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Surviving to be the oldest old—destiny or chance?

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Abstract

Human beings have always been fascinated by super-longevity and now, as mortality declines to levels never before experienced, living to be a centenarian becomes a real, though still a rather remote, possibility. In most countries of the industrialised world the modal age at death is rising constantly and the number of centenarians is growing exponentially. A growing corpus of research is focussing on the centenarians, their particularities and the verification of their centenarian status. However, if we wish to unravel the secrets for attaining this magnificent age, we need to look beyond the centenarian communities themselves. The number of people becoming centenarians is determined by three different processes: the numbers born 100 years earlier, the probability of reaching old age and the probability of surviving old age to become a centenarian. Mortality up to age 80 and mortality beyond age 80, though loosely related, need to be treated as qualitatively different phenomena. However, there have been few studies of conditions distinguishing between populations and societies with low and high mortality at old ages. Instead, most work has focussed on identifying and carefully documenting high longevity populations, those with an unusually high number of centenarians - usually small, bounded populations - while no attention has been given to their complement, high shortivity populations, those with a lack of centenarians. In the absence of a theory of population longevity and shortivity, we cannot distinguish between populations which are genuinely different from most others, and those which are merely chance outliers. The critical question is thus 'what are the transition mechanisms'? We need to focus less on the centenarians themselves, and more on the conditions which distinguish populations with a relatively high probability of surviving from age 80 to age 100 from those with a relatively low probability of survival.

1 Introduction

Long life fascinates us, and apparently always has. The early generations of the Bible, from Adam to Noah are reported to have all lived phenomenally long lives.[1]

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[1] Genesis 5.

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In Genesis 6 God declares that as we are human we should live no more than 120 years, but subsequent generations of Genesis, from Noah to Jacob, were still given considerable bonuses.[2] Today, as mortality declines to levels never before attained, a growing amount of attention is turning to that small fraction of the population that really does live to be 100, the centenarians, and beyond them to the semi-super- and supercentenarians (ages 105 and 110). Here, it would seem, is where we hope to find the key to further extensions of the average lifespan, and perhaps this is also an attempt to enjoy, albeit vicariously, a status most of us will probably not attain. In the following, I want to present a few comments on the extension of the lifespan and the growth in the number of centenarians. Following a brief review of recent extensions in human longevity, I shall show that we need to distinguish between mortality up to age 80 and beyond age 80, and treat them as qualitatively different phenomena. I shall then discuss why studies focussing on populations with an unusually large number of centenarians should be treated with caution: in the absence of a theoretical formulation identifying *a priori* where such populations are to be found, it is entirely possible that many of the 'blue zone' populations of extreme longevity (Poulain et al. 2004) are merely chance occurrences with no more claim to fame than the winner of a national lottery.

Longevity, the average age at which people die (Carey and Judge 2001), has been increasing consistently for the past 160 years or more (Oeppen and Vaupel 2002), though this increase has not necessarily been linear (Vallin and Meslé 2010) and may even be slowing down. The rate of change also varies by country, and especially by region. However, if our interest is in mortality late in life we would do better to look at the upper end of the life table, the modal age of death and survivorship beyond the mode (Kannisto 2001). The trend has been generally upwards in many countries (Canudas-Romo 2010; Engelman et al. 2010), particularly in the more developed countries of western Europe, North America and Australasia (Edwards 2011) although the evidence is unclear as to whether mortality is expanding or compressing beyond the mode (Thatcher et al. 2010; Ouellette and Bourbeau 2011). The question thus arises: can we identify those populations in which becoming a centenarian is most likely?

2 The dimensions of mortality

The number of people becoming centenarians is determined by three different processes: the numbers born 100 years earlier, the probability of reaching old age and the probability of surviving old age to become a centenarian (Rau et al. 2008; Herm et al. 2012; Robine et al. 2010). A number of papers have looked at the impact of changes in sizes of birth cohorts and have all shown that the rate at which the number of centenarians is growing far outstrips recorded increases in the number of births

[2] See, e.g. Genesis 11.

(Robine and Saito 2003; Robine and Paccaud 2004). If the number of centenarians is growing, this is largely due to changes in patterns of mortality and the growing probability of surviving, first to old age, then to very old age. It is tempting to think that mortality at older ages is directly related to mortality levels at lower ages, but this is not necessarily so.

