Perspectives on Mortality Forecasting

III. The Linear Rise in Life Expectancy: History and Prospects

Social Insurance Studies | No. 3

Editor
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Swedish Social Insurance Agency

Series Editor
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The Swedish Social Insurance Agency (*Försäkringskassan*) has a long standing commitment to promote research and evaluation of Swedish social insurance and social policy. The Social Insurance Agency meets this commitment by commissioning studies from scholars specializing in these areas. The purpose of the series Social Insurance Studies is to make studies and research focusing on important institutional and empirical issues in social insurance and social policy available to the international community of scholars and policy makers.

Published by: Försäkringskassan, Swedish Social Insurance Agency, 2006

Series Editor: Edward Palmer

Issue Editor: Tommy Bengtsson

Social Insurance Studies can be ordered by e-mail to forlag@forsakringskassan.se, or through the homepage, www.forsakringskassan.se, and cost SEK 120 excluding VAT, postage and packing.

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Cover Design: Jenny Övrebö
Printed by Edita

ISSN 1651-680x
ISBN 978-91-7500-340-5

Preface

Mortality projections are an essential input for projections of the financial development of pension schemes. Governments and insurance companies all over the world rely on good mortality projections fro efficient administration of their pension commitments. Ideally, the expected value of the difference between outcomes and projections would be close to zero. In practise, during recent decades, demographers have continually underestimated improvements in life expectancy for persons 60 and older. The demographic models used in projecting mortality are usually based on statistical modelling of historical data. The question is, it is possible to bring the results of mortality modelling closer to the ideal, and if so, what do demographers need to do to achieve this result?

This is the question that provided the impetus for forming the Stockholm Committee on Mortality Forecasting. The Swedish Social Insurance Agency (formerly National Social Insurance Board, RFV) is the national agency in Sweden responsible for providing a financial picture of Sweden's public pension system. The Swedish Social Insurance Agency has a long-standing interest in the development of modelling of pension schemes and participates actively in the international dialogue among experts in this area. The Stockholm Committee on Mortality Forecasting was created by RFV to bring together scholars from different disciplines working on issues in projecting mortality. The aim of the Committee is to survey the state of the art and to provide an impetus for the advancement of knowledge and better practice in forecasting mortality.

This is the third volume in a series presenting papers from workshops on mortality organized by the Stockholm Committee on Mortality Forecasting. Jim Oeppen and James Vaupel's study "Broken limits to life expectancy", published in *Science* in 2002, provided the background for this volume. This study showed that increases in life expectancy were initially due to reductions in death rates in the younger ages, later followed by a decrease in rates for older persons. This development was initially triggered by a decline in infectious diseases and at a later stage a downward trend in chronic diseases. The resulting substantial improvements in life expectancy led to what these authors identify as "best-practice populations." The authors show that the development of "best-practice populations" are best approximated by a linear trend, estimated over the past 160 years. Females have continuously gained almost 3 month per year, males slightly less. The amazing fact is not the increase as such, since countries entering the mortality transition at a later point of time will experience an even faster improvement in life expectancy than those that preceded them, but the *regularity* with which the world record has been broken. This leads at once to the questions: What are the causes of this linear increase and how much longer can it proceed? These are the questions discussed in this volume.

The first chapter, by Jim Oeppen and James Vaupel, brings their 2002 article up to the forefront once more, developing further the arguments put forward there. In this chapter they also discuss the implications of their findings for mortality forecasting. They argue that the increase in life expectancy is not slowing down and that in the near future we should expect average life expectancy to continue to increase at the same rate as before. They also argue that countries lagging behind tend to catch up with the best-practice populations. Thus, best-practice life expectancy should be used when making national forecasts.

In the chapters by Ronald Lee and Juha M. Alho respectively, this standpoint is partly called into question and, from different perspectives, they argue that individual countries are unable to stay at the best-practice line for long time periods. Instead, the trends for leading countries tend to “bend down” as time passes. When making forecasts, the issue is thus not only to capture the catch-up phase but also thereafter a phase when improvements no longer keep pace with newly emerging best-practice countries.

In his chapter, Jim Oeppen explores further the discussion of identifying the processes that have lead to the linear increase in life expectancy over the past 160 years. By employing a causal model acknowledging the significance of factors such as per capital income and technical change for a large number of countries, Oeppen analyzes convergence in national trends in life expectancy. The final chapter by Tommy Bengtsson is also devoted to the causes of the linear decline. Bengtsson argues that there is a variety of factors changing over time that determine trends in life expectancy, economic performance only being one of these and not always the most important one. A circumstance that has to be taken into consideration is that countries catching up and taking over the lead have had relatively small elderly populations. This would also imply that the elderly in these populations have gone though a process of selection. In addition, they may have access to more modern care resources per capita than their counterparts in countries that have experienced a slower mortality transition, albeit combined with a similar economic development. Since this advantage is not permanent, it disappears and the advantage of backwardness turns into a penalty for taking the lead.

Tommy Bengtsson Edward Palmer

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The Linear Rise in the Number of Our Days*

Jim Oeppen[a] and James W. Vaupel[b]

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If life expectancy[1] – also known as the expectation of life, is the mean lifespan of a cohort of newborns if current age-specific death rates remain unchanged – in developed countries were close to an ultimate limit, then increases in record life expectancy – the average length of life in the best-practice population – should slow as the ceiling is asymptotically approached.

Best-practice national life expectancy has, contrary to what many believe[2] (Olhansky et al. 2001; Riley 2001; Dublin 1928; Dublin and Lotka 1936;

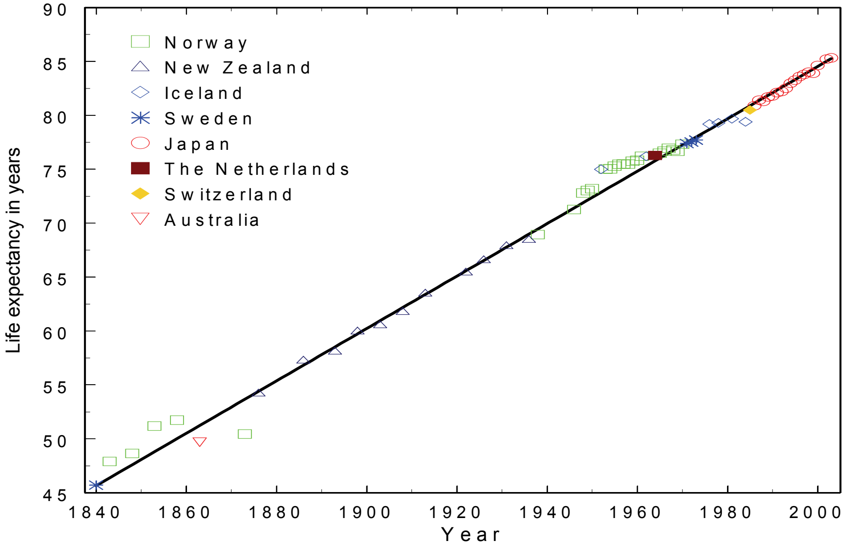
* We are grateful to the many people who have provided comments and information, including Kenneth Wachter and Yasuhik Saito. A version of this article that does not include some of the material here but that includes some additional material was published by Oeppen and Vaupel in 2002.

1 Most of the life-expectancy calculations in this article are based on data on death rates over age and time in the Human Mortality Database, see http://www.demog.berkeley.edu/wilmoth/mortality. Recent Japanese data can be found at http://www.mhlw.go.jp/english/database/index.html. Some data for the period before 1950 are from Keyfitz and Flieger (1968) and other sources.

2 For reviews, see Preston 1974; Keilman 1997. For a critical account of the low mortality assumptions used by the U.S. Social Security Administration, see Lee 2000. A review of mortality forecasting in 13 European Union countries in the early- and mid-1990s found that all assumed that mortality improvements would decelerate and 10 constrained life expectancy to reach an ultimate limit by a target date (Cruijsen and Eding 2001). In a report notorious for missing the baby boom, Whelpton et al. (1947) focused their discussion on life-expectancy limits for U.S. native white males. They concluded that for this population a life expectancy in the year 2000 of 72.1 years was the upper limit of what could be achieved by the largest mortality "declines that seem reasonable" and close to what could be attained at the "biological minimum of mortality". In two publications Frejka (1973, 1981) focus on population growth rather than life expectancy. In the first, Frejka writes that "within broad limits mortality can be fairly well predicted." He believes that life expectancy will approach a limit and that 77.5 is the most likely limit. He notes, however, that "mortality might even take a course absolutely different from what has been assumed."

