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Actuarial Aging Rates in Human Cohorts

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Abstract—Aging rate is an important characteristic of human aging. Attempts to measure aging rates through the Gompertz slope parameter lead to a conclusion that actuarial aging rates were stable during the most of the 20th century, but recently demonstrate an increase over time in the majority of studied populations. These findings were made using cross-sectional mortality data rather than by the analysis of mortality of real birth cohorts. In this study we analyzed historical changes of actuarial aging rates in human cohorts. The Gompertz parameters were estimated in the age interval 50-80 years using data on one-year cohort age-specific death rates from the Human Mortality Database (HMD). Totally, data for 2,294 cohorts of men and women from 76 populations were analyzed. Changes of the Gompertz slope parameter in the studied cohorts revealed two distinct patterns for actuarial aging rate. In higher mortality Eastern European countries actuarial aging rates showed continuous decline from the 1910 to 1940 birth cohort. In lower mortality Western European countries, Australia, Canada, Japan, New Zealand, and USA actuarial aging rates declined from the 1910th to approximately 1930th cohort and then increased. Overall, in 50 out of 76 populations (68%) actuarial aging rate demonstrated decreasing pattern of change over time. Compensation effect of mortality (CEM) was tested for the first time in human cohorts and the cohort species-specific lifespan was estimated. CEM was confirmed using cohort data and human cohort species-specific lifespan estimates were similar to the estimates obtained for the cross-sectional data published earlier.

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Keywords: aging, mortality, compensation effect of mortality, species-specific lifespan, aging rate

INTRODUCTION

Studies of age-specific mortality patterns and actuarial aging rate in particular are important for understanding the fundamental biology of aging and to develop genuine anti-aging interventions [1]. The aging rate is often estimated as a slope coefficient of the Gompertz law describing exponential increase of mortality rate with age (also known as the Gompertz slope or actuarial aging rate) [2, 3]. This approach looks reasonable, because hypothetical non-aging populations have slope coefficient equal to zero, and because the slope parameter characterizes the rate of mortality increase with age.

Earlier studies of actuarial aging rate in humans showed increasing trend during the last 30 years in most countries [2, 3]. These results of increasing aging rates in contemporary populations look counterintuitive given continuous decline of mortality among adults. Mathematical reliability theory of aging indicates that the slope coefficient is determined not only by the rate of functional loss with age ("true aging rate"), but also by the initial redundancy levels (initial reserve capacity) [1, 4]. Thus, actuarial aging rate is determined not only by intrinsic deterioration of organs and tissues, but also by other factors including environmental effects.

Actuarial aging rates are different across different populations and are organized in such a way that lower initial mortality is compensated for by its more rapid growth with age. This means that high mortality rates in disadvantaged populations (within a given species) are compensated for by a low actuarial aging rate (longer mortality doubling period). As a result of this compensation, mortality rates tend to converge at older ages [1]. This phenomenon is called compensation effect of mortality (CEM) [2].

Abbreviations: CEM, compensation effect of mortality.

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We have previously examined the historical changes of the actuarial aging rates and the compensation effect of mortality using cross-sectional mortality data [2]. However, this approach was subjected to a constructive criticism that the CEM should be studied with cohort data [5]. This paper takes this criticism into account and investigates historical changes in the actuarial aging rate and the compensation effect of mortality using cohort data.

MATERIALS AND METHODS

One of the goals of this study was to analyze historical changes of actuarial aging rates and test the compensation effect of mortality in human cohorts. These analyses were not conducted before with cohort data and all studies of actuarial aging rates and CEM so far were made using cross-sectional data [1-3, 6].

Methods. In the first step of the analyses, we have calculated parameters R_0 and α of the Gompertz equation (1):

$$\mu(x) = R_0 \exp(\alpha x), \quad (1)$$

where $\mu(x)$ is a cohort mortality (age-specific cohort death rate) at age x and R_0 and α are the Gompertz parameters. For historical cross-sectional data, actuarial aging rate is usually estimated using the Gompertz–Makeham equation with additional age-independent Makeham term. In the case of cohort data (unlike cross-sectional data) the Makeham term (or background mortality) is not stable over age, because it is changing with calendar time. It was also found that in contemporary populations background mortality is very low [1, 7] and hence has no noticeable effect on the estimates of the Gompertz parameters. In this case we use the fact that after the 1960s background mortality decreased to very low levels close to zero [2, 8]. Thus, the Makeham parameter can be ignored for parameter estimates at ages over 50 years and 1910 and later birth cohorts. Bongaarts estimated background and senescent (age-dependent) mortality by age using cause-of-death data and found that after age 50-60 years mortality is determined almost entirely by the senescent mortality [7].

