those most problematic in terms of age reporting, the birth certificate was additionally collected. In these data, age misreporting is believed to be minimal. The project includes all those 105 and older in the period 1 January 2009 to 31 December 2015, so that the data are also free of age ascertainment bias.

The present study based on ISTAT data includes 3836 cases, 463 of whom are males, across 15 birth cohorts (1896 - 1910). Less than 4% of these individuals were born abroad. Of those, many have clear Italian origins (13). Some 472 individuals born before 31 December 1903 (birth cohorts 1896 -

1903) enter the study at ages greater than exactly 105 and, as such, provide left-truncated survival trajectories. Death during the follow-up was observed in 2883 cases and, as a result, 953 individuals are right-censored, i.e., still alive at the end of the study. Table 1 displays the distribution of observed deaths and censored trajectories across gender and cohort. Increases in samples from row to row bear testimony to improvements in survival from cohort to cohort at ages before 105, and lead us to expect the downward cohort trend in hazards beyond 105 in our data to be described below.

Table 1: Distribution of the observed cases

Cohort	Age at entry into study (computed)	Males		Females		Reaching age 105
		Censored cases	Observed deaths	Censored cases	Observed deaths	
1896	112	0	0	0	4	4
1897	111	0	0	0	1	1
1898	110	0	0	0	5	5
1899	109	0	0	1	12	13
1900	108	0	0	0	23	23
1901	107	0	7	0	46	53
1902	106	0	17	2	134	153
1903	105	0	23	2	195	220
1904	105	0	35	5	302	342
1905	105	2	40	10	331	383
1906	105	2	48	19	348	417
1907	105	11	55	40	354	460
1908	105	19	57	106	345	527
1909	105	28	33	219	296	576
1910	105	64	22	423	150	659
Total		126	337	827	2546	3836

For context, Fig. 1a shows confidence intervals for logarithms of yearly hazards for the single-year cohort of Italian women born in 1904. Before age 105 intervals derive from vital statistics in the Human Mortality Database (HMD), *www.mortality.org*. These widening intervals, also likely distorted by age misreporting, only hint at decreasing slopes. Beyond age 105 intervals derive from ISTAT data restricted to this single cohort, with separate inter-

vals for each year of age. Even with these high-quality data, separating out cohorts and ages leave too much uncertainty to tell whether hazards continue upward, level out, or decrease beyond 105. We fit a model which combines cohorts and ages to circumvent this challenge. Our best-estimated trajectory for the 1904 cohort from our modeling is the flat curve, the plateau, shown in Fig. 1b. On a log scale, exponential curves become straight lines. A straight-line fit based on ages 65 to 80, where the Gompertz model does appear to hold, fails at later ages and far overshoots our estimated plateau beyond age 105.

To determine from the full ISTAT data whether log-hazard slopes after 105 are level, upward, or downward, our modeling approach compares a null hypothesis of constant hazards to alternatives with a non-zero Gompertz slope parameter. We include a (modest) exponential cohort trend and a proportional gender effect, setting the hazard at age x years beyond 105 equal to

$$a \exp(bx) \exp(\beta_1 C + \beta_2 M)$$

with b constrained to zero for the null model. Here C is cohort birth year minus 1904, M equals 1 for males, zero else. Parameters include initial hazard a at 105, Gompertz slope b , cohort effect β_1 and gender effect β_2 .

Parameters estimated by standard maximum likelihood methods for truncated and censored survival data (14) are shown in Table 2. A likelihood ratio test fails to reject the constant-hazard null model at a level as generous as 0.44. Under the alternative hypothesis, the Gompertz slope parameter estimate $b = 0.013$ with standard error 0.017, is not statistically significant at the 5% level and is practically indistinguishable from zero. This near-negligible slope stands in striking contrast to the slope as large as 0.103 at younger ages (65–80) in Fig. 1b, which is paired with a log hazard at 65 of $\log(0.015)$. For variant models and power calculations, see Tables S1 and S2.

