Living to 100 and Beyond: Survival at Advanced Ages

Session 3: Mortality Laws and Models Session – Part II

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Approaches and Experiences in Projecting Mortality Patterns for the Oldest Old

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Using Dynamic Reliability in Estimating Mortality at Advanced Ages

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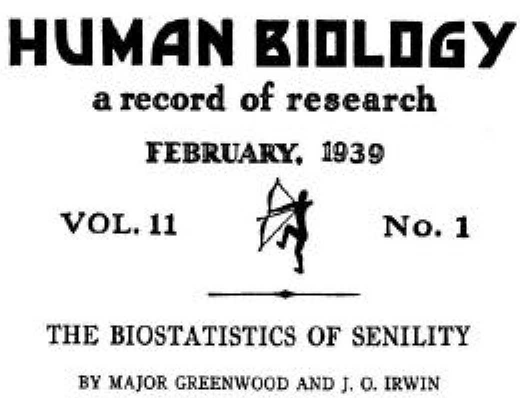
The paper by Dr. Buettner describes the current methodology for projecting mortality rates above age 80, which is adopted and used now by the Population Division of the United Nations. This is a very important issue for accurate forecasting of the population aging, and for ensuring the compatibility of life tables and life expectancy estimates across different nations by using standard procedures of life table closing. The advantage of author's approach is an attempt to find some kind of unified approach to the old but very important problem of life table closing.

The discussed paper presents a detailed review and evaluation of two methods: the method proposed by Himes, Preston and Condran (1994), known as HPC standard, as well as the approach suggested by Coale and Kisker (1990), known as Coale-Kisker method. Both methods are based on extrapolation of mortality rates at age 80-100 years to the ages over 100 years with specific assumptions. In the discussed paper Dr. Buettner not only reviews these methods but also makes an attempt to test their validity using real data. The results of the testing revealed certain weaknesses of both methods in data fitting.

In my opinion, the revealed weaknesses and problems of poor fitting may arise because both methods extrapolate mortality to the ages where mortality is changing its pattern in a dramatic and fundamental way. Perhaps it is worth to consider alternative approaches, which take into account the existing knowledge on specific mortality patterns beyond age 100. The history of mortality studies at extreme ages is very rich in ideas and findings. Specifically, I would like to bring your attention to one seminal article, which was published more than 60 years ago: Greenwood M., Irwin J.O. Biostatistics of Senility. *Human Biology*, 1939, vol.11, pp.1-23. Interestingly, this article was considered to be so important that it was featured at the front page of the journal "*Human Biology*" in the following way:


HUMAN BIOLOGY
a record of research
FEBRUARY, 1939
VOL. 11 No. 1
THE BIOSTATISTICS OF SENILITY
BY MAJOR GREENWOOD AND J. O. IRWIN

This study, accomplished by the famous British statistician and epidemiologist, Major Greenwood, may be interesting to discuss again now for two reasons:

First, it is devoted to the studies of mortality at extreme ages (the topic of this Symposium). The authors of this paper admitted that the topic of their paper had "little actuarial importance" (in 1939), but may be of interest to biologists. However now, 60 years later this topic has great actuarial importance, as it is evident from the papers presented at this Symposium.

Second, this 1939 article correctly describes and forestalls the main specific regularities of mortality at advanced ages.

The first important finding was formulated by Greenwood and Irwin in the following way: "***…the increase of mortality rate with age advances at a slackening rate, that nearly all, perhaps all, methods of graduation of the type of Gompertz's formula over-state senile mortality***" (Greenwood, Irwin, 1939, p.14). This observation is confirmed now and it is known as the "late-life mortality deceleration" (Fukui et al., 1993; 1996; Khazaeli et al., 1996; Vaupel et al., 1998; Partridge & Mangel, 1999).