Parameters of the Gompertz model were estimated using method of non-linear regression in the age interval 50-80 years (*nlin* procedure in Stata package, version 14) as it was suggested before for cross-sectional data [6]. Age interval 50-80 years is characterized by increasing life table aging rate for females (mortality acceleration), whereas for male cohorts this regularity is not so clear [9, 10]. It is believed that this age interval shows pattern of age-specific mortality change for senescent mortality [10]. Some researchers use logistic model to study historical changes in period mortality in order to capture mortality deceleration after age 85 years [6, 7]. In our study we analyze mortality below age 85 years, so that applying the Gompertz model is justified.

There is concern that the least squares fit often leads to an ill-defined non-linear optimization problem, which is extremely sensitive to sampling errors and the smallest systematic demographic variations [11]. This problem was discussed in our earlier publication [2].

Historical trends of actuarial aging rates for each population of men and women (from 1910 to 1940 cohort) were estimated using linear regression model and analyzing the sign and statistical significance of the regression slope parameter.

CEM can be quantified using the inverse relationship of the Gompertz parameters (2):

$$\ln R_0 = \ln M - B\alpha. \quad (2)$$

Species-specific lifespan (parameter B in equation 2) was obtained by running linear regressions between the Gompertz parameters ($\ln R_0$ and α) of the form presented in equation 2. Thus, the species-specific lifespan (slope parameter, B) and the intercept parameter ($\ln M$) have been estimated.

Data. Human Mortality Database (HMD) was used as a source of mortality data for this study [12]. This database contains mortality data for 42 countries with reasonably good quality of demographic statistics. Totally we used age-specific cohort death rates for 3304 cohorts available in HMD covering data for 1900-1940 birth cohorts. Study of historical changes in aging rates was focused on more recent trends for 1910 to 1940 cohorts and used 2294 cohorts. The age-specific cohort death rates of men and women are available in the database from ages 0 to 110 and older. However, cohort mortality data are often not available for the whole age range, because many cohorts are not extinct. Data are available in one-year age and time increments denoted as *Mx*, where *x* indicates single year of age.

Historical changes of actuarial aging rates in human cohorts. Historical changes of actuarial aging rates in demographic cohorts were not studied before. Cohort mortality data are not as numerous as cross-sectional data and require availability of long time series of mortality for cohort mortality reconstruction. For this study we selected single-year cohorts born from 1900 to 1940 in order to cover maximal number of countries.

Historical trends of cohort actuarial aging rate were analyzed for time interval from 1910 to 1940 (birth years of corresponding cohorts). For each country/sex we run linear regression of the Gompertz slope parameter on year of birth for corresponding cohort in order to estimate the general trend for actuarial aging rate. Table 1 presents slope coefficients of this linear regression together with corresponding *p*-values. Note that in contrast to cross-sectional data, actuarial aging rates

Table 1. Historical changes of actuarial aging rates from 1910 to 1940 human birth cohorts*