Olshansky et al. 1990; Bourgeois-Pichat 1952, 1978; Fries 1980, 1990; Siegel 1980; Demeny 1984; United Nations 1973, 1985, 1989, 1999, 2001; NIPSSR 1997), risen for 160 years at a steady pace of three months per year as shown in Figure 1.

Figure 1 Best-practice national life expectancy over the last 160 years



Before 1950 most of the gain in life expectancy was due to large reductions in death rates at younger ages. The conventional view is that "future gains in life expectancy cannot possibly match those of the past, because they were achieved primarily by saving the lives of infants and children – something that happens only once for a population" (Olhansky et al. 2001). The sustained improvement in best-practice life expectancy belies this contention. In the second half of the 20th century improvements in survival after age 65 propelled the rise in the length of people's lives. For Japanese females, remaining life expectancy at age 65 grew from 13 years in 1950 to 22 years today, and the chance of surviving from 65 to 100 soared from less than 1 in 1000 to 1 in 20.[3]

The linear climb of record life expectancy suggests that reductions in mortality should not be seen as a disconnected sequence of unrepeatable revolutions

[3] Recent Japanese data can be fond at http://www.mhlw.go.jp/english/database/index.html.

but rather as a regular stream of continuing progress. Mortality improvements result from the intricate interplay of advances in income, salubrity, nutrition, education, sanitation, and medicine, with the mix varying over age, period, cohort, place and disease (Riley 2001). Reinforcing processes may help sustain the increase. For instance, reductions in premature deaths reduce bereavement, an important risk factor for mortality. The improvements also increase the number of people who survive to high ages, leading to greater attention to health at those ages. Increasingly prosperous, educated populations aided by armies of researchers, physicians, nurses and public-health workers incessantly seize opportunities to push death back. The details are complicated but the resultant – the straight line of life-expectancy increase – is simple.

For the world as a whole life expectancy has more than doubled over the past two centuries, from about 25 years to about 65 for men and 70 for women (Riley 2001). This transformation of the duration of life has greatly enhanced the quantity and quality of people's lives. It has fueled enormous increases in economic output and in population size, including an explosion in the number of the elderly (Fogel and Costa 1997; Martin and Preston 1994).

Better Forecasts

Although students of mortality eventually recognized the reality of improvements in survival, they blindly clung to the ancient notion that under favorable conditions the typical human has a characteristic lifespan, the Biblical three score and ten. As the expectation of life rose higher and higher, most experts were unable to imagine it rising much further. They envisioned various biological barriers and practical impediments. The notion of a fixed lifespan evolved into a belief in a looming limit to life expectancy.

Continuing belief in imminent limits is distorting public and private decision-making. Forecasts of the expectation of life are used to determine future pension, health-care and other social needs. Increases in life expectancy of a few years can produce large changes in the numbers of the old and very old, substantially augmenting these needs. The officials responsible for making projections – at the United Nations, the World Bank, and various national bureaus – recalcitrantly insist that life expectancy will increase slowly and not much further. The official forecasts distort people's decisions about how much to save and when to retire. They give politicians license to postpone painful adjustments to social-security and medical-care systems (Vaupel 2000).

Officials charged with forecasting trends in life expectancy over future decades should base their calculations on the empirical record of mortality improvements over a corresponding or even longer span of the past[4] (Lee and Carter 1992; Alho 1998; Tuljapurkar et al. 2000; Wilmoth 1998; Olshansky et al. 2001; Lee 2001). Because best-practice life expectancy has increased linearly by two and a half years per decade for a century and a half, one reasonable scenario would be that this trend will continue in coming decades. If so, record life expectancy will reach 100 in about six decades. This is far from immortality: modest annual increments in life expectancy will never lead to immortality. It is striking, however, that centenarians may become commonplace within the lifetimes of people alive today.

In all countries except the record holder, female life expectancy will be shorter than the best-practice level. Life expectancy could be estimated by forecasting the gap. The U.S. disadvantage varied from a decade in 1900 to less than a year in 1950 and about 5 years in 2000. If the trend in record life expectancy continues and if the U.S. disadvantage is between a year and a decade in 2070, then female life expectancy would be between 92.5 and 101.5, considerably higher than the U.S. Social Security Administration's forecast of 83.9.

An alternative method for forecasting life expectancy is to compute the average rapidity of improvement in age-specific death rates over many decades and then to use this information to project death rates over coming decades [5] (Lee and Carter 1992; Alho 1998; Tuljapurkar et al. 2000; Wilmoth 1998; Olshansky et al. 2001; Lee 2001). In the early 1940s, when he was a student at Princeton University, the eminent demographer Ansley Coale developed and applied a version of this method (Notestein et al. 1944). Today vastly superior data resources are available[6] and powerful, practicable methods have been developed to do more than Coale attempted (see e.g. Lee and Carter 1992; Alho 1998; Tuljapurkar et al. 2000). These methods use information about fluctuations in the speed of change in the past to estimate confidence bounds for the uncertainty enveloping life expectancy in the future. The official Japanese forecast, issued in 1997, for life expectancy (for

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[4] Olshansky et al. (2001) use changes in age-specific probabilities of death over the decade from 1985 to 1995 to make long-term projections, one out to the year 2577. It is more appropriate to base long-term projections on long-term historical data and to use changes in central death rates. See Wilmoth 1998, Notestein et al. 1944, and Lee 2001.

[5] See footnote 4 above.

[6] See footnote 1 above.

males and females combined) in the year 2050 is 82.95 years (NIPSSR 1997). Projections based on the pattern of reductions in death rates in Japan since 1950 result in a life expectancy some 8 years longer, 90.91 years, with a 90% confidence range from 87.64 to 94.18 years (Tuljapurkar et al. 2000).

Progress in reducing mortality might be systematically slower than in the past. Officials could produce low life-expectancy scenarios to capture this eventuality. Then, however, they should also publish high scenarios that recognize that biomedical research may yield unprecedented increases in survival. Given the extraordinary linearity of the increase in best-practice life expectancy and given the ludicrous record of specious life-expectancy limits, the central forecast should be based on the long-term trend of sustained progress in reducing mortality.

Continuing Belief in Looming Limits

Faith in proximate longevity limits endures, sustained by *ex cathedra* pronouncements and mutual citations. In their quest to impose a cap on average longevity, students of mortality ignored essential research questions. Major changes in life expectancy hinge on improvements in survival at advanced ages, but comprehensive analysis of the remarkable reductions since the mid-20th century in death rates after age 80 first flourished in the 1990s (Kannisto et al. 1994; Kannisto 1996; Vaupel 1997; Wilmoth et al. 2000; Vaupel et al. 1998). Hypothesized biological barriers to longer lifespans also first received systematic attention (and refutation) a decade ago (Vaupel et al. 1998; Carey et al. 1992; Curtsinger et al. 1992; Wachter and Finch 1997; Carey and Judge 2001). The impact of continuing mortality improvements on life expectancy attracted empirical and theoretical attention in the late 1980s, with refined methods developed over the past decade (Lee and Carter 1992; Alho 1998; Tuljapurkar et al. 2000; Vaupel 1986; Vaupel and Canudas Romo 2000). It now appears plausible that life expectancy in several post-industrial countries may approach or exceed 90 by the middle of this century (Tuljapurkar et al. 2000; Wilmoth 1998) and that half the girls born today in countries such as France and Japan may become centenarians (Vaupel 1998; Vaupel 1997).