The authors also suggested "***the possibility that with advancing age the rate of mortality asymptotes to a finite value***" (Greenwood, Irwin, 1939, p.14). This observation is also confirmed now and it is known as the "mortality leveling-off" at advanced ages (Carey & Liedo, 1995; Clark & Guadalupe, 1995; Vaupel et al., 1998), and as the "late-life mortality plateau" (Mueller & Rose, 1996; Pletcher & Curtsinger, 1998; Wachter, 1999). Moreover, Greenwood and Irwin made the first estimates for the asymptotic value of human mortality at extreme ages using data from the life insurance company. According to their estimates, "***… the limiting values of q_x are 0.439 for women and 0.544 for men***" (Greenwood, Irwin, 1939, p.21). It would be interesting to compare these first estimates of the limiting mortality values at extreme ages with current mortality rates of supercentenarians.
Greenwood and Irwin also proposed a possible explanation of very slow growth of mortality with age among centenarians. They suggested that very old people were less subjected to external stresses and shocks because they restricted their activities and rarely appeared in public (Greenwood, Irwin, 1939, p.14). Although this explanation could be challenged now, it still deserves an attention as a possible contributing factor to mortality deceleration at advanced ages. It is interesting that the authors also tried to analyze animal mortality at advanced ages and found the same regularities as in humans (Greenwood, Irwin, 1939, p. 21). Here are some original excerpts from this remarkable seminal publication:

M. Greenwood, J. O. Irwin. BIOSTATISTICS OF SENILITY

" the increase of mortality rate with age advances at a slackening rate, that nearly all, perhaps all, methods of graduation of the type of Gompertz's formula *over-state* senile mortality. "

"… *possibility* that with advancing age the rate of mortality asymptotes to a finite value. "

"… The limiting values of q_x are 0.439 for women and 0.544 for men. Some tests of the ultimate mortalities in non-human experience were not unfavorable. "

Further studies of mortality at advanced ages confirmed the major findings of Greenwood and Irwin (1939). The method of extinct generations proposed by Vincent (1951) and developed by Depoid (1973) and Kannisto (1988; 1994) opened new opportunities for more accurate mortality estimation at extreme ages. The study by Vaino Kannisto (1988; 1994) who collected a large body of data for mortality at ages beyond 100 deserves particular attention. On my opinion, his collection of mortality data may be used as a basis for new model life tables describing mortality at ages over 100 years.

The problem of life table closing is related to another important problem considered in the Buettner's paper – the problem of mortality forecasting at older ages. This topic raises questions on how low the mortality rates can go. From the view of the common sense it seems that mortality at older ages cannot decline indefinitely. However, when we look at the actual trends of mortality decline, it is very difficult to find any indication for the limits to mortality decline. Figure 1 presents the tails of the survival curves at extreme ages as well as the historical evolution of these tails. Since the numbers of survivors are presented in the log scale (vertical axis), the force of mortality can be easily visualized as the slope of the survival curves. The remarkable feature of this graph is a dramatic (10-fold!) increase in chances for nonagenarians to survive and to become a centenarian. There is no indication that the survival improvement at extreme ages becomes less rapid now, in fact the opposite trend is evident from this graph (Figure 1):

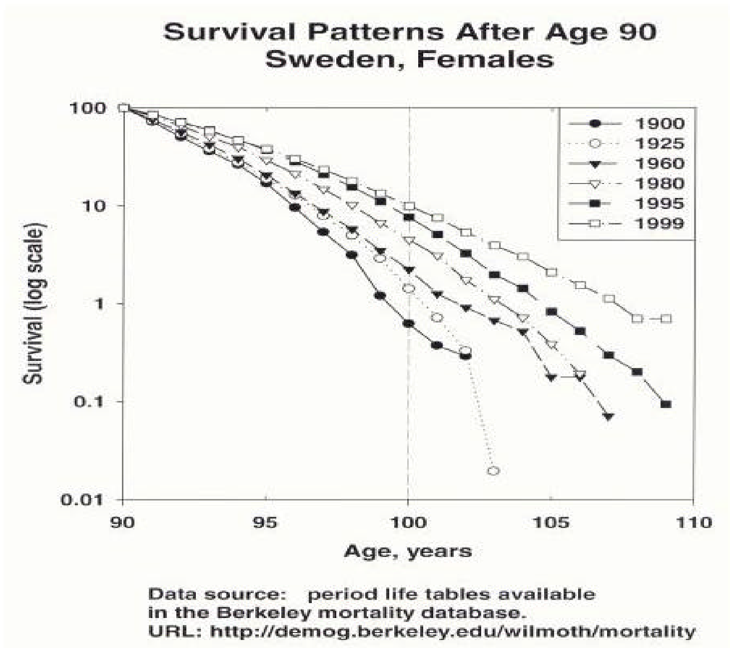


Figure 1.

