Measurement of Mortality among Centenarians in Canada

Nadine Ouellette* and Robert Bourbeau†

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* Nadine Ouellette, PhD, is a Postdoctoral Fellow at the Institut national d'études démographiques (INED), 133 boulevard Davout, 75980 Paris Cedex 20, France, nadine.ouellette@ined.fr.

† Robert Bourbeau, PhD, is a Professor in the Department of Demography at the Université de Montréal, C.P. 6128, succ. Centre-Ville, Montréal, QC, H3C 3J7, Canada, robert.bourbeau@umontreal.ca.

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[1] Nadine Ouellette, Ph.D., is a postdoctoral fellow at the Institut national d'études démographiques (INED), 133 boulevard Davout, 75980 Paris Cedex 20, France, nadine.ouellette@ined.fr.
[2] Robert Bourbeau, Ph.D., is a professor in the Department of Demography at the Université de Montréal, C.P. 6128, succ. Centre-Ville, Montréal, QC, H3C 3J7, Canada, robert.bourbeau@umontreal.ca.

1. INTRODUCTION

In high-income countries, recent trends in human mortality suggest future gains in life expectancy will be fuelled mostly by a decrease in death rates above the age of 80. This evidence stresses the need and importance of obtaining precise mortality measurements at very old ages, which are often subject to substantial uncertainty notably due to age overstatement. In addition to exaggeration in age reporting, the small number of survivors at the most extreme ages further complicates the task. Over the past 20 years, a considerable accumulation of studies have suggested the rate of mortality increase with age slows down at very old ages, a phenomenon commonly known as *mortality deceleration* (Horiuchi and Coale 1990; Gavrilov and Gavrilova 1991; Manton 1992; Kannisto 1994; Horiuchi and Wilmoth 1998; Thatcher, Kannisto and Vaupel 1998; Vaupel et al. 1998; Lynch and Brown 2001; Robine and Vaupel 2001; Rau, Muszynska and Baudisch 2009; Gampe 2010; Wrigley-Field 2014). In other words, the age pattern of mortality at the highest ages deviates from an exponential growth model, i.e., the Gompertz (1825) model of mortality, which is valid through most of the adult age range, and is instead best described by a logistic curve (Perks 1932). A similar slowdown (and sometimes even a decrease) in death rates with advancing age has also been found among a broad spectrum of nonhuman populations (Gavrilov and Gavrilova 1991; Carey et al. 1992; Curtsinger et al. 1992; Curtsinger, Gavrilova and Gavrilov 2006; Vaupel and Carey 1993; Vaupel et al. 1998).

For human and nonhuman populations with accurate data, there are at least two possible theoretical explanations for the occurrence of such mortality deceleration at very old ages (Horiuchi and Wilmoth 1998). One is the *heterogeneity hypothesis*, according to which the healthier or more robust individuals in a given cohort are more likely to survive to older ages than their unhealthier or frailer counterparts, resulting in an increasingly selected healthy group of individuals with advancing age (Beard 1959, 1971; Vaupel, Manton and Stallard 1979; Vaupel and Yashin 1985; Kannisto 1991). Another possible explanation is the *individual-risk hypothesis*, according to which the mortality risk increase slows down at very old ages at the individual level (Carey et al. 1992; Curtsinger et al. 1992; Steinsaltz and Wachter 2006; Mueller, Rauser and Rose 2011).

Despite this collection of empirical and theoretical evidence in favor of a slowdown in the death rate increase at very old ages, an article by Gavrilov and Gavrilova (2011) challenged the fact that this phenomenon is real, at least for humans. The authors identified three factors that could potentially explain why mortality deceleration is often observed.

(1) The aggregation of data for several birth cohorts (or countries), a common practice to increase the number of survivors at very old ages, may result in an excessively heterogeneous group because of their different mortality experiences and produce an apparent slowdown.
(2) The standard assumptions regarding hazard rate (i.e., instantaneous death rate or *force of mortality*) estimates, in particular the assumption of a uniform distribution of deaths within each one-year age interval, may be invalid when the risk of death is extremely high at old ages and thus lead to a slowdown in the hazard rate increase at very old ages.
(3) The use of data for populations with inaccurate reporting of age among the very old may bias the hazard rate downward with advancing age.

Using U.S. data from the Social Security Death Master File (DMF), which includes information on the years and months of birth and death for each individual, Gavrilov and Gavrilova estimated hazard rates at every month of age for single-year birth cohorts, thereby limiting issues (1) and (2). They found no noticeable deceleration in the hazard rate increase up to age 106 for the various birth cohorts. Hazard rates, instead, showed a steady exponential growth between ages 88 and 105.[3]

Gavrilov and Gavrilova's new results somehow question our understanding of the age-trajectory of mortality at the highest ages among humans and also put at least two decades of research on the topic of mortality deceleration in jeopardy. Moreover, if these new findings are accurate, they will be of great importance for actuarial practice because life table calculations often involve fitting a mathematical model to observed death rates at older ages. Replacing the currently widely used logistic functions to fit observed cohort death rates at the oldest ages (implying a slowdown in the death rate increase over age) by exponential functions (implying a steady death rate increase over age) will result in greater probabilities of death at the highest ages and therefore lower expectations of life both at birth (e_0) and at advanced ages such as 65 (e_{65}).