If the expectation of life in developed countries were approaching an imminent maximum, then the pace of improvement in mortality in the countries with the highest life expectancies would be slower than the pace in countries with shorter life expectancies. There is, however, no correlation between the level of life expectancy and the pace of improvement (Kannisto et al. 1994; Wilmoth 1997). Indeed, in the current life-expectancy leader, Japan, death rates are falling exceptionally rapidly. Furthermore, as life expectancy rose over the course of the 20th century, the pace of mortality improvement at older ages *accelerated* (Kannisto et al. 1994; Kannisto 1996; Vaupel 1997, Wilmoth et al. 2000; Wilmoth 1997). Even after age 100, death rates are falling (Kannisto 1996; Vaupel 1997; Wilmoth et al. 2000). Female life expectancy is higher than the male level in long-lived countries, but female life expectancy is increasingly somewhat more rapidly (Kannisto et al. 1994; Wilmoth 1997).

Olshansky et al. (2001) emphasize a theoretical barrier: "entropy in the life table means that small but equal incremental gains in life expectancy require progressively larger reductions in mortality…. Projections based on biodemographic principles that recognize the underlying biology within the life table would lead to more realistic forecasts of life expectancy that reflect the demographic reality of entropy in the life table." Entropy in the life table is merely the statistic

$$\int s(a,t)\ln s(a,t)da \Big/ \int s(a,t)da\,,$$

where $s(a,t)$ is the probability of surviving from birth to age a at age-specific death rates prevailing at time t. Contrary to Olshansky et al.'s claim, in countries with long life expectancies a continuing rate of decline in age-specific death rates of N percent per year will increase life expectancy at birth by about N years per decade (Vaupel 1986; Vaupel and Canudas Romo 2000). Note that steady *rates* of change in mortality levels produce steady *absolute* increases in life expectancy: this relationship may underlie the linear trend of record life expectancy. In any case, valid biodemographic principles impose no insurmountable barriers to longer lives (Vaupel et al. 1998; Carey et al. 1992; Curtsinger et al. 1992; Wachter and Finch 1997; Carey and Judge 2001).

In sum, the past decade of mortality research has refuted the empirical misconceptions and purported theories that underlie the belief that the expectation of life cannot rise much further. In this article we have added a further line of cogent evidence. If life expectancy were close to its maximum, then the increase in the record expectation of life should be slowing. It is not. For 160 years, best-performance life expectancy has steadily increased by a quarter of a year per year, an extraordinary constancy of human achievement.

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Mortality Forecasts and Linear Life Expectancy Trends*

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Introduction

Two important articles on aggregate mortality trends were published in the spring of 2002, with important implications for our perspective on modeling, forecasting, and interpreting mortality trends. One such article was Oeppen and Vaupel (2002, henceforth OV), which shows a remarkable linear trend in the female life expectancy (at birth, period basis) of the national population with the highest value for this variable from 1840 to 2000. Of course the set of nations reporting credible life expectancy values has greatly expanded over this period, but that is unlikely to have mattered much for the results. Over this entire 160-year period, the record life expectancy consistently increased by 0.24 years of life per calendar year of time, or at the rate of 24 years per century. Extrapolation would lead us to expect a female life expectancy of around 108 years at the end of the 21st century.

A closely related article by White (2002) finds a linear trend in sexes-combined life expectancy for 21 industrial nations from 1955 to 1995, with an increase of 0.21 years of life per calendar year. White also finds that a linear trend in life expectancy gives a better fit to the experience of almost all the individual countries than does a linear trend in the age-standardized death rate, or the log of the age standardized death rate. He also found that when a quadratic time trend was fitted to the standardized rates, the coefficient on the squared term was significantly positive, indicating that the rate of improvement has been accelerating.

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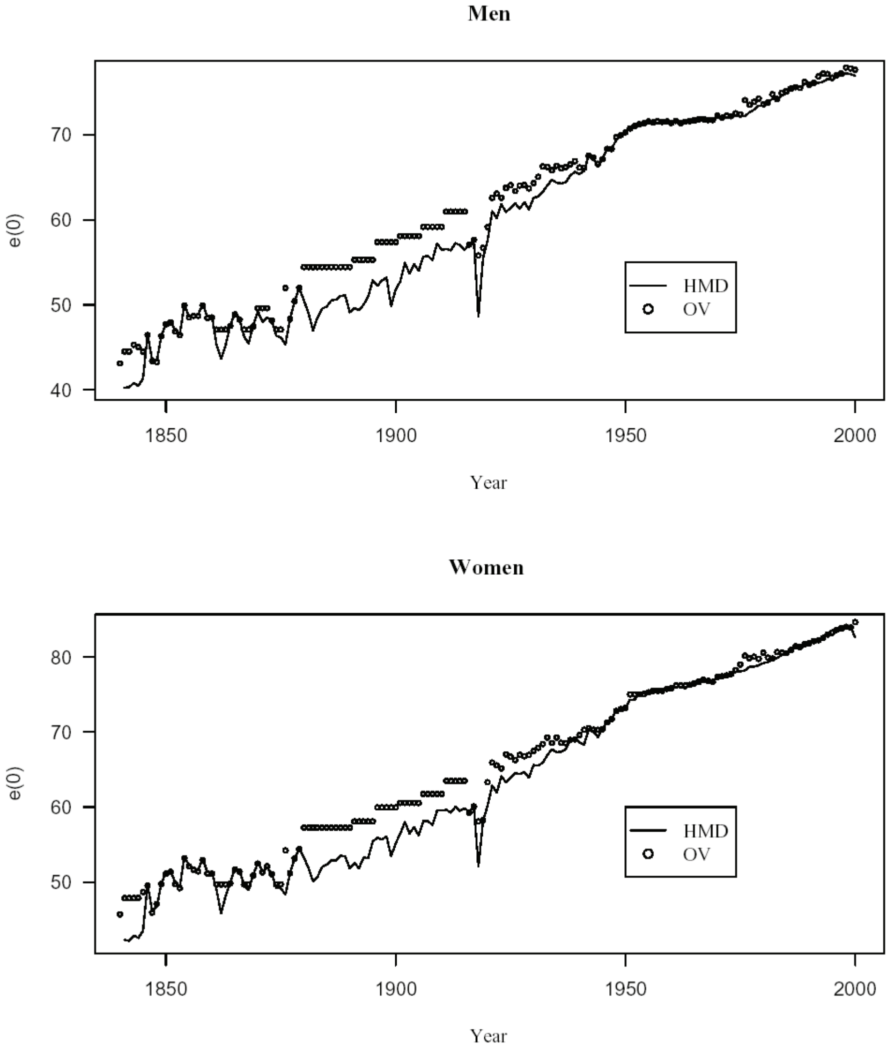
* Research for this paper was funded by a grant from NIA, R37-AG11761. Tim Miller carried out all computations for this paper. Monique Verrier provided editorial assistance. I am grateful to workshop participants for helpful comments on an earlier draft.

Both OV and White discuss the processes of catch-up and convergence. OV notes that some countries converge toward the leader (e.g. Japan), some have moved away from it (e.g. the US in recent decades), and some move more or less parallel to it. White finds that nations experience more rapid e_0 gains when they are farther below the international average, and conversely, and therefore tend to converge toward the average. The variance across countries has diminished markedly over the forty years. However, there has been no tendency for the rate of increase of average e_0 to slow down. Based on the current position of the US, which is somewhat below the average (just as OV shows that the US is below the record line), White predicts that e_0 will grow a bit more rapidly than the average rate of 0.21 years per year, perhaps at 0.22 years per year. At this rate, the US would reach e_0=83.3 in 2030—about 1.5 years above the Lee-Carter (1992) forecast, and about 3.8 years above the Social Security Administration (2002) projection for that year. Extrapolation of the linear trend in either OV or White generates more rapid gains in future longevity than are foreseen by Lee-Carter (1992, henceforth LC), which projects increases of 0.144 years per year between now and 2030. This is only two-thirds as fast as 0.22 years per year in White, and 0.23 years per year in OV (averaging the female and male rates for OV).

Two major points are made in both articles. First, life expectancy (record or average) appears to have changed linearly over long periods of time. Second, national mortality trends should be viewed in a larger international context rather than being analyzed and projected individually. In this paper I will discuss both these points, and conclude with suggestions for incorporating them in forecasting methods. I will draw on the Human Mortality Database or HMD (at http://www.mortality.org/), to fit various models.