Country/Region	Men		Women	
	Slope coefficient of linear regression $\times 10^3$	*p*-value	Slope coefficient of linear regression $\times 10^3$	*p*-value
Australia	0.2194	**0.001**	0.1387	**0.019**
Austria	–0.3734	**<0.001**	–0.1755	**0.004**
Belgium	–0.0585	**0.031**	–0.0137	0.721
Bulgaria	–1.1383	**<0.001**	–0.7642	**<0.001**
Belarus	–1.3228	**<0.001**	–1.3422	**<0.001**
Canada	–0.0321	0.415	–0.0740	0.076
Switzerland	–0.1837	**0.001**	–0.0882	**0.033**
Czech Republic	–0.0871	**<0.001**	–0.6300	**<0.001**
Germany	–0.2687	**<0.001**	0.0352	0.347
Denmark	–0.7425	**<0.001**	–0.8647	**<0.001**
Spain	–0.3475	**<0.001**	0.0445	0.346
Estonia	–1.4662	**<0.001**	–1.5405	**<0.001**
Finland	–0.0140	0.750	–0.2237	**0.008**
France, total population	–0.3126	**<0.001**	–0.1574	**<0.001**
England and Wales, total population	–0.1505	**0.032**	–0.1443	**0.030**
Northern Ireland	–0.000006	0.892	0.0960	0.283
United Kingdom	–0.1622	**0.020**	–0.1272	0.053
Scotland	–0.2686	**<0.001**	0.0398	0.541
Hungary	–1.2918	**<0.001**	–0.7143	**<0.001**
Ireland	–0.5714	**<0.001**	–0.2981	**0.001**
Iceland	–0.1458	0.435	0.3480	0.195
Italy	0.0291	0.614	0.0944	**0.039**
Japan	–0.2001	**<0.001**	0.0812	**0.003**
Lithuania	–1.1191	**<0.001**	–1.0182	**<0.001**
Luxemburg	–0.3288	**0.001**	–0.0594	0.668
Latvia	–1.2239	**<0.001**	–1.2308	**<0.001**
Netherlands	–0.4269	**<0.001**	–0.5814	**<0.001**
Norway	–0.4545	**<0.001**	–0.5405	**<0.001**
New Zealand	0.0900	0.335	0.0643	0.401
Poland	–1.3398	**<0.001**	–1.1047	**<0.001**
Portugal	–0.5002	**<0.001**	–0.5316	**<0.001**

Table 1 (*cont.*)

Country/Region	Men		Women	
	Slope coefficient of linear regression $\times 10^3$	*p*-value	Slope coefficient of linear regression $\times 10^3$	*p*-value
Russia	−1.0891	**<0.001**	−1.3581	**<0.001**
Slovakia	−1.0837	**<0.001**	−0.6272	**<0.001**
Slovenia	2.1571	**<0.001**	2.9576	**<0.001**
Sweden	−0.2394	**<0.001**	−0.2537	**<0.001**
Taiwan	−0.1583	**<0.001**	−0.4012	**<0.001**
Ukraine	−1.0314	**<0.001**	−1.1605	**<0.001**
USA	0.1323	**0.003**	0.0343	0.400

Note. Slope coefficients of linear regression for dependencies of actuarial aging rate on birth cohort.
* Gompertz parameters were estimated in age interval 50-80 years. Linear regression of the Gompertz slope coefficient on time (cohort) was run over 31 cohorts for each region/sex. Cases with statistically significant ($p < 0.05$) changes of actuarial aging rate are highlighted in bold.

for cohort data tend to decrease over time in the majority of studied populations. Actuarial aging rates decreased in 22 cases for both sexes, in 7 cases for men only and one case for women only. In 10 cases for men and 15 cases for women actuarial aging rates showed no statistically significant change. Thus, 68% of populations demonstrated decreasing trend of actuarial aging rate.

While analyzing individual trends for each country we found two distinct patterns of change for actuarial aging rate. In lower mortality Western European countries (Austria, Germany, Denmark, Spain, Finland, France, England and Wales, Northern Ireland, Italy, Scotland, Great Britain, Ireland, Netherlands, Norway, Portugal, Sweden), Australia, Canada, Japan, New Zealand, and USA actuarial aging rates decreased until approximately the 1930th cohort and then increased (Fig. 1a).

In higher mortality Baltic countries and countries of the Eastern Europe (Bulgaria, Belarus, Czech Republic, Estonia, Hungary, Lithuania, Latvia, Poland, Russia, Slovakia, Ukraine) actuarial aging rates always declined (Fig. 1b). Figure 1 is only an illustration, but the same two patterns are observed for other countries as well. There are a few exceptions. In Belgium actuarial aging rates remained flat for both men and women. In Switzerland actuarial aging rate increased for later birth cohorts only for women and remained flat for men. In Taiwan actuarial aging rate increased for men and continued its decline for women.

Figure 2 shows mortality for 1920th, 1930th, and 1940th cohorts of Swedish and Polish men. Note that mortality trajectories diverge for all three cohorts in Poland, which corresponds to declining actuarial aging rates over subsequent birth cohorts. On the other hand, only 1920th and 1930th cohorts show mortality divergence in the case of Sweden corresponding to the pattern presented in Fig. 1 for the lower mortality Western European country.