In this paper, we replicate the Gavrilov and Gavrilova study using a highly reliable set of data on French-Canadians centenarians that will allow us to examine issues (1) to (3) outlined above. In Canada, for the province of Quebec, a collection of data on verified ages at death of individuals who have lived past 100 is available (Bourbeau and Desjardins 2002; Beaudry-Godin 2010; Desjardins and Bourbeau 2010), although access is highly restricted due to confidentiality clauses. Here, we extend this database further and use it to compute new estimates of the trajectory of mortality at ages 100 and above, taking advantage of the information available on the years, months and days of birth and death for each individual.

We begin by describing briefly the validation procedure for verifying the age at death of French-Canada centenarians with church parish registers in section 2. We also explain how the data set for this study was constructed. In section 3, we present the methods used to compute observed death rates and probabilities of death for age intervals of various lengths. The results are displayed in section 4. Section 5 offers a few concluding remarks.

2. Age at death validation of French-Canadian centenarians using Quebec's church parish registers

At the outset of the 17th century, when the first missionaries from France settled in the province of Quebec, they implemented the Catholic tradition of registering meticulously all baptisms, marriages and burials. By 1679, the authorities even required that two registration copies were made—one was kept at the parish, the other was sent to the government body for civil registration purposes. This practice lasted until the end of the 20th century. Total loss of records was thus kept to a minimum during this time for the population of French-Canadians of Quebec, which was homogeneously Catholic. This precious knowledge from Quebec's parish registers is now readily

[3] After age 105, the hazard rate increase slows down slightly, but, according to the authors, this mortality deceleration is more apparent than real because the quality of age reporting in the DMF is significantly lower around age 107 and above.

available on microfilm for each parish and was used to develop the *Registre de la population du Québec ancien* (Légaré 1981; Desjardins 1998), a population register of historical Quebec that provides a unique and highly reliable source of data for the 17th and 18th centuries.

More recently, archives from Quebec's parish registers were used to verify the age at death of French-Canadian supercentenarians—individuals 110 and older—for their inclusion in the International Database on Longevity[4] (Bourbeau and Desjardins 2000; Desjardins and Bourbeau 2010). This work was extended to deaths of those age 100–109 (Beaudry-Godin 2010; Bourbeau and Desjardins 2002), first with the objective of investigating more comprehensively the quality of extreme-age-at-death registration among French-Canadians in Quebec and, second, to obtain preliminary estimations of mortality at ages 100 and older for this population. In the present study, we make further validation efforts to broaden our coverage by including the most recent extinct birth cohorts and we provide new results on the age pattern of mortality at very old ages.

Ideally, the validation of age at death consists in confirming the individual's date of birth indicated on his/her death certificate with the date of birth appearing on the birth registration document (e.g., baptismal certificate).[5] Given Quebec's comprehensive parish register archives, such link between the two official documents on the basis of the individual's name is possible for most Catholic French-Canadians born in Quebec before the end of the 20th century.

The task of recovering baptismal certificates is, however, not as simple as it would seem because post-18th century baptisms are not exhaustively indexed in Quebec. They are indexed annually for each parish though, which means detailed information about the place of birth of an individual could help identify one or a handful of possible parishes where he/she was baptized and thus narrow down the search substantially. The exact place of birth is unfortunately not usually recorded on death certificates—only the country or province of birth has to be indicated. But the names of the individual's parents, often available on the death certificate, can be used to indirectly determine where the baptism took place. Indeed, marriages are exhaustively indexed up to the 1930s in Quebec (contrary to baptisms) and the parent's marriage certificate can thus be readily recovered. The information on the places of residence of the individual's mother and father, respectively, detailed on their marriage certificate, is what is most useful here. Given the common practice for marriages to be celebrated in the wife's parish and for the spouse to settle down in that of the husband's, an individual's baptismal certificate is likely to be found in his/her father's parish. In cases where this information proves unfruitful in finding the baptismal certificate, the individual's spouse name (if applicable) may offer another possibility, through the recovery of their own marriage certificate. Indexed nominative census returns can also help fill in the gaps or support existing information.[6]

The data set used in this study is an expanded version of an earlier collection of verified data on centenarians prepared by Beaudry-Godin (2010). The latter collection is the outcome of