Returning to the discussion of the Buettner's paper, the following innovative feature of his study should be mentioned: the Makeham adjustment to mortality changes. Adding constant Makeham term to the age-dependent mortality may be justified by the fact of relative stability of Makeham term during the last 30-40 years in the developed countries. Although during the first half of the 20th century mortality declined almost exclusively due to decline in the Makeham term (in Gompertz-Makeham equation) (Gavrilov, Gavrilova, 1991), this tendency has been changed in the second half of the 20th century. Another interesting problem raised in the Buettner's paper is the discussion of the convergence versus divergence of mortality patterns in different countries.

Dr. Buettner concludes his paper with suggestion to make a recommendation to the national statistical offices to collect mortality data up to the age 100, which is a very important and useful suggestion. If it becomes true, it will create a real breakthrough in understanding mortality trends at extreme old ages.

Acknowledgments. I would like to thank the organizers of this Symposium for the unique opportunity to take part in this very interesting scientific meeting.

References

Carey, J.R. & Liedo, P. (1995) Sex-specific life table aging rates in large medfly cohorts. *Exp. Gerontol*. **30**, 315-325.

Clark, A.G. & Guadalupe, R.N. (1995) Probing the evolution of senescence in Drosophila melanogaster with P-element tagging. *Genetica* **96**, 225-234.

Coale A.J., Kisker E.E. (1990) Defects in data on old-age mortality in the United States: New procedures for calculating schedules and life tables at the higher ages. *Asian and Pacific Population Forum* **4**: 1-31.

Depoid, F. , (1973) La mortalité des grands vieillards, *Population* **28**:755-792.

Fukui, H.H., Xiu, L. & Curtsinger, J.W. (1993) Slowing of age-specific mortality rates in Drosophila melanogaster. *Exp. Gerontol.* **28**, 585-599.

Fukui, H.H., Ackert, L. & Curtsinger, J.W. (1996) Deceleration of age-specific mortality rates in chromosomal homozygotes and heterozygotes of Drosophila melanogaster. *Exp. Gerontol.* **31:** 517-531.

Gavrilov, L.A. & Gavrilova, N.S. (1991) *The Biology of Life Span: A Quantitative Approach*, New York: Harwood Academic Publisher.

Greenwood, M. & Irwin, J.O. (1939) The biostatistics of senility. *Hum. Biol*. **11:** 1-23.

Himes Ch.I., Preston S.H., Condran G.A. (1994) A relational model of mortality at older ages in low mortality countries. *Population Studies* **48**: 269-291.

Kannisto, V. (1988) On the survival of centenarians and the span of life. *Population Studies* **42**: 389-406.

Kannisto, V. (1994) Development of Oldest-Old Mortality, 1950-1990: Evidence from 28 Developed Countries. *Odense Monographs on Population Aging*, 1. Odense University Press, Odense, Denmark.

Khazaeli, A.A., Xiu, L. & Curtsinger, J.W. (1996) Effect of density on age-specific mortality in Drosophila: a density supplementation experiment. *Genetica* **98:** 21-31.

Mueller, L. & Rose, M.R. (1996) Evolutionary theory predicts late-life mortality plateaus. *Proc. Natl. Acad. Sci. USA* **93:** 15249-15253.

Partridge, L. & Mangel, M. (1999) Messages from mortality: the evolution of death rates in the old. *Trends in Ecology and Evolution* **14**: 438-442.

Pletcher, S.D. & Curtsinger, J.W. (1998) Mortality plateaus and the evolution of senescence: why are old-age mortality rates so low? *Evolution* **52**: 454-464.

Vaupel, J.W., Carey, J.R., Christensen, K., Johnson, T., Yashin, A.I., Holm, N.V., Iachine, I.A., Kannisto, V., Khazaeli, A.A., Liedo, P., Longo, V.D., Zeng, Y., Manton, K. & Curtsinger, J.W. (1998) Biodemographic trajectories of longevity. *Science* **280**: 855-860.

Vincent, P. (1951) La mortalité des vieillards, *Population* **6**:181-204.

Wachter, K.W. (1999) Evolutionary demographic models for mortality plateaus. *Proc. Natl. Acad. Sci. USA* **96**: 10544-10547.