Mortality data for human cohorts provided us an opportunity to study time trends of cohort actuarial aging rate in different countries. Overall, cohort actuarial aging rate demonstrates a declining trend. On the other hand, lower mortality countries show a V-shaped pattern of the actuarial aging rate changes.

These results are different from results obtained for cross-sectional mortality data. Our earlier studies demonstrated that the period actuarial aging rates are relatively stable over time at least until the 1960s [1, 8]. Studies by Bongaarts confirmed this initial finding [6, 7]. With longer time series it became clear that actuarial aging rates have more complex trajectories after the 1960s and demonstrate an increasing pattern after the 1980s [2, 3].

Compensation effect of mortality for human cohorts. Compensation effect of mortality (CEM) refers to mortality convergence, when higher values for the slope parameter (in the Gompertz function) are compensated by lower values of the intercept parameter R_0 in different populations of a given biological species [1, 13]. CEM can be quantified using inverse relationship of the Gompertz parameters of the Gompertz–Makeham equation presented in equation (2). Study of CEM was inspired by the pioneer publication of Strehler and Mildvan who found an inverse correlation between the Gompertz parameters [14]. However, these authors did not take into account the Makeham parameter when using rather old mortality data and hence obtained a spurious correlation. The term “compensation effect of mortality”

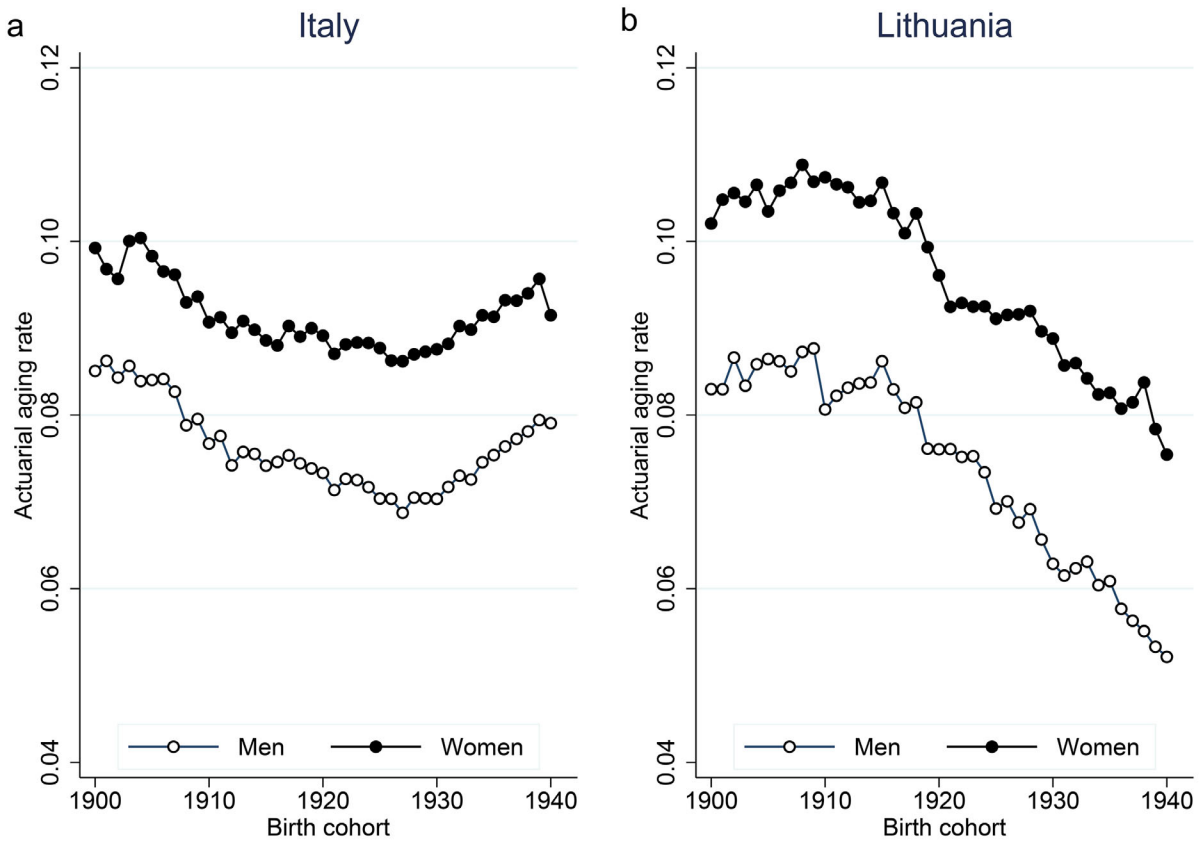

Fig. 1. Historical changes of actuarial aging rate in the lower mortality Western European (Italy) (a) and higher mortality Baltic (Lithuania) (b) countries.