[4] The International Database on Longevity (available at www.supercentenarians.org) is a selection-bias-free list of verified long-lived individuals from Europe, North America, Australia and Japan, which allows for the demographic analysis of mortality at the highest ages (Maier et al. 2010).
[5] In reported cases of exceptional longevity, longevity records in particular, a more thorough scientific validation of age is required (Wilmoth and Lundström 1996; Wilmoth et al. 1996; Robine and Allard 1995, 1999).
[6] For a more detailed explanation of the age-at-death validation procedure for French-Canadians in Quebec, see Bourbeau and Desjardins (2002, section 4) and Beaudry-Godin (2010, section 2.2).

strenuous efforts to verify the age at death of all reported French-Canadian Catholic centenarians who died in Quebec between 1970 and 2004 and were born in Quebec between 1870 and 1894.[7] A total of 1,900 cases were investigated individually and the results confirmed that reporting of ages at death among French-Canadian centenarians in Quebec is very accurate, although systematic verification at the highest ages (105 and older) is still recommended. Indeed, 1,646 cases out of the 1,900 (86.6 percent) were such that the date of birth on the death certificate and on the baptismal certificate or Canadian census returns exactly matched or differed by only one to three days. (Such small discrepancies are probably due to confusion between the date of birth and date of the baptism.) In addition, 43 (2.3 percent) other cases seemed highly probable despite the fact that the baptismal certificate was not found because the date of birth on the death certificate was indirectly confirmed by several sources (e.g., date of marriage and age at marriage of the centenarian, his/her parent's date of marriage). There were 136 (7.2 percent) erroneous cases, but only 74 (3.9 percent) revealed a discrepancy of one year or more between the date of birth on the death certificate and on the baptismal certificate. These errors were much more likely to occur among the oldest centenarians: they account for 3.9 percent and 6.3 percent of those aged 100–104 and 105+, respectively, hence Beaudry-Godin's recommendation of a systematic verification at the highest ages. Only a few remaining cases out of the 1,900 (75, or 3.9 percent) could not be verified satisfactorily through any of the abovementioned channels.

For the present study, we augmented the collection of data described above to include deaths of French-Canadian Catholic centenarians up to 2009. Through a strict confidentiality protocol, we obtained nominative lists of deaths of centenarians in Quebec for single calendar years between 2005 and 2009 from the Institut de la statistique du Québec (Quebec Institute of Statistics). For each alleged centenarian, the following information, if available on the death certificate, is provided: first and last names of the deceased, sex, date of birth, date of death, age at death, place of birth (name of the province if born in Canada and name of the country otherwise), first and last names of parents, and last name of the spouse (if the deceased ever married). It should be noted that similar lists covering years 1970–2004 were used by Beaudry-Godin (2010) in her validation study. Given Beaudry-Godin's findings, we verified all deaths reported at an age greater or equal to 105 (excluding individuals born outside the province of Quebec, as well as those with English or foreign surnames) using Quebec's parish register archives and the 1901 and 1911 Canadian census returns. All remaining reported deaths of French-Canadian Catholics born in Quebec that occurred below the threshold age of 105 were included in our data set without additional verification.

Our final data set includes a total of 2,198 French-Canadian Catholics born in Quebec between 1870 and 1896 who died between 1970 and 2009 (table 1). Individuals born after 1896 (i.e., celebrating their 112th birthday in 2009 or later) were excluded from our study because they belong to birth cohorts that are probably not yet extinct. As shown in table 1, only one death occurred at an age greater than 112,[8] and thus we consider birth cohorts 1870–96 to be extinct. Given that almost 80 percent of French-Canadian centenarians included in our dataset are females, the results presented here are for females only.

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[7] Beaudry-Godin's work extended earlier work by Bourbeau and Desjardins (2002), who had verified the ages at death of French-Canadian Catholic centenarians in Quebec for a sample of 209 individuals who died between 1985 and 1999.

[8] Julie Winnifred Bertrand was born Sept. 16, 1891, and died Jan. 18, 2007, at the age of 115 years and 124 days.

Table 1. Age distribution of centenarians deaths by sex, French-Canadian birth cohorts 1870–96

Age at death	Female	Male	Age at death	Female	Male
100	543	181	108	13	2
101	405	133	109	7	1
102	265	59	110	6	0
103	178	32	111	2	0
104	154	27	112	2	0
105	77	11	113	0	0
106	45	13	114	0	0
107	32	9	115	1	0

Note: The centenarians died in Quebec between 1970 and 2009.