We focus on a random sample of 108 pairs of abridged period life tables drawn from the Human Mortality Database.[3] We began with 3788 pairs of male and female life tables for 41 countries, after excluding countries for which subsets exist in the data (UK, Germany, New Zealand, England and Wales Total, France Total) for the two sexes, from ages 0, 1, 5, . . . 95, a total of 21 values for each life table. Figure 1 presents a variable-clustering analysis[4] using Harrel's varclus procedure in R (Harrell et al. 2013). The analysis was based on the Hoeffding measure of dependence, D, between the ${}_np_x$ values for the males and females combined, and using average linkage clustering. Hoeffding's D is a rank-based measure of association, recommended by Fujita et al. (2009) as being preferable to Pearson and Spearman correlations for identifying non-linear and non-monotonic associations and as being less sensitive to outliers. Variable clustering is akin to factor analysis with oblique rotation in that each variable is assigned to one factor, or cluster, with the stipulation that each variable is assigned to one cluster only, in a manner that maximises separation of the factors, as defined by the clustering algorithm. In average-link clustering, separation is defined by the distance between the average location of the points making up each cluster.

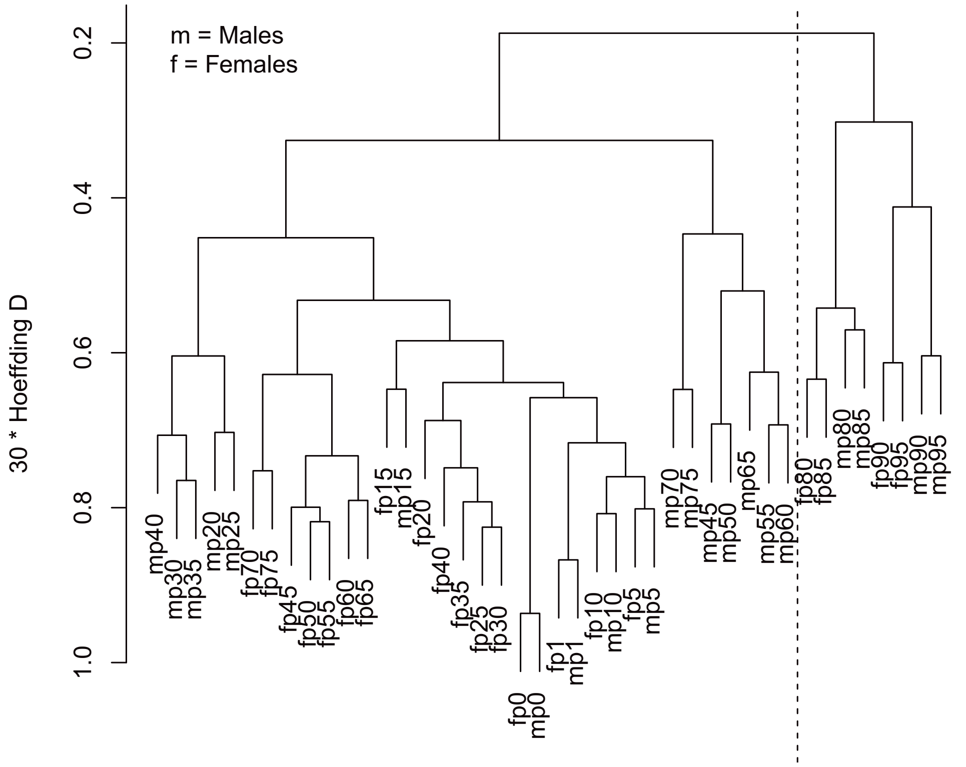
Our major interest is in the primary split in the cluster hierarchies, between survivorship above age 80, and the rest of the life table. Survivorship above age 80 stands out as separate from survivorship probabilities at younger ages, with a close correlation between survivorship at older ages for males and for females. This result is borne out by various other analyses (principal and factor analyses; multidimensional scaling; Pearson and Spearman correlation, and other clustering algorithms) all of which show a close affinity between survivorship probabilities at the highest ages, and a relatively low correlation of these with period survivorship values at earlier ages in the life table. The implication is that at any point in time, the probability of further survival for those who attain the oldest ages, at or near the modal age at death, cannot necessarily be derived directly from the probability of living to that age. It is thus very possible that models of mortality at younger ages will not be applicable when seeking to understand mortality in the ninth and tenth decade of life, nor the probability of living to be a centenarian for those who have lived to celebrate their 80th birthday.