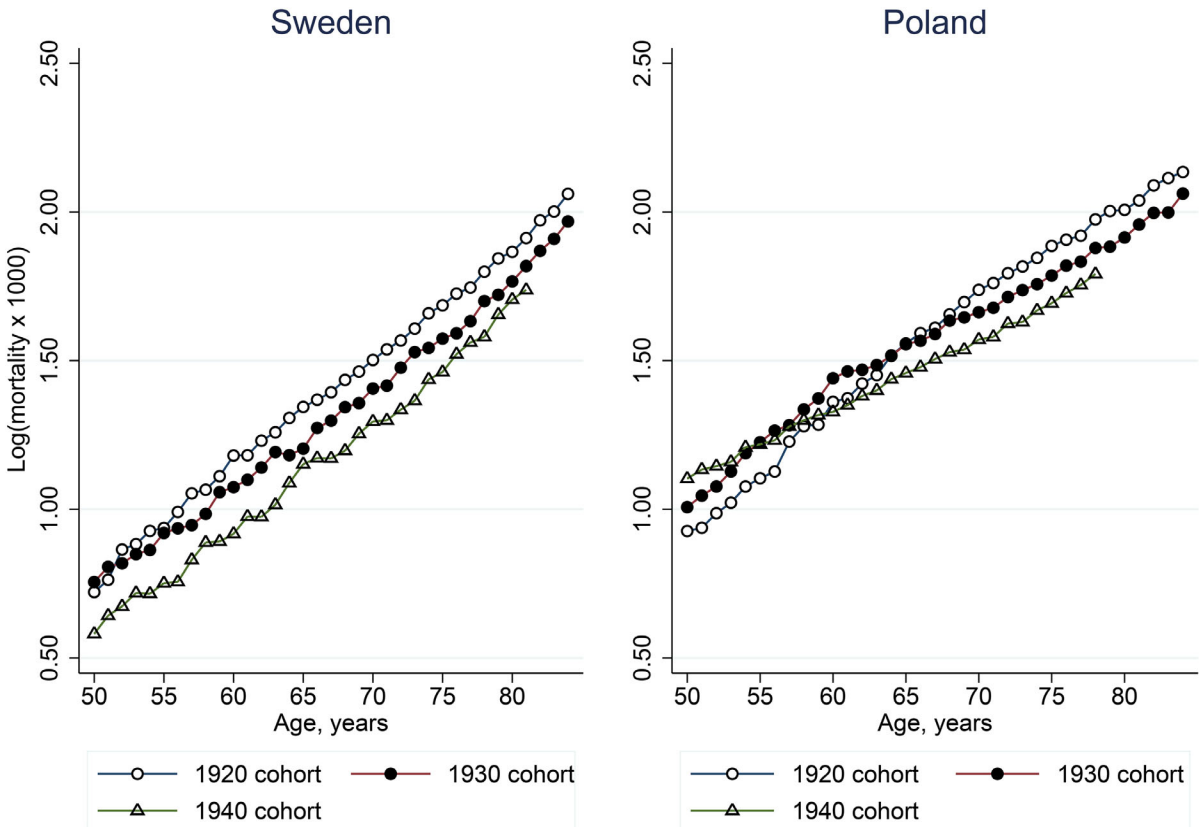

Fig. 2. Mortality (common log scale) as a function of age for three cohorts of Swedish and Polish men.