3. DEATH RATE AND PROBABILITY OF DEATH CALCULATIONS

In demography, crude and age-specific rates[9] often correspond to what is known in statistics as "occurrence/exposure rates," that is a number of occurrence of some event of interest in the numerator and an indicator of the population's amount of exposure to the risk of the event in the denominator (Preston, Heuveline and Guillot 2001). For the analysis of mortality, death rates consist of death counts divided by the population's exposure to the risk of death. In this paper, we computed age-specific cohort death rates for one-year, 0.5-year (i.e., six months) and 0.25-year (i.e., three months) age intervals. To make these rates comparable, "year" is the unit in which exposure time was measured in all our calculations. Thus, for a given group of birth cohorts, the death rate between ages x and $x + n$,[10] denoted ${}_nM_x$, is equal to the number of deaths to the group of cohorts between ages x and $x + n$ divided by the number of person-years lived by the group of cohorts in the same age interval. The outcome is a number of events per person-year. Using the information on the exact date of birth and date of death of each centenarian in our data set, we directly counted the number of person-years lived in each age interval, whatever its length, by adding the contribution of each individual to the denominator of the cohort rates.

The risk of death is often measured for discrete age intervals (usually because of data limitations) despite the fact that cohorts are continuously submitted to such risk. The calculation of death rates for progressively narrower age intervals lets us get closer to the key concept of instantaneous death rate (or force of mortality or hazard rate) at age x, denoted μ(x) and defined as $\lim_{n\to 0} {}_nM_x$. Gavrilov and Gavrilova (2011) identified the use of one-year rather than shorter age intervals as one of the factors that could explain why previous studies reported mortality deceleration at very old ages. The computation and comparison of death rate trends for age intervals of various lengths thus also allows us to verify the validity of Gavrilov and Gavrilova's claim. In this paper, observed death rates for one-year, 0.5-year and 0.25-year age intervals were

[9] Unlike age-specific rates, crude rates are computed without regard to age.
[10] For one-year, 0.5-year and 0.25-year age intervals, n = 1, 0.5 and 0.25, respectively.

smoothed with penalized B-splines, known as P-splines (Eilers and Marx 1996).[11] Differences between the P-spline-smoothed mortality curves were then assessed with their corresponding 95 percent confidence bands.

We also computed age-specific probabilities of death for one-year, 0.5-year and 0.25-year age intervals, taking advantage of the information available on the years, months and days of birth and death of each centenarian, just as in the case of death rates. Following the conventional notation, the probability of dying between ages x and $x + n$, ${}_nq_x$, for a given group of birth cohorts is expressed as the number of deaths to the birth cohorts between ages x and $x + n$ divided by the number of individuals in the birth cohorts of exact age x (i.e., at the beginning of the age interval). Although it may be tempting to make the probabilities of dying for age intervals of various lengths comparable by multiplying those for 0.5-year age intervals by 2 and those for 0.25-year age intervals by 4, this procedure is incorrect.[12] The proper way to move from probabilities of death for shorter than one-year age intervals to annual probabilities of death is with the following identity:

$$ {}_1q_x = 1 - \prod_{k=0}^{\frac{1}{n}-1} {}_np_{x+kn}, \qquad [1] $$

where ${}_np_x$ is the probability of surviving between ages x and $x + n$.

Death rates and probabilities of death are two different concepts. Their age trajectories differ, especially when progressively shorter age intervals are used. Failing to distinguish between the two concepts could lead to inaccurate claims about mortality deceleration at very old ages, as illustrated in the next section.

4. RESULTS

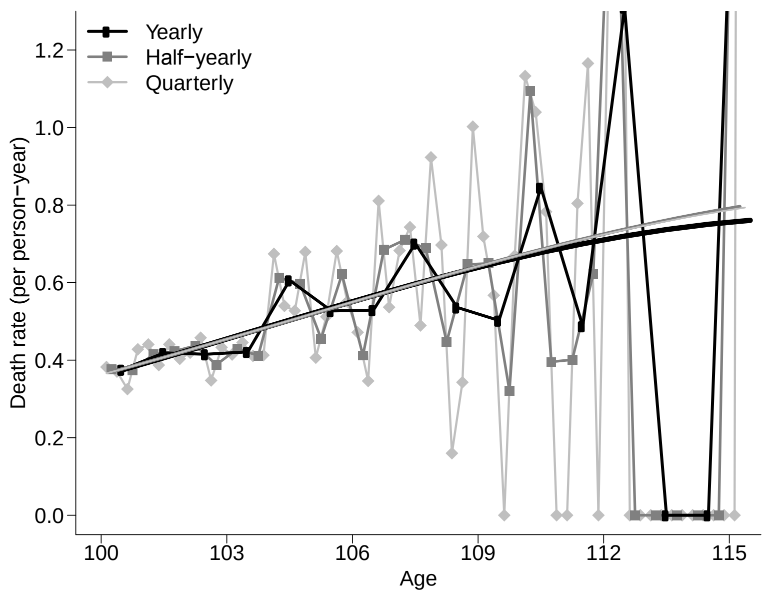
Figure 1a displays age-specific death rates for one-year, 0.5-year and 0.25-year age intervals among French-Canadian female centenarians born between 1870 and 1896. It shows that the variability in the age trajectories increases as the length of the age interval shortens, but that the three trajectories are clearly embedded. To put it differently, the three death rate series differ only in terms of how variable they are, not in levels or trends. The increasing amount of random fluctuations with narrowing lengths of the age interval was expected because the number of deaths and person-years lived used in the numerator and denominator of the death rate decline as the age interval shortens. After smoothing, the death rate trends are undistinguishable up to age 110 (figure 1a). Beyond age 110, the mortality curve for yearly age intervals falls slightly below those for narrower lengths of the age interval, but the confidence bands indicate that all three trajectories are highly uncertain at these most extreme ages (figure 1b). The similarity in the age-trajectory of death rate series for various lengths of the age interval was, however, recently challenged by