Figure 1 plots the OV maximum life expectancy together with that of the HMD and we see that they sometimes coincide, and sometimes the OV record exceeds the HMD, which includes fewer countries.

Figure 1 Record life expectancy, by sex, from Oeppen-Vaupel and the Human Mortality Database, 1840 to 2000



Linear Change in Life Expectancy over Long Historical Periods

Before reading the OV article, I had expected that the trajectory of record life expectancy over the past two centuries would have a tilted S shape, in which life expectancy began at first to increase slowly, then accelerated, and then decelerated in the second half of the 20th century. If we go back far enough in time, we know that life expectancy had no systematic trend at all, although there might have been long fluctuations. We also can be pretty sure that initial gains in life expectancy, once the trend began, were slow. Based on the OV results, it appears that these portions of the history occurred out of our sight, before the start date of 1840. Indeed, Figure 5 in the OV Supplementary Materials on the Science Web site plots English life expectancy over a longer period, and its trajectory conforms to this description.

OV do not actually test or explore the constancy of the slope for record life expectancy, so it is worth examining this point more carefully here. As a start, we can compute the average rates of life expectancy increase for the OV data by sex and sub-period, as follows:

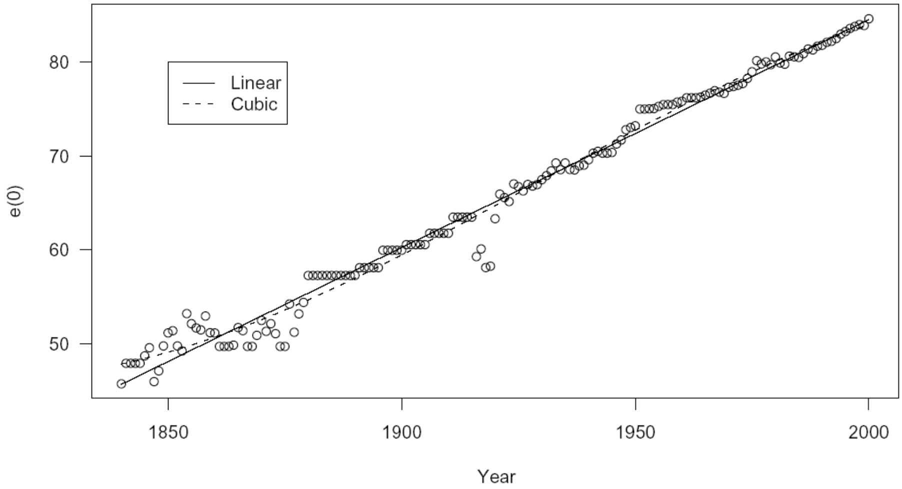
Average Annual Rates of Decline of Record e_0 By Subperiod

	Females	Males	Average
1840-1900	0.24	0.24	0.24
1900-1950	0.27	0.26	0.27
1950-2000	0.23	0.15	0.19

From this we see that the regularity of the linear decline is not quite as strong as it appears from the striking figure in OV. For males in particular, there has been a noticeable deceleration over the past 50 years. For both sexes, there is a hint of the S shaped path that I had expected to see.

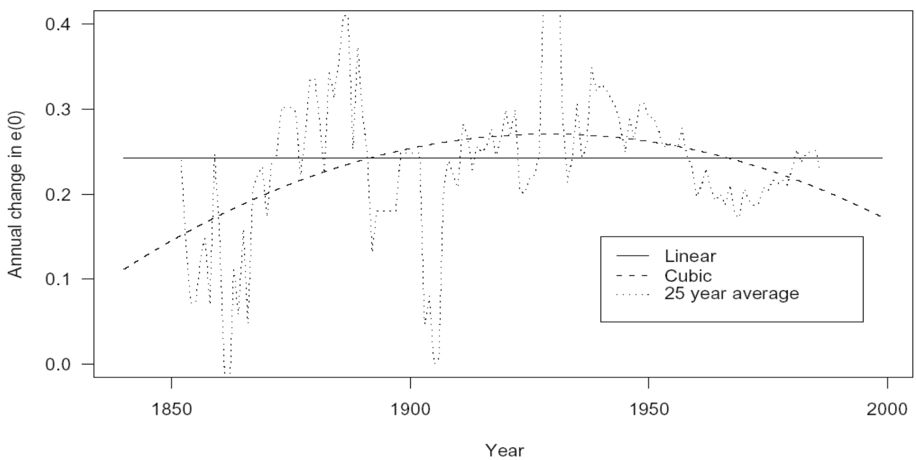
I have taken two more simple steps. First, I fitted a cubic polynomial to the data, and found that all three terms were significantly different than zero. The fitted curve, as shown in Figure 2 for females, does have a slight S-shape. To see more clearly the implied rate of change, I plot the first derivative of the polynomial for females in Figure 3. This suggests that the rate of change in fact increased substantially, more than doubling from 1840 to 1925 or so, and then substantially declining again thereafter, challenging the linear interpretation of the OV plot. Second, I calculated a twenty-five-year moving average of the annual pace of increase for females, and this also is plotted in Figure 3.

Figure 2 Linear and cubic trends fitted to the Oeppen-Vaupel record female life expectancy, 1840-2000



This less severe smoothing of the rate of change cautions us against drawing any firm conclusions from the data about linearity or nonlinearity. A case could be made for either.

Figure 3 Rate of change in female life expectancy calculated from linear and cubic fits to Oeppen-Vaupel record and 25-year moving average of change in record



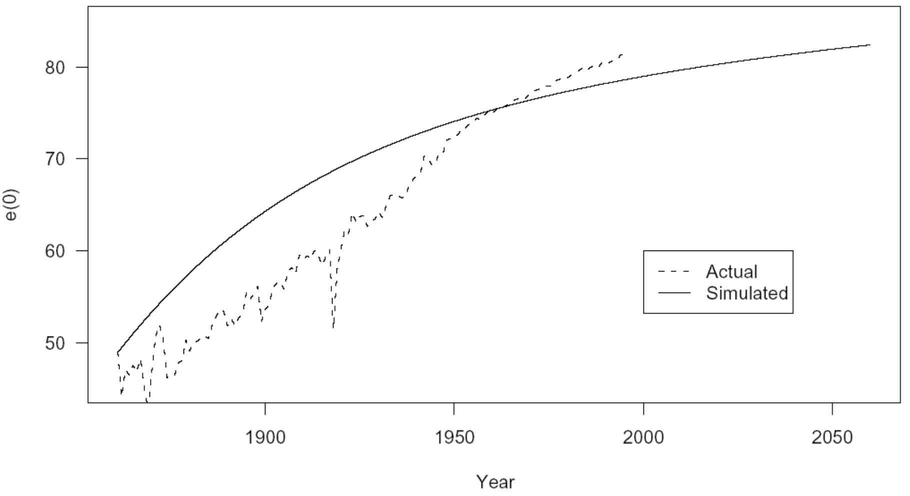
If we accept that the OV trajectory is strikingly close to linear, then we are led to ponder why the record life expectancy might have risen in this way. After considerable thought, I find I have little useful to contribute on this important question. I find I am equally unable to explain the relative constancy of age-specific proportional rates of mortality decline, as summarized by the trend in the Lee-Carter (1992) k for the US since 1900, and the G7 countries since 1950 (Tuljapurkar et al. 2000).

Of the two striking regularities, linear life expectancy trends and constant rate of decline of age-specific mortality, it is the linearity of life expectancy increase which I find most puzzling. In my mind, the risks of death (that is, the force of mortality or death rates, by age) are the fundamental aspect of mortality which we should model and interpret. One view, perhaps an incorrect view, is that period life expectancy is just a very particular and highly nonlinear summary measure, with little or no causal significance. If age-specific death rates (ASDRs) decline at constant exponential rates, then life expectancy will rise at a declining rate, at least for a long time.