Table 2. Characteristics of compensation law of mortality for three birth cohorts based on the Gompertz model*. Human Mortality Database

Population	Regression coefficients		Correlation coefficient between $\ln R_0$ and α	Number of observations
	$\ln M \pm \sigma$	$B \pm \sigma$, years		
All single-year birth cohorts from 1920 to 1940				
Men	−2.39 ± 0.10	84.02 ± 1.33	−0.9085	850
Women	−4.36 ± 0.11	66.13 ± 1.28	−0.8716	850
Both sexes	−3.29 ± 0.09	75.35 ± 1.23	−0.9029	850
All single-year birth cohorts from 1930 to 1940				
Men	−1.57 ± 0.09	97.81 ± 1.29	−0.9624	460
Women	−3.36 ± 0.15	79.18 ± 1.77	−0.9025	460
Both sexes	−2.38 ± 0.10	89.59 ± 1.32	−0.9536	460
1940 birth cohort				
Men	−1.68 ± 0.16	97.33 ± 2.23	−0.9894	43
Women	−2.87 ± 0.39	86.24 ± 4.53	−0.9479	43
Both sexes	−2.45 ± 0.19	89.89 ± 2.53	−0.9842	43

* Gompertz parameters were estimated in age interval 50-80 years.

was introduced in 1978 when account for the Makeham parameter resulted in totally different parameter estimates of the Strehler–Mildvan correlation [15]. Compensation effect of mortality is defined as a convergence of age-specific senescent (age-dependent) mortality dependencies at advanced ages [1, 15].

The coordinate corresponding to the age at which all the mortality trajectories intersect (B) has been called the species-specific life span [1]. It was found that for humans its value is equal to 95 ± 2 years when using cross-sectional data [1, 2]. It should be noted that the compensation effect of mortality can be observed by a simple visual inspection of mortality trajectories without calculation of the Gompertz parameters [2]. Also, CEM can be observed not only for humans, but for some other biological species [1, 13].

Data on cohort mortality for different countries allows us to test the existence of the compensation law of mortality among cohorts. Compensation law of mortality for cohort data was never tested before. We estimated parameters of linear regression presented by equation (2) using cohort data.

This linear regression was run for more recent birth cohorts of 1920-1940 using estimates of the Gompertz parameters available for 76 populations of men and women obtained in the age interval 50-80 years. Table 2 presents the results of these estimations. These results

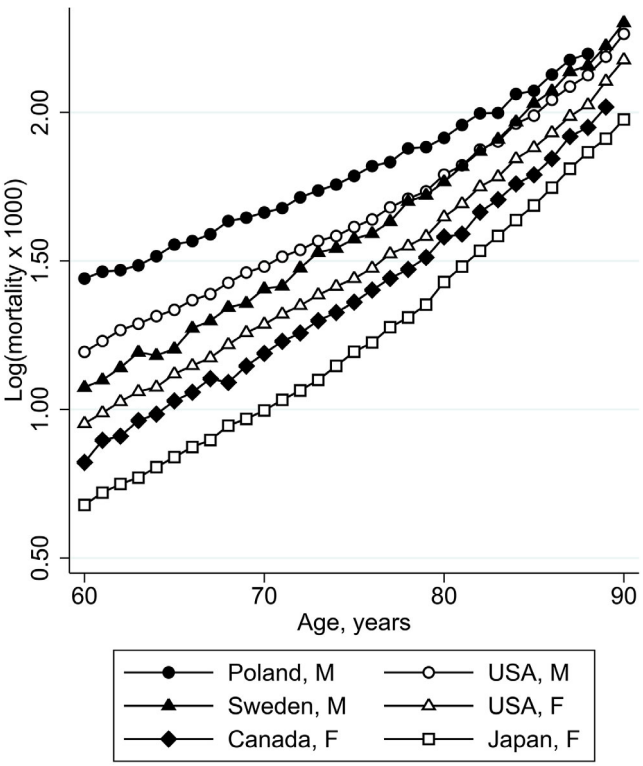

Fig. 3. Compensation effect of mortality for human cohorts. Mortality (common log scale) of 1930 birth cohorts in six populations. Designations: M, male; F, female.

confirm the existence of compensation effect of mortality for human cohorts, although values of species-specific life span [parameter B of linear regression in equation (2)] are somewhat lower compared to the cross-sectional data [1, 2]. These results also show lower values of the species-specific life span for historically older birth cohorts, which is in agreement with findings obtained for cross-sectional data [2].

Overall, we can conclude that estimates of the species-specific lifespan based on cohort data (for later birth cohorts) demonstrate a good agreement with earlier publications based on cross-sectional data [1, 2]. These results mean that quantitative measures of CEM for humans are rather stable.