The above analysis shows that at any one point in time (period) the ranking of survival probabilities for those who survive to age 80 may differ from the rankings of survival probabilities at other ages. Perhaps, however, we should be considering the

[3] www.mortality.org, downloaded 8 October 2013.

[4] http://biostat.mc.vanderbilt.edu/s/Hmisc/html/varclus.html.

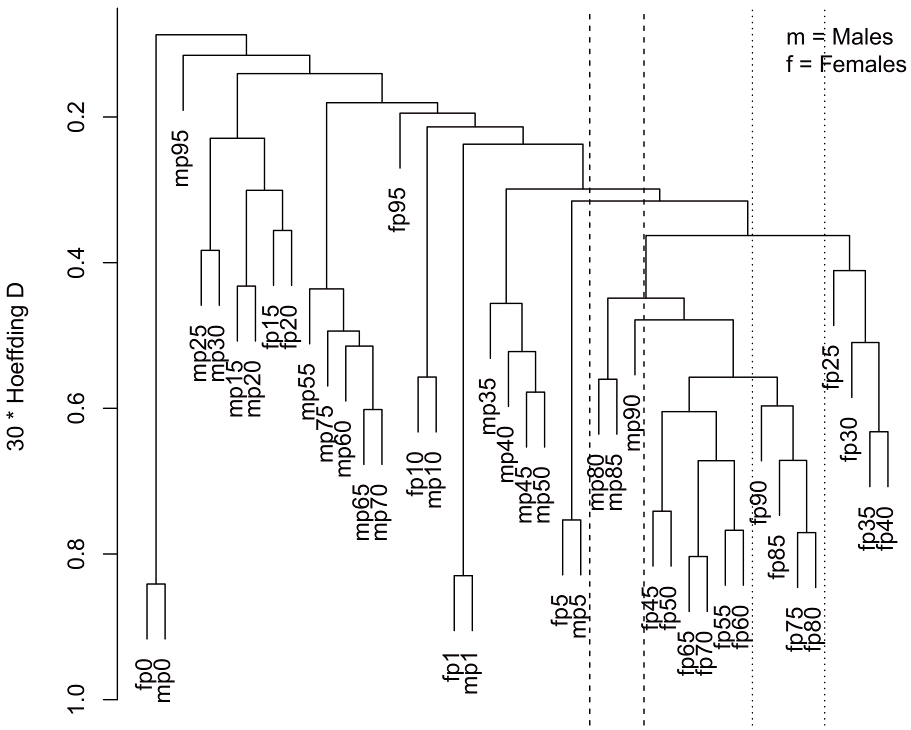
Figure 1:
Variable clustering of period ${}_np_x$ values



cohort probabilities: how closely related are the survival probabilities of a particular cohort at later ages to the probability of surviving to reach a very old age? This analysis is more limited, first because there are far fewer cohort life tables available, in HMD and elsewhere (HMD includes cohort life tables for just 11 countries, if we exclude super-sets)[5] and for considerably fewer birth years. Using a similar method to that for period life tables, but allowing for life tables from the same birth year and excluding only tables 10 years or less distant from those already selected, we sampled 56 pairs of cohort life tables ranging from the 1759 birth year (Sweden) to 1910 (Switzerland). Figure 2 repeats the variable clustering analysis for the sample of 56 male and female cohort life tables. The distinctiveness of later-life mortality

[5] Total populations for England and Wales, and for France, countries for which there are also civilian population life tables.

Figure 2:
Variable clustering of cohort ${}_{n}p_{x}$ values



is reproduced, but is not as apparent as in the period life tables, and survivorship probabilities above age 95 are separated out.

In interpreting these results we need to recall the ontological limits of cohort life tables—not only is the life table recording the mortality experience of the cohort over what are often dramatically changing mortality conditions (Murphy 2010), the cohort itself may not be constant over the years, as emigrants leave and immigrants enter the country. Both of these limitations will change from one cohort to another so that in comparing cohort life tables we are liable to be comparing like with unlike. Furthermore, we need to recall that in cohort life tables there will be a tendency for contiguous ages to cluster together due to the secular decline in mortality over time, which will appear both as a period and as an age effect. Cohort life tables should thus be seen as an approximate historical record of the experience of the particular cohort at hand, rather than an analytical tool comparable to period life tables (Anson 2002). Nonetheless, although the cohort life tables do not reproduce the clear distinction between the very old (80 and above) and the rest of the population that we saw in the period life tables, there is still a close intercorrelation between mortality levels at these ages which tends to draw them apart from other ages.