[11] We used a penalized Poisson likelihood and the smoothing parameter controlling the trade-off between parsimony and accuracy of the model was selected according to the Bayesian information criterion (BIC). For the B-spline basis, we used cubic B-splines and one knot per every five data point on the age range. In cases where only a few equidistant observation points were available, we also experimented with a discrete smoothing method, as set forth by Whittaker (1923). The results were practically identical to those presented here.
[12] It may also inconveniently lead to probabilities of death greater than 1 at extreme old ages.

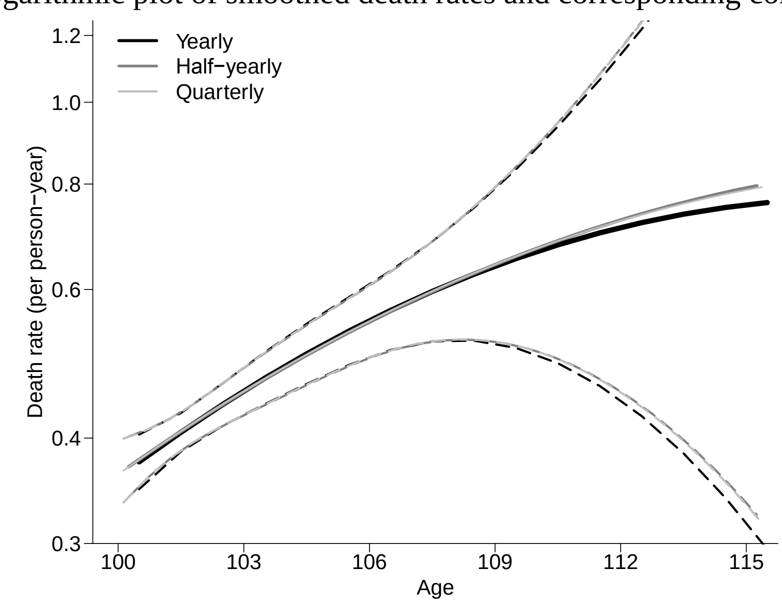
Gavrilov and Gavrilova (2011, 437; see their figure 1 for one-year vs. one-month age intervals), despite that one would expect comparable trends given the definition of the death rate. The death rates series for French-Canadian female centenarians in figure 1 provides evidence that using one-year or shorter age intervals results in highly similar levels and trends.

Figure 1. Death rates among centenarians for yearly, half-yearly and quarterly age intervals, French-Canadian female birth cohorts from 1870–96

a) Observed and smoothed death rates



b) Semi-logarithmic plot of smoothed death rates and corresponding confidence intervals

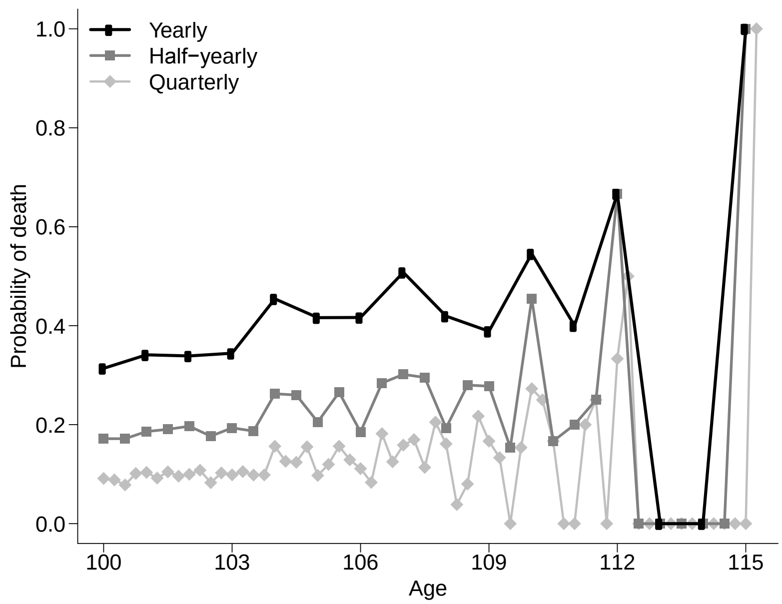


Note: Solid plain lines show a P-spline-smoothed mortality curve based on penalized Poisson likelihood and dashed lines show the corresponding 95 percent confidence bands.