Figure 3 demonstrates mortality convergence at older ages (compensation effect of mortality) for 1930 birth cohorts of several populations. Note that men of Poland have lower actuarial aging rates compared to men of Sweden and women have higher actuarial aging rates compared to men. Also, note that age trajectories for women show slightly accelerated trend confirming earlier studies of life table aging rate [10].

Figure 3 is another illustration of CEM existence, which does not require statistical estimation of the Gompertz parameters.

DISCUSSION AND CONCLUSIONS

It was found that the compensation effect of mortality does exist for cohort data. Study of the quantitative measures of CEM using cohort data confirmed that the inverse correlation between the Gompertz intercept parameter, $\ln(R_0)$, and the Gompertz slope parameter (α) of the Gompertz equation does exist and is highly statistically significant when we compare different human populations. Estimates of the species-specific lifespan (parameter B) for later birth cohorts are close to estimates obtained for cross-sectional data [1, 2] although still are somewhat lower. It was also found that the estimates of the species-specific lifespan are lower for historically older birth cohorts. Thus, compensation effect of mortality is confirmed for human birth cohorts.

In this study we also analyzed historical changes of the actuarial aging rates (Gompertz slope parameter) for human cohorts. In our study we analyzed time trends in cohort actuarial aging rates for each population separately from 1910 to 1940 birth cohort. It turns out that the majority of populations (52 out of 76 or 68%) demonstrate declining pattern of actuarial aging rate. Actuarial aging rates remain stable for 23% of human cohorts. This result obtained for the cohort actuarial aging rates is different from the result obtained for cross-sectional data. It was found that period actuarial aging rates demonstrate an increasing pattern after the 1980s for the majority of studied populations [2, 3]. Before the 1980s period actuarial aging rates showed stability over time [1, 2, 8]. On the other hand, actuarial aging rates measured for birth cohorts of the same country and sex has a tendency to decrease over time.

When studying cohort mortality, it is important to realize that over the life course, a cohort is affected both by aging, which increases mortality, and by improvement in living conditions, which reduces mortality. It is theoretically possible that the actuarial aging rate may eventually decrease to very low levels close to zero, which can be considered as an apparent aging arrest. For example, if the increase in mortality with age is 8% per year, but mortality decreases over time at a rate of 2% per year, then the observed increase in mortality in the cohort would end up being only 6% per year (8–2 = 6) [16]. If the rate of historical decline in mortality is age-dependent, this might look on the cohort data like a decrease in the actuarial aging rate in more recent cohorts of people. In any case, a decrease in the actuarial aging rate looks like a slowing down of aging. It is still unclear what can explain the increase in the actuarial aging rate in the lower mortality countries among more recent birth cohorts. One possible explanation is that these countries already exhausted most resources for mortality decline such as decline in cardiovascular mortality and smoking habit. Indeed, mortality in many of these countries stabilized during the last 10-15 years suggesting that the main force of decreasing actuarial aging rate almost disappeared [17]. Thus, now the actuarial aging rate in the lower mortality countries is determined mostly by the aging process and depends on the senescent mortality. Higher mortality countries like countries of the Eastern Europe still have some remaining room for mortality decline and hence their actuarial aging rate continues to decline.

It appears that aging should be measured not by the rate of mortality increase with age, but by the rate of loss of functional elements (mainly specialized cells) in the body. Such an approach to measuring the true aging rate was proposed by the reliability theory of aging [1, 4, 18]. According to this theory, a rough estimate of the true aging rate can be obtained by measuring one of the CEM parameters [inverse of the species-specific lifespan in equation (2)]. Another theory of aging (metronomic theory of aging) has been proposed by Alexey M. Olovnikov [19]. Although he considered the aging process as a program, he emphasized that this program refers mainly to the reproduction aspects of this process. Indeed, the time of the beginning and the end of reproduction in women have certain signs of a program [20]. However, the total lifespan can be better described by reliability models, which assume gradual destruction of the organism and loss of functional elements including telomeres and specialized cells.

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Contributions. Leonid A. Gavrilov designed the study, analyzed, and interpreted results, and edited the manuscript. Natalia S. Gavrilova conducted statistical analyses, and prepared the manuscript.

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