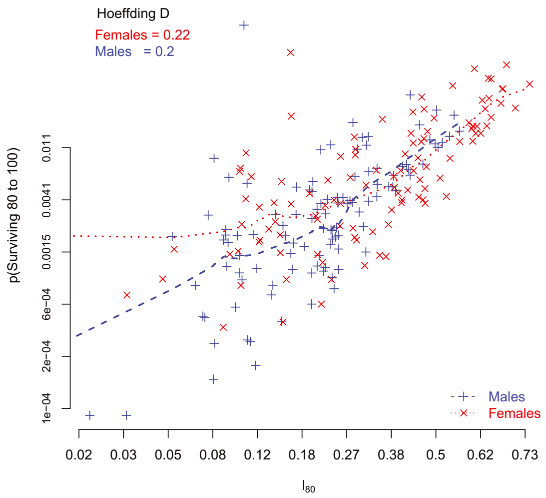
To bring out the meaning of the clustering, Figure 3 looks at the relation between the life table probability of surviving 20 years (20_{px}) and the probability of surviving to the starting age (l_x), in our sample of 108 national life tables. In Panel (a) we consider the relation between ${}_{20}p_{80}$ and l_{80}. The general trend is upwards, as we might expect, with survivorship above age 80 being higher the greater the probability of surviving to age 80. However, there is considerable scatter around the trend line, and while at higher levels of mortality (low survivorship) female chances of survival are greater than male chances, for any given level of l_{80}, at lower levels of mortality this relative female advantage effectively disappears. At the same time, as Panel (b) shows, there is a very close relationship between old age survival among men and women in the same population, with almost universally higher female survivorship at these ages, as evidenced by the linear correlation of 0.90. Survivorship at these ages is therefore not a random event but a response to local conditions which are affecting men and women similarly—with an advantage for women. However, as Panel (a) indicates, whatever these conditions may be, they are not necessarily the same as those which make for high or low survivorship at younger ages. By contrast, at lower ages, there is a far closer relationship between surviving to a particular age and subsequent mortality. Panel (c) shows the relationship between l_{50} and ${}_{20}p_{50}$ for the same set of life tables. Unlike the older ages, there is a clear monotonic relationship between the two probabilities, as is indicated by the far smaller scatter of points around the trend line, and the higher values of Hoeffding's D. Except at the very lowest level of mortality, female ${}_{20}p_{50}$ is consistently higher than male ${}_{20}p_{50}$ for any given value of l_{50}.

To date, there have been very few analyses of conditions which make for a high probability of survival at older ages (but see Grundy 2011; Xie et al. 2008; Gavrilov and Gavrilova 2011; Doblhammer 2000). Most analyses have concentrated on populations with a known high probability of survival or have sought to identify individual traits making for longevity (Givens et al. 2009; Terry et al. 2004), Yet what is required is a comparison with other populations, those which have a lower probability of survival. Even if senescence is not pre-programmed (Carnes and Olshansky 2007), historical evidence suggests that our 'warranty period' runs out after we have lead an active life for about seven decades,[6] including providing aid, directly or indirectly, to the third generation (Sear and Mace 2008). Beyond this age our evolutionary role, in the sense of contributing to reproduction, is largely played out (Xie et al. 2008; Gurven and Kaplan 2007) and bodily maintenance and repair functions begin to break down (Olshansky and Carnes 1994). Yet the modal age of death in most modern populations is considerably above this age, and increasing, so we may already be seeing a moderation in the rate of ageing (Olshansky et al. 2002).

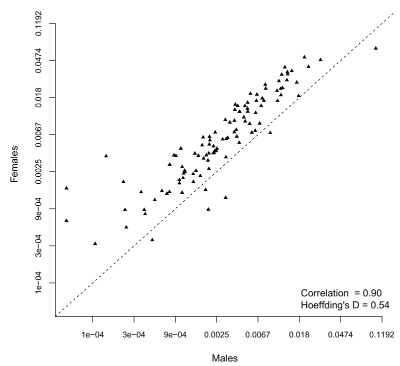
[6] There is nothing new in this observation, see "The days of our life are 70 years, and if in good strength, 80 years" (Psalms, 90:10, my translation).