This point is worth elaborating because OV, in the Supplementary Materials on the Science Web site, say: "Note that steady rates of change in mortality levels produce steady, absolute increases in life expectancy: This relationship may underlie the linear trend of record life expectancy." I agree that ultimately, it is likely that life expectancy would rise linearly, once death rates below the ages which obey Gompertz's Law have fallen to near zero, as Vaupel (1986) has pointed out. If θ is the Gompertz parameter (rate of increase of mortality with age in a period life table or cohort life table) and ρ is the annual rate of decline over time in mortality at all ages above, say, 50, then the rate of increase of e_{50} will be ρ/θ years per year (Vaupel 1986). However, there is substantial mortality at younger ages before Gompertz's Law applies, particularly in the 19th century. There we would expect a "steady" rate of decline in death rates to lead to a declining rate of increase in life expectancy.

These points are illustrated in Figure 4, based on Swedish mortality experience. The average exponential rate of decline is calculated for each age-specific death rate for the period 1861 to 1961. This rate of decline is then applied to the initial age-specific death rates, and used to simulate them forward for 200 years. The resulting life expectancy is plotted in Figure 3 along with the actual life expectancy. It can be seen that the simulated life expectancy trajectory is highly nonlinear, and its pace of improvement decelerates.

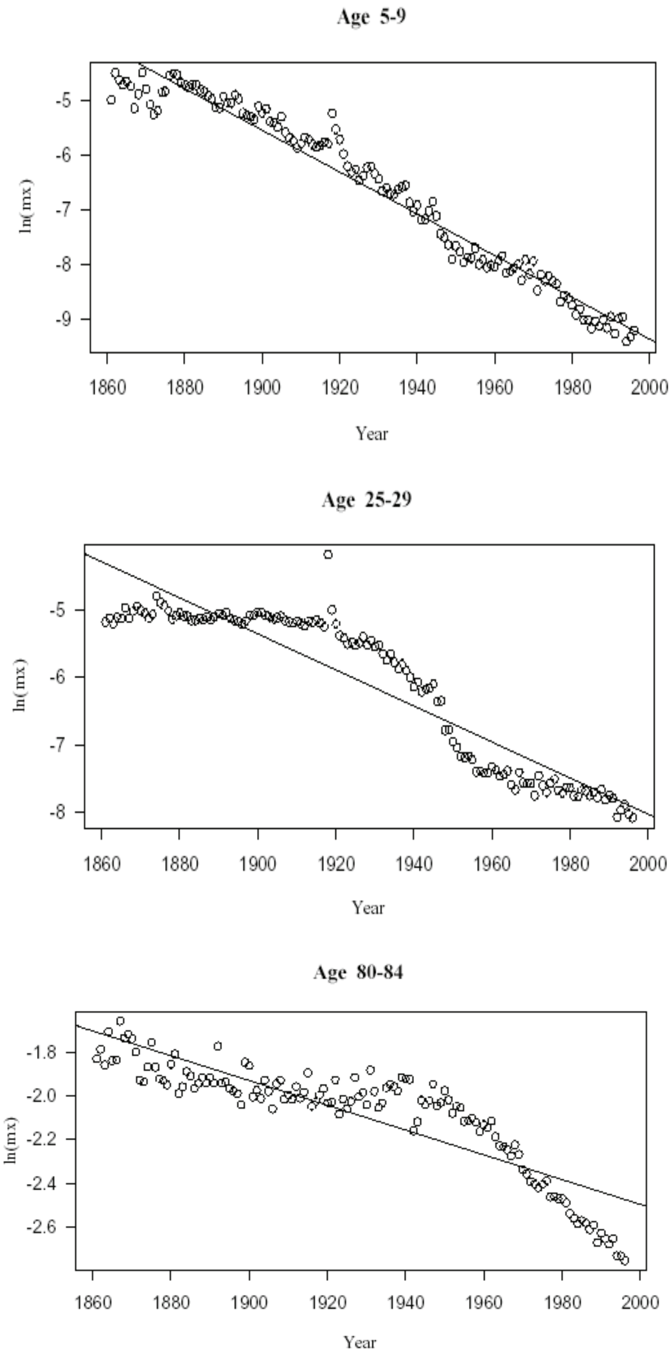
Figure 4 Actual and simulated Swedish female life expectancy assuming constant proportional rates of decline for age-specific death rates, at average rates for 1861-1961



As time passes, the gains in life expectancy become more nearly linear, and for the last fifty years, are quite close to linear. By construction, the lines cross in 1961. Figure 4 shows that the constant exponential rates of decline in age-specific death rates could not account for the linearity of the increase in record e_0 since 1840.

When we look at the trajectories of the logs of the Swedish ASDRs from 1861 to 2000, they appear very far from linear, even if we restrict attention to the last fifty years, see Figure 5 for selected rates. Most rates decline rapidly in some periods, and slowly in others, with patterns varying across the age span. One would not think to characterize these patterns as showing a constant rate of decline at each age. Yet this is a period over which the Lee-Carter model does a good job of fitting life expectancy, and projecting it within sample (Lee and Miller 2001). Evidently, the Lee-Carter method succeeds by picking out average tendencies from among a welter of variation, not by describing strong real-world regularities.

Figure 5 Log of selected age-specific death rates for Swedish females, 1861-2000, showing irregular rates of decline



What is Fundamental, Age at Death or Risk of Death?

The OV and White findings challenge the view that risks of death are fundamental, and age at death is derivative. If life expectancy (e_0) changes linearly, then rate of decline of death rates must be nonlinear, and in particular must be accelerating for at least some ages, as found by White for many of the 21 countries he analyzed. How can we reconcile the linearity of the change in e_0 with the fact that when LC models are fit, they have almost always revealed linear changes in k over rather long periods, such as a century in the US? To focus on the US case, there are two explanations. First, as the second figure in OV makes clear, over the 20th century the US first approached the record line, then briefly was close to being the leader, and finally fell away from the line starting in the 1960s. (This falling away very likely reflects the relatively early uptake of smoking in the US.) Since the trajectory of US e_0 in fact had the shape we would expect with a constant rate of decline in ASDRs, perhaps there is no puzzle to explain for the US case. But can the same story hold for all the G7 countries analyzed and projected by Tuljapurkar et al. (2000)? This brings us to the second explanation, which is that contrary to the LC assumptions, the rates of decline have not been constant for each age, which is to say that the LC b_x coefficients have not been constant over the sample period. Instead, they have changed shape between the first half of the century, when the mortality decline was much more rapid for the young than for the old, and the second half, when there is little difference among the rates of decline above age 20 or so. Just when the ASDRs of the young became so low that their further decline could contribute little to increasing e_0, the rates of decline at the older ages began to accelerate, as noted by Horiuchi and Wilmoth (1998). This tilting of the b_x schedule has meant that a given rate of decline of k can produce more rapid rates of increase in e_0 than would have been the case with the old b_x schedule. The tilting of the b_x schedule is shown for the US in Figure 6, and for Sweden, France, Canada, and Japan in Figure 7. In each case the annual rate of decline for mortality is plotted by age for the first and second halves of the 20th century, except for Japan, for which the break point is 1975.