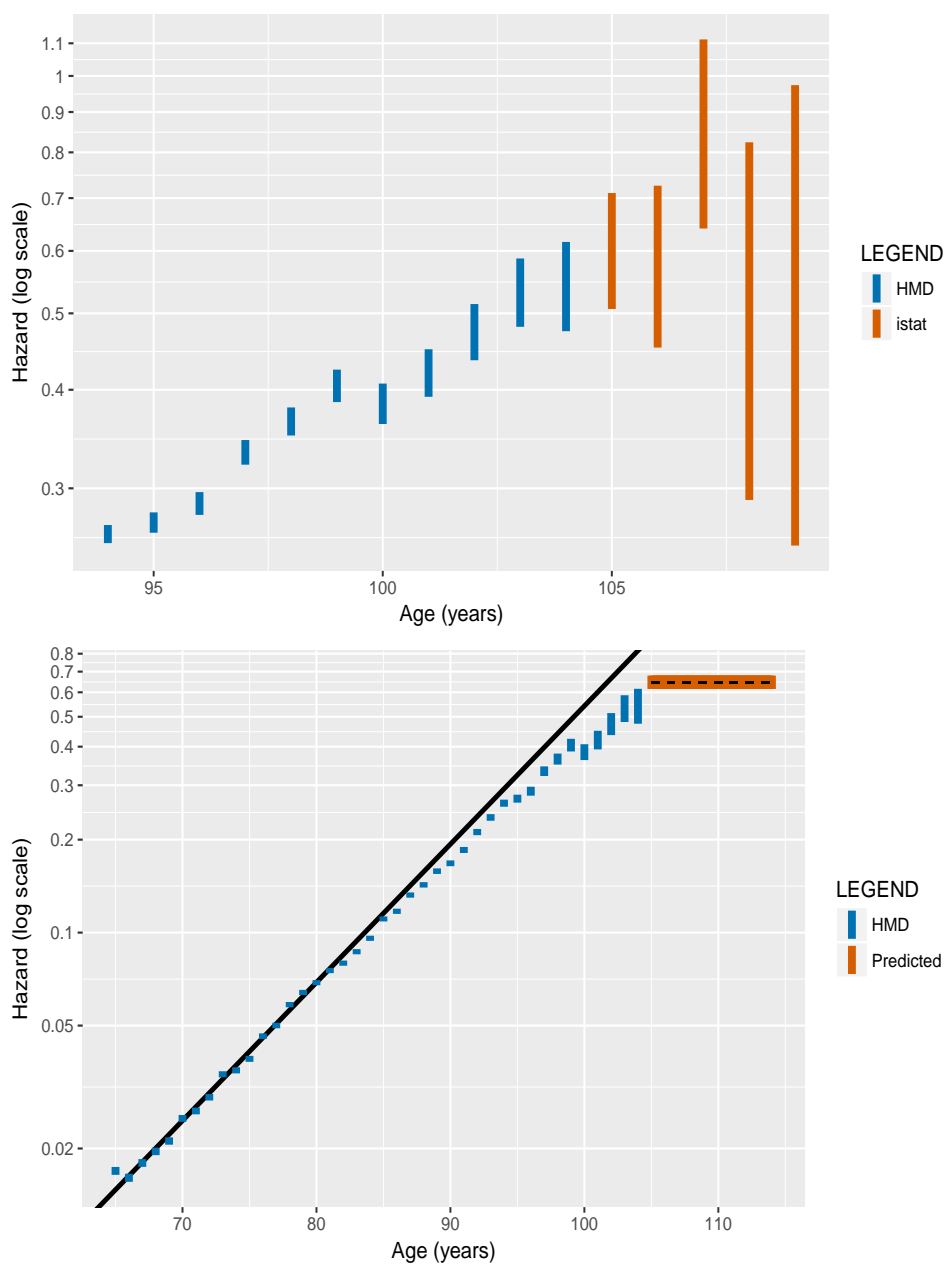


Figure 1: Yearly hazards on a logarithmic scale for the cohort of Italian women born in 1904, from the Human Mortality Database (blue) and from ISTAT data beyond age 105 (orange). Panel a (left): closeup with 95% confidence intervals based solely on single-cohort data; Panel b (right): broad view with estimated plateau beyond 105 (black dashed line) and 95% confidence bands (orange) predicted from the model parameters based on the full ISTAT database, along with a straight-line prediction (black) from fitting a Gompertz model to ages 65 to 80.

Table 2: Parameter Estimates for Preferred Model

Model	Parameter	Estimate	(SE)	Log-likelihood	AIC
Constant hazard	a	0.645	(0.016)	-4250.662	8507.325
	β_1	-0.020	(0.008)		
	β_2	0.033	(0.058)		
Gompertz hazard	a	0.629	(0.026)	-4250.370	8508.74
	b	0.013	(0.017)		
	β_1	-0.016	(0.009)		
	β_2	0.034	(0.058)		

Difference in Log-likelihoods is 0.292

AIC is the Akaike Information Criterion

The estimated cohort effect $\beta_1 = -0.020$ with standard error 0.008, though small, is in line with expectations, statistically significant, and important (13). The 463 male survivors beyond 105 are too few for the gender effect to come out statistically significant, though the estimate $\beta_2 = 0.033$ is plausible.