Figure 3:
Survivorship probabilities to middle, to old and to very old ages (logit scales)

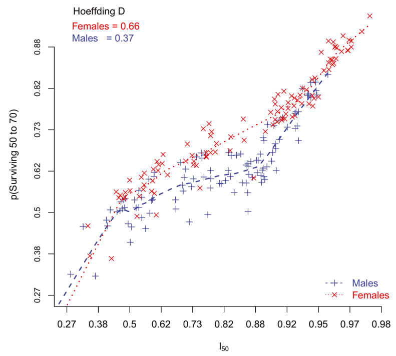
(a) Surviving to age 80, and from 80 to 100



(b) Surviving 80 to 100, males and females



(c) Surviving to age 50, and from 50 to 70



Note: One outlier (Iceland 1846) omitted from all plots.

In part, there may be a trade-off between infirmity and survival (Robine et al. 2010), with certain countries investing more in keeping the infirm and aged population alive, so that even if most centenarians are cognitively or physically impaired to some extent (Xie et al. 2008), there may be important differences between populations in the distribution of infirmity by age. Both these considerations (ageing and infirmity) point to the importance of the control of environmental threats (Robine and Saito 2003; Robine and Paccaud 2004), winter cold and summer heat, and the availability of medical services for the aged (Shkolnikov et al. 2011). We need, in other words, to switch our focus from ageing to longevity, the conditions which enable people to live a longer life. However, this is not just a question of the spread of technology for keeping people alive (Edwards 2011): in the balance between external shocks and coping mechanisms (Gurven and Kaplan 2007), we need to focus on the former as much as on the latter, and in humans both of these include taking into account the forms of social organisation, and the manner in which the old, and particularly the very old, are integrated into the broader social life of the society (Carey and Judge 2001; Wister and Wanless 2007).

3 Populations with super-longevity—chance or destiny?

If mortality at very high ages, and hence the probability of becoming a centenarian, is qualitatively different from mortality at younger ages, then clearly we need to study separately the conditions under which octogenarians and nonagenarians live out their century. An intuitive first step is to single out populations with an apparently large number of centenarians and identify common conditions which may explain this prevalence, but such inductive reasoning must ultimately be corroborated through comparisons with other populations, identified in terms of these criteria (Hempel 1965). Over the past decade there have been a number of such studies (see e.g. Poulain and Naito 2004; Caselli and Lipsi 2006; Martin et al. 2012; Poulain et al. 2004), often identifying locations with a high prevalence of centenarians. Such apparent concentrations of centenarians may of course be a reflection of problematic data (Poulain 2011; Bennet and Garson 1983; Gomes and Turra 2009), but on the other hand, they could indeed be examples of high survivorship at older ages, even if their current mortality levels at younger and at older ages are incongruent. They could also be a chance occurrence, identified *post hoc*.

Mortality is probabilistic and so is surviving. No one is guaranteed long life, though certain circumstances make it more or less likely. This being the case, the number of centenarians in a population should be seen as a random variable, the outcome of a probabilistic process conditional on a variety of local conditions. The process itself can be broken down into phases: of those born 100 to 115 years ago, a certain proportion will have survived to age 80 and of these a certain proportion will have survived to age 100. Of course, the smaller the population, the greater the relative variability, that is, the greater the chance of finding many more centenarians than we might expect. If the distribution is Poisson, and we expect to find just one centenarian, the probability of finding five times that number or more is almost four in a thousand. If we expect to find 100 centenarians, by contrast, the probability of finding 150 or more, just one and a half times that number, is only two in a million. It is thus perhaps not surprising that all the identified multi-centenarian populations have been comparatively small. One particularly compelling example is that of Okinawa, in which Poulain and Naito (2004) report 55 male and 402 female centenarians in 2001, out of a total population of 1.3 millions. In all, out of an average of 53,301 persons per year born 100 years previously (1899–1903), 888 lived to be centenarians, giving a longevity index[7] of 1.666 per 100,000, four times higher than that for Japan as a whole (421/100,000). Similarly Sardinia, with 577 survivors out of 130,000 births (longevity index of 410), significantly exceeds the equivalent value for the Italian cohort life table of 1901 (373/100,000). The probabilities of obtaining such results range from the extremely small to the infinitesimal, and Poulain (2011) is correct in calling for a careful validation of these data before we construct vast theoretical edifices on what may be very shifting sands. However, given the large number of populations, and in particular of small, bounded populations, there will no doubt be a number of genuine outlier cases in which the number of centenarians considerably ('significantly') exceeds the expected value. However, just as there are populations with very large values, there will also be populations with very low values of longevity ('shortivity', Givens et al. 2009), and these have yet to receive the equivalent attention which they deserve.