Figure 6 **Average annual reductions in age-specific death rates, US (sexes combined), showing the changing age pattern of decline**

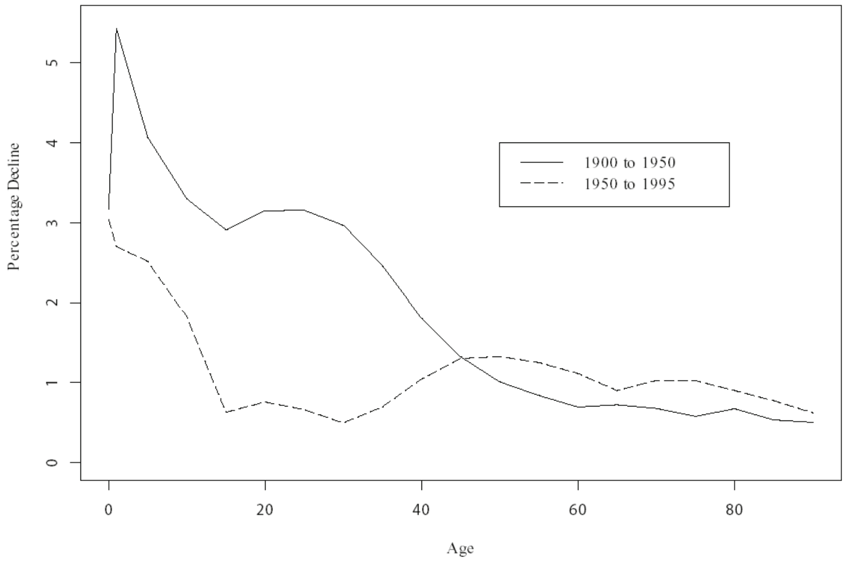
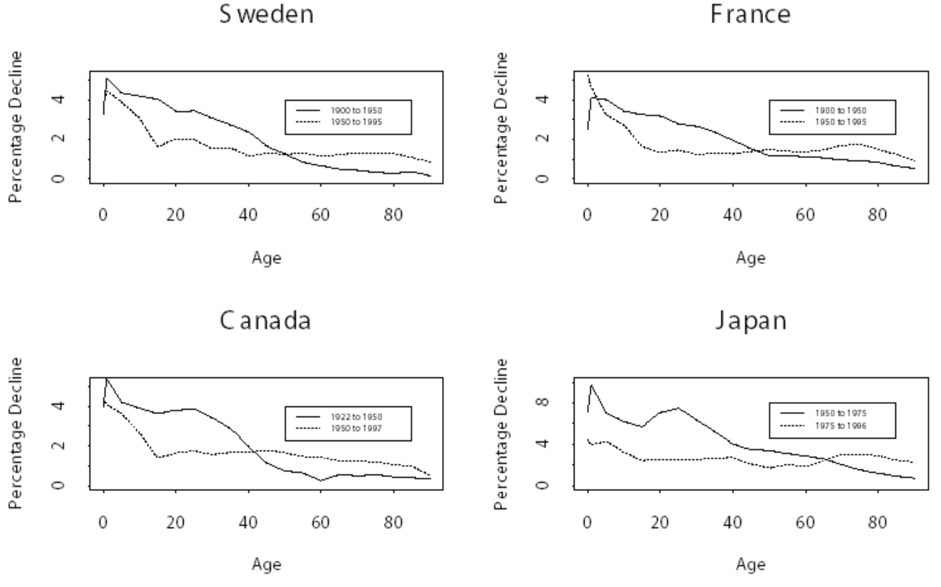


Figure 7 **Average annual reductions in age-specific death rates, selected low mortality countries (sexes combined), showing the changing age pattern of decline**



Using These Findings to Improve Mortality Forecasts

The first question is whether or not we should expect record e_0 to continue to increase at this rate in the future, and if so for how long? Since I do not understand why this linearity has occurred in the past, I have no reason to think it should, or should not, continue in the future. The regularity in the past invites the forecaster to assume it will continue in the future, at least for a while. Suppose then that we do assume it will continue. How can we use that assumption to mold our forecasts? This line of thinking leads us unavoidably to consider national mortality change in an international context, to which we now turn.

Considering National Mortality Change in an International Context

Let E(t) be the best-practice life expectancy at time t. It is imperfectly estimated by the OV record series. The White average e_0 measure reflects a different concept. Let $e_i(t)$ be actual life expectancy at birth for country i in year t. I will consider a number of possible kinds of models describing the relation between changes in $e_i(t)$ and E(t). I will write the equations in continuous time, but they are readily rewritten for discrete annual changes for purposes of estimation.

First Category of Models: All Countries Are Structurally Similar, But Start at Different Levels

$$de_i(t)/dt = \phi + \alpha\left(E(t) - e_i(t)\right) + \varepsilon_i(t) \qquad (0.1)$$

Here, life expectancy tends to increase at some constant rate ϕ, and in addition it tends to move a proportion α toward the best practice level (record level) E(t) each year. It is also subject to a disturbance ε which could move it toward or away from this trajectory. This specification is consistent with the equation estimated by White. In estimation, I allow the $\varepsilon_i(t)$ for each country to be autocorrelated ($\varepsilon_i(t) = \rho\varepsilon_i(t-1) + \eta_i(t)$) with all countries sharing the same autocorrelation coefficient ρ.

I fit this and later models to life expectancy series for 18 countries with relatively low mortality, with data drawn from the Human Mortality Database (HMD) at http://www.mortality.org/. The data series are of varying historical depth, with the shortest covering 29 years and the longest 159 years. Models are fit using an unbalanced design, so that the full range of data could be exploited. However, the estimation range is sometimes restricted to the period since 1900.

Table 1a reports estimates of α for females and for males, based on model specifications with and without autocorrelated errors, and using the OV record.

Table 1a Estimated rate of convergence of national life expectancy to Oeppen-Vaupel record level in eighteen countries of the Human Database (Equation 0.1)

	Females, 1841-1999	Females, 1900-1999	Males, 1841-1999	Males, 1900-1999
O-V record gap (α)	0.0615** [0.0137]	0.0683** [0.0162]	0.0777** [0.0171]	0.0802** [0.0195]
Constant	0.0160 [0.0723]	0.0308 [0.0783]	-0.1368 [0.0918]	-0.1134 [0.0997]
Observations	1332	1155	1332	1155
Number of countries	18	18	18	18
Rho	-0.109	-0.126	-0.064	-0.076
R-squared	0.037	0.045	0.043	0.045

Estimates are based on panel corrected SE using Prais-Winstein regression (assuming first-order autocorrelation. SE of the coefficients are in brackets. * significant at 5%; ** significant at 1%.

In all cases α is highly significantly different than 0, with values lying between 0.06 and 0.08, indicating a tendency for the life expectancy of the countries to converge towards the leader country. The half-life of a deviation from the record level is around 10 years ($e^{-10*.07} = 0.5$). Here and throughout, results are very similar if the equation is estimated with no constant, so that the only source of life expectancy increase is catching up with the leader, or if there is no allowance for autocorrelated errors. Note that the R^2 is low at around 0.04, and that the estimated autocorrelation is negative, which is somewhat surprising. Table 1b is the same, except that it uses the HMD record life expectancy in place of OV. The results are also very similar, but with a slightly slower rate of convergence and lower R^2.

Table 1b Estimated rate of convergence of national life expectancy to the highest level in the eighteen countries of the Human Database (Equation 0.1)

	Females, 1841-1999	Females, 1900-1999	Males, 1841-1999	Males, 1900-1999
HMD record gap (α)	0.0506** [0.0117]	0.0454** [0.0130]	0.0681** [0.0163]	0.0666** [0.0180]
Constant	0.1095 [0.0639]	0.1484* [0.0696]	-0.0229 [0.0793]	-0.0024 [0.0884]
Observations	1332	1155	1332	1155
Number of countries	18	18	18	18
Rho	-0.136	-0.153	-0.092	-0.101
R-squared	0.020	0.017	0.030	0.029

Estimates are based on panel corrected SE using Prais-Winstein regression (assuming first-order autocorrrelation). SE of the coefficients are in brackets. * significant at 5%; ** significant at 1%.

Rather than taking the actual record e_0 from OV or HMD as an estimate of the target trajectory toward which life expectancy in all countries is tending, we can instead estimate the implicit unobserved target as part of fitting the model, as in the following equation:

$$de_i(t)/dt = \phi + \gamma_t D_t - \alpha e_i(t) + \varepsilon_i(t) \quad (0.2)$$

Here D_t is a period dummy for year t (else 0) and γ_t is its coefficient. γ_t/α gives the target trajectory, playing a role much like the OV record level. Results are reported in Table 2 (with estimates of γ not shown, to save space). Because the target is chosen to maximize its explanatory power, the R^2 is now much greater, while rates of convergence, α, are somewhat slower.