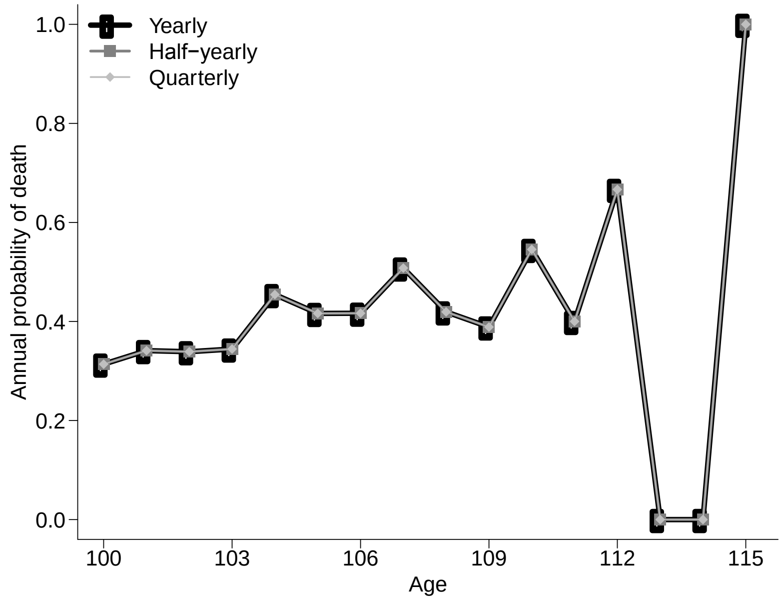
Figure 2a shows probabilities of death for age intervals of the three lengths. As expected, the probabilities for shorter intervals are systematically smaller than those for larger intervals, and this explains the differences in levels between the three series. Moving from probabilities of death for shorter-than-one-year age intervals to annual probabilities obviously results in a perfect overlap of the three series (figure 2b). A different conclusion is reached, however, if probabilities of death are improperly manipulated. Indeed, figure 3 shows the results obtained when multiplying 0.5- and 0.25-year probabilities of death by factors of 2 and 4, respectively. In such cases, higher levels are observed for shorter age intervals and the discrepancy between the three series increases with age. Moreover, the trajectories for shorter age intervals seem straighter than those for wider age intervals (i.e., the slowdown in the increase with age is less pronounced for 0.25-year than for 0.5-year age intervals, and for 0.5-year than for one-year age intervals). Given that probabilities of death consist of the number of deaths in the studied age interval (numerator) divided by number of individuals alive at the beginning of the interval (denominator), these results were also expected. The high level of mortality at advanced ages makes the denominator substantially smaller for shorter rather than for longer age intervals, thus probabilities of death are greater for 0.5-year and even more so for 0.25-year age intervals than for one-year intervals.

Figure 2. Probabilities of death among centenarians for yearly, half-yearly and quarterly age intervals, French-Canadian female birth cohorts 1870–96

a) Observed for each age interval



b) "Annualized" using equation [1]



The mortality trajectories displayed in figure 3 are comparable to those obtained by Gavrilov and Gavrilova (2011, 437, figure 1) because their estimation of the instantaneous death rate (i.e., hazard rate) for one-year and $0.08\overline{3}$-year (one month) age intervals was done as follows:

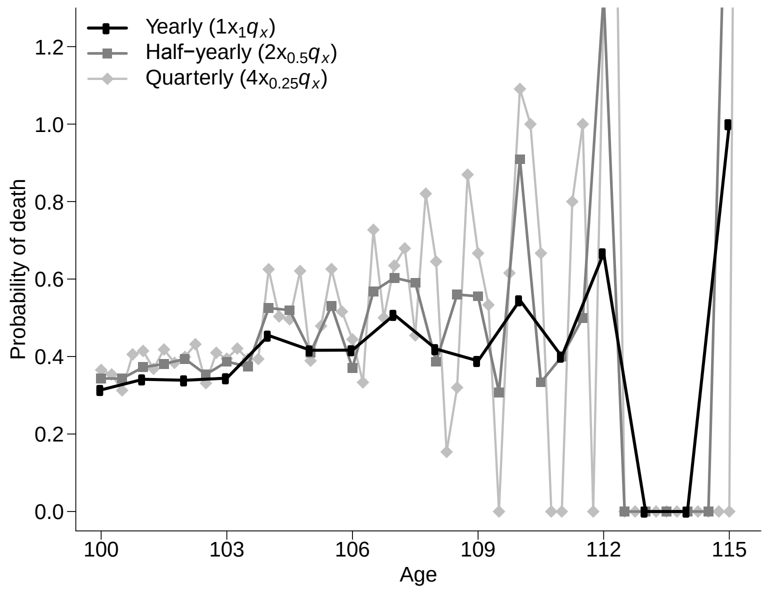
> In our study we used Nelson-Aalen hazard rate estimates provided by Stata (StataCorp 2009). … The way of hazard rate estimation conducted in Stata is similar to calculation of life-table probability of death (StataCorp 2009); that is, the number of deaths in the studied age interval is divided by the number alive at the beginning of age interval.

and:

> For the purpose of comparability with other published studies, which typically use the year^{-1} time scale, we transformed the monthly hazard rates to the more conventional units of year^{-1}, by multiplying these estimates by a factor of 12 (one month in the denominator of hazard rate formula is equal to 1⁄12 year).