For the baseline cohort born in 1904, the estimated level of the plateau is $a = 0.645$. It corresponds to an annual probability of dying of $1 - \exp(-0.645) = 0.475$, and an expectation of further life of $1/0.645 = 1.55$ years. This outcome is in keeping with the probability estimated elsewhere for supercentenarians (12). With 90% of person-years at risk coming before age 108, the ISTAT data cannot rule out alternatives like a plateau followed somewhat later by decline, but supercentenarian estimates argue against such alternatives.

Our estimates based on all ISTAT cohorts together produce excellent fits for single cohorts. We examine the cumulative hazard, the integral under the hazard curve, for which non-parametric confidence bounds are available. Hazards that are constant imply cumulative hazards that are linearly increasing. Poor fit would stand out as curvature. Fig. 2 shows heartening absence of curvature for Italian women born in 1904, as do plots for other cohorts not included here.

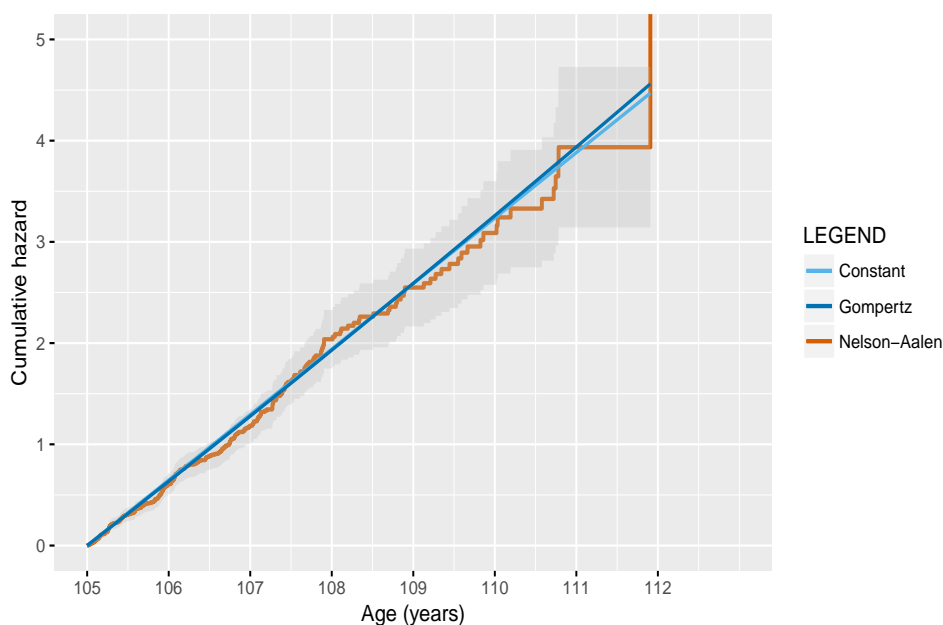


Figure 2: Cumulative hazard beyond age 105 (orange) with non-parametric confidence bands for the cohort of Italian women born 1904. The straight lines are the translation to cumulative hazards of the estimated plateau predicted from ISTAT data, under a constant hazard (light blue) and a Gompertz hazard model (blue).

The increasing number of exceptionally long-lived people in Table 1 and the fact that their mortality beyond 105 is seen to be declining across cohorts lowering the mortality plateau or postponing the age when it appears strongly suggest that longevity is continuing to increase over time and that a limit, if any, has not been reached. Our results contribute to a recently rekindled debate (15-17) about the existence of a fixed maximum lifespan for humans, underwriting doubt that any limit is as yet in view.

Our findings further provide fundamental knowledge about the biodemography of human longevity. In this setting with clean data from a single nation and straightforward estimation, death rates which increase exponentially up to about age 80 do, as we report here, decelerate thereafter and reach or closely approach a plateau after age 105. Thus these well-estimated hazard curves share the qualitative pattern observed at extreme ages in widely

differing species (8, 18), regularities calling for common structural and evolutionary explanations.

An important structural contributor to deceleration must be the impact of selective survival in heterogeneous populations. The fixed-frailty proportional hazard model of Vaupel, Stallard, and Manton (19) (with precursor 20) implies approach to plateaus (5, 8, 18), and elegant Gamma-Gompertz distributions for deaths arise naturally in the framework (21-24). Enhanced care for the extremely old may help to hold increases in mortality in check. Evolutionary theories of senescence including the mutation accumulation theory and age-dependent effects of genetic load (25) also offer promising ingredients toward a joint explanation of both the phases of exponential increase and extreme age plateaus. Ongoing theoretical progress depends on empirical clarity. We hope to promote such clarity with the data and estimates for Italians 105 and older reported here.