Table 2 Estimated rate of convergence of national life expectancy to an annual implicit target in the eighteen countries of the Human Database (Equation 0.2)

	Females, 1841-1999	Females, 1900-1999	Males, 1841-1999	Males, 1900-1999
Current e(0) (α)	0.0428** [0.0042]	0.0354** [0.0050]	0.0633** [0.0059]	0.0641** [0.0067]
Constant	2.5344** [0.2417]	3.1652** [0.2704]	3.0326** [0.3185]	4.2880** [0.3656]
Observations	1332	1155	1332	1155
Number of countries	18	18	18	18
Rho	-0.131	-0.171	-0.053	-0.045
R-squared	0.607	0.678	0.500	0.511

Estimates are based on panel corrected SE using Prais-Winstein regression (assuming first-order autocorrrelation). SE of the coefficients are in brackets. * significant at 5%; ** significant at 10%.

Figure 8 plots the estimated values of γ_t/α, corresponding to the implicit target trajectory. For comparison the record life expectancy for the HMD is also plotted. We see that the target trajectory lies above the maximum about half the time and also that the target trajectory is highly erratic, possibly with negative autocorrelation.

When life expectancy is generally above trend, as might happen in a year with a mild winter affecting many countries, for example, the regression will try to fit this by estimating a very high target value, and conversely. This will lead to an underestimate of the size of the convergence coefficient, α. To avoid these problems, it is desirable to impose a smoothness constraint of some kind on the target trajectory. Here I will take the simplest route, assuming that the target trajectory is a linear function of time, leading to the following equation:

$$de_i(t)/dt = \phi + \alpha(a + bt - e_i(t)) + \varepsilon_i(t) \quad (0.3)$$

The results are shown in Table 3. The estimated rate of convergence, α, is now slightly higher than in the first set of estimates. The rate of increase of the linear target trajectory is found by dividing the coefficient on "year" by the estimate of α, that is the coefficient on $-e_{i,0}$, which is also given in the table. The rate of increase in the target calculated in this way is slightly higher than for the record for OV or the HMD. For example, the gain per year in target e_0 estimated here for the whole period is 0.271 years per year, while in OV it is 0.243 years per year. Other comparisons are similar.

Figure 8 Estimated implicit target of convergence (Equation 0.2) in the eighteen countries of the Human Mortality Database (erratic line), compared to the HMD record life expectancy (smooth line)

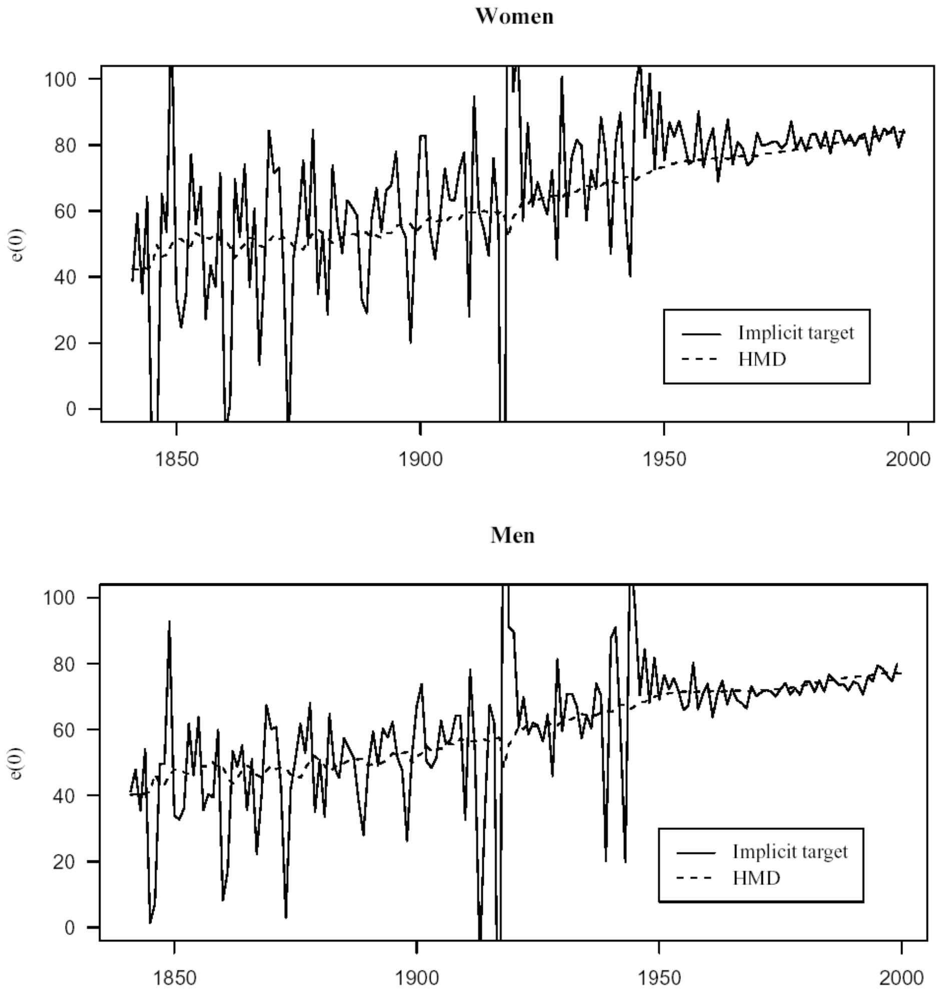


Table 3 Estimated rate of convergence of national life expectancy to a linear implicit target in the eighteen countries of the Human Database (Equation 0.3)

	Females, 1841-1999	Females, 1900-1999	Males, 1841-1999	Males, 1900-1999
Current e(0) (α)	0.0704** [0.0138]	0.0586** [0.0153]	0.0865** [0.0166]	0.0845** [0.0184]
Year	0.0191** [0.0037]	0.0129** [0.0042]	0.0204** [0.0039]	0.0168** [0.0044]
Constant	-32.1870** [6.3273]	-20.8345** [7.4209]	-34.1528** [6.6860]	-27.0685** [7.6882]
Calculated: Year/ α	0.271307	0.220137	0.235838	0.198817
Observations	1332	1155	1332	1155
Number of countries	18	18	18	18
Rho	-0.071	-0.118	-0.037	-0.055
R-squared	0.042	0.045	0.052	0.055

Estimates are based on panel corrected SE using Prais-Winstein regression (assuming first-order autocorrrelation). SE of the coefficients are in brackets. * significant at 5%; ** significant at 10%.

It is possible that countries that are twice as far from E(t) may not converge twice as quickly. To allow for this, we can add a term that is quadratic in the size of the gap (the quantity in parentheses in equation 0.2). A negative coefficient on the quadratic term would indicate that the pace of increase in e_0 is less than proportionate to the size of the gap, and a positive coefficient that it is more than proportionate.

$$de_i(t)/dt = \phi + \alpha\left(E(t) - e_i(t)\right) + \beta\left(E(t) - e_i(t)\right)^2 + \varepsilon_i(t) \qquad (0.4)$$

The results of estimating this specification are given in Table 4a and 4b, and are unambiguous: In every case, the coefficient on the quadratic, β, is highly significantly greater than zero, and the coefficient on the linear term is negative. In order to interpret these coefficients, I show in Figure 9 the derivative of the change in $e_i(t)$ with respect to the size of the gap, E(t) – ei(t).