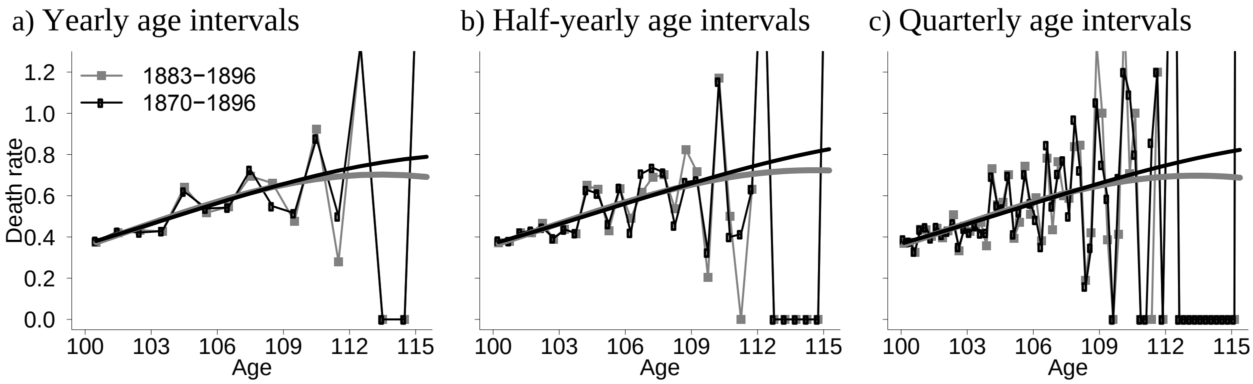
For narrow age intervals of length *n*, the number of individuals alive at the beginning of the interval is actually close to the number of person-years lived in the interval, even if mortality is high, and thus ${}_nM_x \cong {}_nq_x/n$. Of the three trajectories presented in figure 3, the one for quarterly age intervals (i.e., $4 \times {}_{0.25}q_x$) indeed bears the closest resemblance in terms of level and trend to death rate trajectories in figure 1. Thus, as long as *n* is sufficiently small, estimating the instantaneous death rate at age *x*, $\mu(x)$, by ${}_nM_x$ or ${}_nq_x/n$ will lead to similar results. For one-year age intervals (i.e., n = 1), however, $\hat{\mu}(x)$ will surely be biased downward if estimated by ${}_nq_x/n$ when mortality is high, unlike if estimated by ${}_1M_x$ because $\mu(x + 1/2) \cong {}_1M_x$ (Thatcher, Kannisto and Vaupel 1998). Consequently, the three trajectories displayed in figure 3 cannot be used in any way to claim that mortality deceleration is more likely to occur when broader age intervals are considered. The similarity in levels and trends of all three death rate trajectories in figure 1 demonstrates that mortality deceleration at very old ages is just as likely to occur when smaller age intervals are considered.

Figure 3. Incorrectly "annualized" probabilities of death among centenarians for yearly, half-yearly and quarterly age intervals, French-Canadian female birth cohorts from 1870–96



Our study has focused thus far on the mortality experience of French-Canadian female centenarians born during the period 1870–96. Since this population is relatively small, we had to aggregate data for several birth cohorts to increase the number of survivors at very old ages. Mixing different birth cohorts with different mortality was, however, identified by Gavrilov and Gavrilova as one of the three factors that could potentially explain why mortality deceleration is often observed at very old ages (see factor (1) described on p.2). With our data set, we were able to control for the other two factors thus far, namely the inaccurate reporting of age among the very old and the use of broad (e.g., one-year) age intervals. To investigate whether mixing cohorts born from 1870–96 is responsible for the occurrence of mortality deceleration observed in figure 1, we split the group of cohorts in half (i.e., we considered 14 birth cohorts instead of 27) and recomputed female age-specific death rates for one-year, 0.5-year and 0.25-year age intervals for the group of cohorts born 1883–96. Figures 4a to 4c show that for the three lengths of the age interval studied, the slowdown in the death rate increase with age for cohorts from 1870–96 is not more pronounced than for the smaller and less heterogeneous group of cohorts born between 1883 and 1896. Up to age 110, the smoothed mortality curves for the two groups are practically undistinguishable. After age 110, the tendency for deceleration with age even seems greater for cohorts from 1883–96, but the trajectories are highly uncertain at these most extreme ages and should not be over interpreted. Thus, the mortality deceleration observed among French-Canadian female centenarians born between 1870 and 1896 does not appear to be an artifact of mixing different birth cohorts with different mortality experiences.