Materials and Methods

Data

Protocols for the ISTAT database spell out procedures for the validation of days of birth and death. The database furnishes ages of death with single-day resolution. All observations come from a single country, Italy, with a uniform system of vital registration and a degree of shared historical experience, thus avoiding artifacts that could arise from aggregating across countries in previous research. We fit our parametric models directly to the observed or censored ages at death, thus also avoiding artifacts introduced by binning ages at death into intervals for intermediate calculations of hazards.

The 3836 individuals in the ISTAT dataset are legal residents of Italy. Of them, 3694 were born within the present borders of Italy and 44 more within the borders of the Kingdom of Italy or its colonies at the time of their birth. The majority of the remaining 98 immigrated from countries bordering on Italy or contributing return migrants from earlier emigrations. For this small subset, immigration histories are not available, but most are likely to have lived their later years in Italy before entering the dataset at or above age 105.

Parameter Estimates

Demographers define the hazard function or force of mortality to equal minus the slope of the logarithm of a smooth representation of the proportion of a cohort surviving to each age. As usual, we estimate the yearly hazard by the ratio of deaths to person years lived at risk. Fig. 1 displays the confidence intervals of the hazards on a logarithm scale, computed from a Poisson approximation for the distribution of deaths conditional on person-years (26).

The model applied to the ISTAT data beyond age 105 is written in the form

$$a \exp(bx) \exp(\beta_1 C + \beta_2 M)$$

with level parameter a , slope parameter b , cohort effect β_1 , and gender effect β_2 , with C equal to cohort year of birth minus the baseline value 1904 and M equal to 1 for males, 0 else. For the constant-hazard null-hypothesis model, b is constrained to zero. Under alternative hypotheses, b is non-zero, either

positive or negative. Positive slopes b correspond to Gompertz models under which hazards increase exponentially with age.

Tests of the null model against more general non-parametric alternatives are available, at a sacrifice in power. But over the very short intervals of observation before death beyond age 105, all models with upward-trending hazards are essentially indistinguishable, obviating the need for non-parametric alternatives.

Parameter estimates are obtained by maximizing the standard likelihood function for truncated and censored ages at death conditioned on the covariates (14), using the maximization routine `optim` with the quasi-Newton option in the R Statistical System. Along with outcomes presented in the text in Table 2, outcomes from three other specifications are shown in Table 4(S1). Panels 1 and 2 show that omission of cohort effects does introduce distortions. Panel 3, the best parsimonious model according to the Akaike Information Criterion, shows that including a gender effect has negligible impact on other parameter estimates. Estimates have also been computed excluding the five observations from cohorts born in 1896 and 1897. Each estimate of the Gompertz slope drops by 0.002 while estimates of the cohort effect β_1 become less negative by 0.001 or less. Standard errors barely change.

Table S1. Sensitivity of parameter estimates to variations in model specification.

Panel 1 (models without covariates)					
Model	Parameter	Estimate	(St. Er.)	Log-likelihood	AIC
Constant hazard	a	0.622	(0.012)	-4254.171	8510.342
Gompertz hazard	a	0.597	(0.016)	-4252.095	8508.190
	b	0.029	(0.014)		
Panel 2 (models with gender effect)					
Model	Parameter	Estimate	(St. Er.)	Log-likelihood	AIC
Constant hazard	a	0.620	(0.012)	-4254.068	8512.136
	β_2	0.026	(0.058)		
Gompertz hazard	a	0.595	(0.017)	-4251.949	8509.898
	b	0.029	(0.014)		
	β_2	0.031	(0.058)		
Panel 3 (models with cohort effect)					
Model	Parameter	Estimate	(St. Er.)	Log-likelihood	AIC
Constant hazard	a	0.647	(0.016)	-4250.821	8505.643
	β_1	-0.020	(0.008)		
Gompertz hazard	a	0.631	(0.026)	-4250.540	8507.079
	b	0.013	(0.017)		
	β_1	-0.016	(0.009)		

(AIC is the Akaike Information Criterion)

Cohort Effects.

The relationship between the parameters b and β_1 merits further discussion. In our data earlier-born cohorts are observed at later ages, creating a design in which cohort and age are partially confounded (the correlation between birthdate and age at onset is -0.600). Thus, estimates of b and β_1 can trade off against each other to some limited extent and the presence of the cohort effect is important. Close examination indicates that the downward trend in hazards across cohorts is not a phantom from a Gompertz b-factor in disguise. Fig. 3 (S1) shows separate hazard levels for each of the thirteen cohorts born 1898 through 2010 computed by maximum likelihood aggregating over age (only five observations come before 1898). A tendency toward decreasing levels is clear. The decrease appears less linear than the superimposed estimated cohort effect line, but larger samples would be needed to pin down a more complicated specification.