The credibility of a particular finding, and in particular, whether its super-longevity is associated with particular local circumstances, cannot be assessed by recourse to statistics alone, but only through comparative analysis. "[C]ausal inference is certainly in the mind . . . but causality itself is in the external world" (Ní Bhrolcháin and Dyson 2007, p. 3–4) and any claim to singularity must be based on identifying the mechanisms which distinguish that population from others. Thus an apparently special case may be no more than a chance occurrence on the tail of a statistical distribution and hence nothing exceptional, even if the probability is low and the number of centenarians appears very large. The situation is made more complicated by the time frame of demographic changes, which should be counted in generations rather than in calendar years. Even chance events will thus have a continuity that will give them an aura of permanence, so to the casual observer, and certainly to the residents of such outlier populations, it might well appear that they are blessed with a special longevity.

[7] Number living to be 100/Total born 100 years previously · 1000, equivalent to l_{100} in the cohort life table.

4 Conclusion

Human beings have always been fascinated by super-longevity and now, as mortality declines to levels never before experienced, living to be a centenarian becomes a real, though still a rather remote, possibility. In most countries of the industrialised world the modal age at death is rising constantly and the number of centenarians is growing exponentially (Robine and Saito 2003). A growing corpus of research is focussing on the centenarians, their particularities and the verification of their centenarian status. However, if we wish to understand the how and the why of centenarian status, in particular if we wish to unravel the secrets for attaining this magnificent age, we need to look beyond the centenarian communities themselves.

Mortality is a probabilistic process, and simple binomial models are certainly a drastic oversimplification of this process. Nonetheless, they do bring out the pitfalls involved in focussing on communities with known, or even putatively, high levels of longevity (Desjardins 2001). Such an approach cannot distinguish between communities which are genuinely different from most others, from those communities which are no more than chance outliers. For a particular locality to be pronounced genuinely different, it is not enough merely to point to an unusually high presence of centenarians. Such a presence must be associated with identifiable social, historical, cultural, genetic, dietetic, and even topographical conditions which, wherever they are found, singly or in combination, increase the chances that people will survive to be centenarians. Furthermore, just as their presence needs to be associated with longevity, so their absence needs to be associated with shortivity.

The explanations we seek must, necessarily, be multifaceted. Despite attempts at finding the genetic bases for longevity, for instance, (Arai et al. 2006; Westendorp and Kirkwood 2001; Gavrilov and Gavrilova 2001; Givens et al. 2009) it is unlikely that genetic differences account for more than about a quarter of the differences in lifespan (Vaupel 1998), and even that in interaction with the conditions in which people are living. Focussing on the peculiarities of the survivors (Martin et al. 2012) and comparing them with non-survivors may help us understand who is likely to survive under propitious circumstances, but tells us nothing about what these circumstances may be. Furthermore, even if longevity is in some sense heritable (Terry et al. 2004) we know little of the variation between, rather than within communities, and given the long human history of migration and intermarriage, and the irrelevance of super-longevity for selection (Gurven and Kaplan 2007) we may surmise that variation within populations far exceeds variation between them. What is important is the interaction between genetic dispositions and the world in which people grow up and live (Hobcraft 2006). As Caselli and Lipsi (2006, p. 288) note, “besides having ‘good’ genes a favourable environment is also essential for longevity.”

The critical question is thus ‘what are the transition mechanisms’? In the 1970’s, following works by Antonovsky (1967), Goldscheider (1971), Kitagawa and Hauser (1973) and others there came a burst of activity documenting the relation between social inequalities and mortality differentials. These studies focussed on comparisons between populations, and the correlates of higher and lower mortality. The time is ripe for a similar 'assault' on the conditions of mortality and survivorship in later life. There are a growing number of comparative community studies on nonagenarians (see e.g. Wister and Wanless 2007; Robine and Paccaud 2004), prospective studies comparing survivors to non-survivors (Xie et al. 2008) and comparative studies comparing the survival probabilities of different populations by reference to the physical, social, cultural and medical environments in which they live their lives (Okamoto 2006). What we are still lacking is a conceptual framework which will identify the conditions which are conducive to super-longevity on the one hand and shortivity on the other. If we really want to understand the secret of surviving to 100, we need to recognise that this may not be simply an extension of mortality reduction at younger ages. However, the answer probably does not lie with the centenarians themselves, but rather with their younger brothers and sisters, the octo- and nonagenarians, for it is through a study of their mortality patterns that we will see who does, and does not, live to be 100, and under what circumstances.

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