The paper by Dr. Lin suggests a new statistical model for fitting and estimation of mortality rates at advanced ages. This model can also be described as phenomenological model, because it is not based on any fundamental mechanism or theory, but is simply an empirical fitting formula with 4 parameters. For the purpose of theoretical justification for this formula, the author argues that a similar approach is applied in reliability engineering. The idea to apply the reliability theory to explain the late-life mortality trends is indeed very appealing and it resonates strongly with our own studies on the same topic (Gavrilov, Gavrilova, 1991; 2001). However, a clear distinction should be made between the fundamental reliability theory based on particular mechanisms of failure, and empirical fitting methods occasionally used in the practice of reliability engineering. The model suggested in this paper represents the second, empirical approach of reliability engineering, although it might be possible that a theoretical justification for the suggested formula could be found later.

The discussed paper is using a somewhat non-traditional approach. It relates hazard function with survival function (also called reliability function). Taking into account that both functions are related to each other by definition, it raises questions on the interpretation of results for such analyses. This topic may deserve some discussion because this is the second time when I encounter mortality analysis, which relates two variables linked to each other by definition. The first case is a series of papers by Azbel (1999a; 1999b) who compared cumulative survival functions at different ages (related to each other by definition) and found remarkably strong relationship between two values of l_x (which is not surprising taking into account functional dependence between two values of survival probabilities). The problem of interpretation for the results of such analyses may deserve a special discussion.

I would like to say a few words about parameters of reliability formula used by the author. The formula used by the author is rather complicated, but two parameters of it look familiar: parameters B and C. Parameter B looks like an analog of Makeham parameter in the Gompertz-Makeham formula. To the author's benefit, Dr. Lin analyzed changes of parameters in history using a set of Taiwan life tables. According to this data, parameter B in history behaves very similarly to the Makeham parameter: it is high at the beginning of the 20th century, then it declines sharply and stabilizes in the second half of the 20th century. As for the parameter C, it represents the limiting mortality at extreme ages (late-life mortality plateau). The values of parameter C presented in the paper by Dr. Lin look too high – 2-3 per year. With so high levels of mortality at advanced ages we could not expect not only the case of Jeanne Calment but even supercentenarians – persons survived by ages 110. For example, using estimates of mortality at extreme ages proposed by Greenwood and Irwin (1939) we can calculate chances of centenarian to become a supercentenarian, which is equal to $(0.5)^{10} = 0.001$. Thus, given the number of centenarians in developed countries, we can expect the emergence of supercentenarians in these countries. On the other hand, the case of Jeanne Calment is a real challenge to the probability theory, because the chances of centenarian to reach age 122 are close to zero: $(0.5)^{22} = 2\cdot10^{-7}$. In order to explain the case of Jeanne Calment we need to postulate that mortality is declining at very advanced ages.

Finally, paper by Dr. Lin compares results of fitting the Gompertz model and the author's reliability model to mortality data. To my opinion, it is not entirely fair to compare the 2-parameter Gompertz model with 4-parameter model proposed by the author. I would suggest a comparison of the author's reliability model with the Gompertz-Makeham model, which has age-independent term similar to the parameter B in the author's formula.
Summarizing, I would like to say that we are now at the beginning of coming to a consensus on the mortality patterns over age 100. This Symposium is definitely a step forward in developing such consensus.

Acknowledgments. I would like to thank the organizers of this Symposium for the unique opportunity to take part in this very interesting scientific meeting.

References

Azbel, M.Y. (1999a) Phenomenological theory of mortality evolution: its singularities, universality, and superuniversality. *Proc. Natl. Acad. Sci. U.S.A.* **96**: 3303-7.

Azbel, M.Y. (1999b) Empirical laws of survival and evolution. *Proc. Natl. Acad. Sci. U.S.A.* **96**: 15368-15373.

Gavrilov, L.A. & Gavrilova, N.S. (1991) *The Biology of Life Span: A Quantitative Approach*, New York: Harwood Academic Publisher.

Gavrilov, L.A. & Gavrilova, N.S. (2001) The reliability theory of aging and longevity. *Journal of Theoretical Biology* **213**(4): 527-545.

Greenwood, M. & Irwin, J.O. (1939) The biostatistics of senility. *Hum. Biol.* **11:** 1-23.