Figure 4. Death rates among centenarians belonging to different groups of birth cohorts, French-Canadian female cohorts born from 1883–96 and 1870–96



Note: Solid plain lines show P-spline-smoothed mortality curve based on penalized Poisson likelihood.

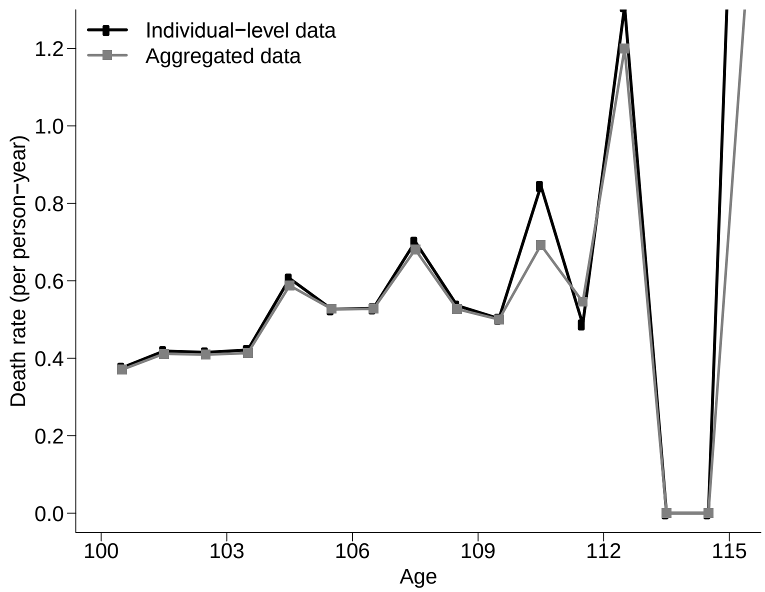
5. CONCLUDING REMARKS

Our analysis was based on the mortality experience of verified Catholic French-Canadian female centenarians, born in Quebec between 1870 and 1896 and died over the period 1970-2009. The evidence reviewed here reveals that the rate of mortality increase with age tends to slow down at very old ages for this population. Using one-year, six-month or three-month age intervals led to highly similar death rates levels and trends. Moreover, the aggregation of several birth cohorts does not seem to be responsible for the late-life mortality deceleration observed in our data. These results refute recent findings suggesting that proper hazard rate estimation in relatively homogeneous populations with accurate data leads to a steady death rate increase over age, up to age 106 and possibly beyond (Gavrilov and Gavrilova 2011, 2014).

Observed death rates reported in this paper were computed using information on the years, months, and days of birth and death of each centenarian. In the denominator of these death rates, the number of person-years lived in the given age interval were directly counted by adding the contribution of each individual. But individual-level data is seldom available in practice. Data usually come in an aggregated form (e.g., by single years of age, death and birth for each sex) and death rates calculations typically rest on the assumption that deaths are distributed uniformly within the given age interval. This assumption was listed as one of the factors that could potentially explain why mortality deceleration is often observed in empirical studies (Gavrilov and Gavrilova 2011). Figure 5 suggests, however, that the assumption is acceptable even at very old ages, at least for one-year age intervals, as the resulting death rates for most ages are practically undistinguishable from those obtained using the individual-level information.

In sum, our results provide additional evidence of a late-life mortality deceleration among humans. We acknowledge that in previous studies, the issue of age exaggeration in the reporting of age and/or the use of excessively heterogeneous populations may have partially contributed the observed slowdown in the death rate increase at very old age. But the data collection used in this paper, free of age exaggeration problems and depicting a relatively homogeneous population, also lends credence to the deceleration of the age-trajectory of human mortality at the highest ages. We recognize, however, that the length of the death rate series examined here is relatively short (ages 100 and over). Longer series may permit more accurate mortality measurements at the highest ages in this population because the estimation procedure would then rely on a greater number of data points. Moreover, these additional data points would necessarily be based on a larger number of deaths due to the younger old age at which the event occurred. We have requested permission to obtain nominative lists of deaths of octogenarians and nonagenarians in Quebec from the Institut de la statistique du Québec to expand the coverage of our current data set of verified centenarians to younger old ages. Our request is currently under review.

Figure 5. Observed age-specific death rates among centenarians calculated using individual-level and aggregated data, French-Canadian female birth cohorts 1870–96



Notes: Age-specific death rates based on individual-level and on aggregated data differ only by their denominators (person-years lived in the given age interval). For individual-level data, the person-years of exposure were counted exactly, based on the information on the day, month, and year of birth and death of each individual. For aggregated data, person-years were estimated according to the assumption that deaths are distributed uniformly within the given age interval.

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