Further evidence that a Gompertz effect is not hiding within a cohort effect is provided by plots like Fig. 2 in the main text. Restricting to a single cohort and to females alone, plots of cumulative hazard (the logarithm of reciprocal proportion surviving) show no visible deviation from the straight line implied by the constant hazard model. No curvature (from any positive b) appears in Fig. 2 for the baseline cohort born in 1904, and plots, not shown, for the other larger cohorts are similar. The confidence bands are non-parametric estimates from the Nelson-Aalen procedure (14). For males, bands are too wide for plots to be as informative. In plots for single cohorts, period shocks may be inducing some fluctuations in estimates by age, a source of variability which is averaged out when the model is fitted across cohorts. Because our interest is in individuals aging across their lifecourse, we concentrate on cohort rather than on synthetic period lifetable measures.

Statistical Power.

The pattern of left truncation and right censoring in the dataset also affect the statistical power of significance tests of the null hypothesis of constant hazards against alternatives with positive values of the Gompertz slope parameter b . Table S2 shows estimates of the probability that a test at the 5% level rejects the null hypothesis under alternative true values of b equal to 0.02, 0.04, 0.06, and 0.08, for relevant settings of the initial hazard parameter a . The entries are each based on a batch of 10,000 simulations of a Gompertz model without covariates with the same design with regard to

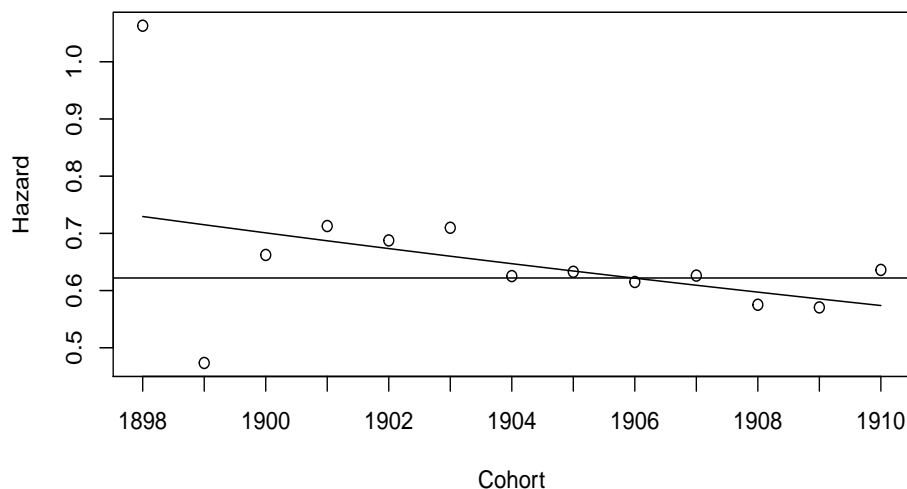


Figure 3: (S1) Cohort-specific mortality hazards (points) vs estimated hazards (lines), 1898-1910. Cohort-specific hazard rates are computed as the ratio between the total number of deaths above age 105 in each cohort and the total person-years contributed by the cohort. The two lines depict the estimated hazards under a constant-hazard model and a constant-hazard model with cohort effect.

truncation and censoring as the dataset. A standard for practical significance is provided by the value $b = 0.103$ for the cohort of women born 1904 (the baseline cohort) over the younger age range from 65 to 80 (Fig. 1) where the Gompertz model is a good approximation (27). The test is seen to have reasonable power against alternatives from $b = 0.04$ and up. Since expected survival beyond age 105 is well under two years for all cohorts according to our estimates, any smaller Gompertz b parameter would have little scope to make a visible impact. Table S3 shows the numbers still alive at each age from all cohorts combined. Beyond 110, resolution is low.

Table S2. Power computation. Probability that a likelihood-ratio test statistics is less than 3.841 (95% percentile of a Chi Square distribution with 1 degree of freedom), under a sample drawn from a Gompertz hazard $a \exp(bx)$, for various values of a and b .

	b	0.02	0.04	0.06	0.08
a					
0.50		0.29	0.73	0.82	0.83
0.55		0.27	0.71	0.97	1.00
0.60		0.25	0.65	0.95	1.00
0.65		0.21	0.60	0.93	0.99
0.70		0.18	0.56	0.92	0.95

Table S3. Numbers still alive at each age for all cohorts combined.

Age	105	106	107	108	109	110	111	112	113	114	115	116
Alive	3836	1874	945	415	199	88	34	16	9	2	1	1

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