Table 4a Estimated quadratic rate of convergence of national life expectancy to Oeppen-Vaupel record level in the eighteen countries of the Human Database (Equation 0.3)

	Females, 1841-1999	Females, 1900-1999	Males, 1841-1999	Males, 1900-1999
O-V record gap (α)	-0.0372 [0.0338]	-0.0659 [0.0366]	-0.0518 [0.0308]	-0.0586 [0.0334]
(O-V record gap)^2 (β)	0.0088** [0.0028]	0.0124** [0.0031]	0.0072** [0.0020]	0.0073** [0.0020]
Constant	0.1871 [0.0971]	0.2635* [0.1036]	0.2132* [0.1013]	0.2648* [0.1103]
Observations	1332	1155	1332	1155
Number of countries	18	18	18	18
Rho	-0.118	-0.153	-0.099	-0.114
R-squared	0.047	0.068	0.074	0.080

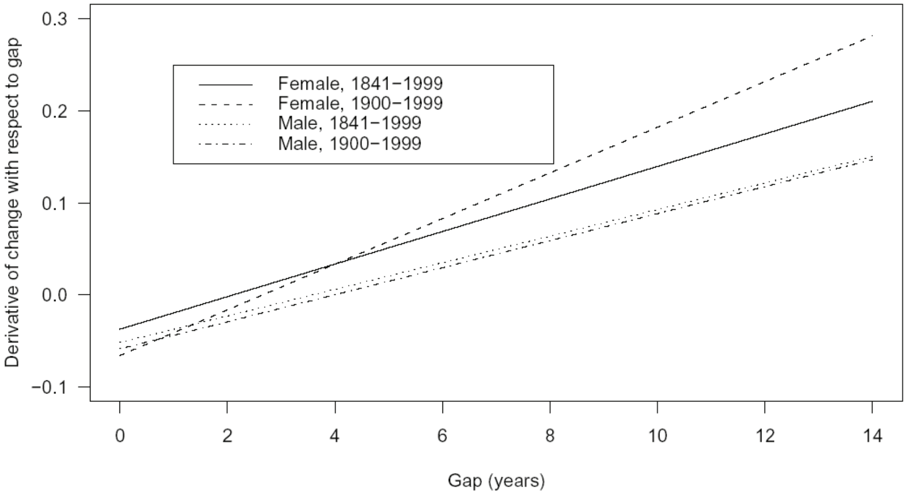
Estimates are based on panel corrected SE using Prais-Winstein regression (assuming first-order autocorrrelation). SE of the coefficients are in brackets. * significant at 5%; ** significant at 10%.

Table 4b Estimated quadratic rate of convergence of national life expectancy to HMD record level in the eighteen countries of the Human Database (Equation 0.3)

	Females, 1841-1999	Females, 1900-1999	Males, 1841-1999	Males, 1900-1999
HMD record gap (α)	-0.0583* [0.0284]	-0.0687* [0.0292]	-0.0611* [0.0269]	-0.0809** [0.0296]
(HMD record gap)^2 (β)	0.0119** [0.0029]	0.0125** [0.0029]	0.082** [0.0021]	0.0089** [0.0022]
Constant	0.2466** [0.0756]	-20.8345** [0.0819]	-34.1528** [0.0803]	-27.0685** [0.0911]
Observations	1332	1155	1332	1155
Number of countries	18	18	18	18
Rho	-0.148	-0.174	-0.110	-0.110
R-squared	0.036	0.038	0.065	0.072

Estimates are based on panel corrected SE using Prais-Winstein regression (assuming first-order autocorrrelation). SE of the coefficients are in brackets. * significant at 5%; ** significant at 10%.

Figure 9 Derivative of quadratic convergence to the Oeppen-Vaupel target: how the proportional effect of a gap increases with the size of the gap



{Note: 90% of male gaps and 95% of female gaps are below 8.}

Under the linear specification used earlier, this plot would be a straight line with height α. Here, however, we see that all the lines slope decisively upward to the right, indicating that the rate of convergence increases more than proportionately with the size of the gap. The initial negative values most likely reflect the limitations of the quadratic specification, rather than a true tendency of the rate of change to decline as the gap increases in this low range. Most of the gaps, 90 to 95% of them, are less than eight years. Only a few fall outside that range, and are subject to the higher sensitivities to the right on the plot. In future work it should be possible to examine the nonlinearity of the response better, drawing on data for Third World countries with higher mortality, but these have not yet been added to the HMD.

Extensions

Heterogeneous Targets

If the foregoing models were the whole story, we would expect the life expectancies of countries to be distributed randomly around E(t), since their mortality would have had decades or centuries in which to converge to E(t) under the influences described in the equations. But of course, this is not the case. A more realistic model would take into account the heterogeneity of international experience, by incorporating additional factors that influence the level toward which each country's e_0 converges, which may not be the best practice level. I will call this modified target the idiosyncratic target. We can take it to equal E(t)+ πX(t), where X is a vector of relevant factors and π is a vector of coefficients. X includes relevant variables such as per capita income, educational attainment, nutritional measures, dietary measures, smoking behavior, and geographic/climatic conditions. πX expresses a deviation from the best practice level. Over time, E(t) rises. If X remained constant, the target level would nonetheless increase with E(t). More likely, πX also increases, indicating an additional source of increase in the target level of e_0. πX could capture influences like those included in Preston's (1980) analysis, in which he fit socioeconomic models to international cross-sections of life expectancy, and then decomposed gains in life expectancy into movements along the πX curve with economic development, and upward shifts in the whole equation, which would here be reflected in the combination of convergence and a common growth rate, ϕ. The ε shocks could reflect political, military, weather, or epidemiological factors of a transitory nature. This model would be:

$$de_i(t)/dt = \phi + \alpha\left(E(t) + \pi X_{i,t} - e_i(t)\right) + \varepsilon_i(t) \qquad (0.5)$$

Once again, it would be possible to estimate E(t) as part of fitting the model, either unconstrained or constrained to have a linear trajectory. If estimated in this way it will reflect changes in the target net of socioeconomic progress, a concept closer to Preston's residual improvement of life expectancy. Country i will have a target or equilibrium life expectancy in year t of E(t) + $\pi X_{i,t}$ so heterogeneity in equilibria is now incorporated. Countries that are poor, smoke, eat a high cholesterol diet, have low education, or perhaps have a tropical climate, will tend towards lower levels of life expectancy.

Heterogeneous Rates of Convergence

It is also possible that different countries will have different rates of convergence, α. For isolated countries, or perhaps for very poor ones, or ones with very little transportation or communication infrastructure, α may be smaller. We can take this into account by making α a function of a set of variables Z.

$$de_i(t)/dt = \phi + \left(\alpha + \delta Z_{i,t}\right)\left(E(t) + \pi X_{i,t} - e_i(t)\right) + \varepsilon_i(t) \qquad (0.6)$$

Z would include factors indicating the degree of integration of country i in the global community, and perhaps other factors bearing on the strength of government and the communications and transportation infrastructure in the country. It might be difficult to identify factors that belonged in Z rather than in X.

Forecasting Mortality

Let us assume that the linear trend in record or average life expectancy will continue. Then the next steps are straightforward. We use the linear trend to project the record life expectancy (or the target trend that was estimated as part of the convergence model). We will know the current life expectancy for a particular country of interest. We can use the appropriate or preferred equation for de_t/dt to estimate e_0 one year later, and then continue recursively. The projected e_0 will gradually approach the projected linear trend.

This procedure could be improved by using a model version which allowed for some heterogeneity, as in equations (.5) and (.6). Not all countries will approach the same trend line, but each should approach a trajectory that is parallel to it. In these specifications, we would also have to consider the advisability of projecting changes in the X and Z variables, and methods for doing so.

The assumption of a pure linear trend could also be questioned, dropping the initial assumption. The central tendency (record, average, or other) could be modeled as a stochastic time series, and forecasted in that way. That could certainly be done for the γ series, for example.

In general, the approach of forecasting mortality for individual countries in reference to the international context is very appealing, and I believe it is the natural way to go in future work. Whether this approach is applied to life expectancy itself, or to a Lee-Carter type k, or in some other way, will have to be settled by further research. In the meantime, these recent papers, and particularly OV, challenge our current perceptions of mortality change and expectations about future trends.

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Forecasting Life Expectancy: A Statistical Look at Model Choice and Use of Auxiliary Series

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Why Forecast Life Expectancy?

Let $\mu(x,t)$ be the hazard (or force) of mortality in age x at time t. Define p(x,t) as the probability of surviving to age x, under the hazards of time t, or

$$p(x,t) = \exp(-\int_0^x \mu(y,t)dy).$$

Then, the expectation of the remaining life time in age x≥0, equals

$$e_x(t) = \int_0^\infty p(x+y,t)dy \,/\, p(x,t).$$

These are synthetic period measures, i.e., they are intended to summarize the chances of survival at time t. Life expectancy at birth, $e_0(t)$, is the most frequently used summary measure. Despite their popularity life expectancies are not directly used in cohort-component population forecasting. Instead, proportions of type

$$p(x+1)/p(x) = \exp(-\Lambda_x(t)),$$

where $\Lambda_x(t)$ is the increment of the cumulative hazard in age [x, x + 1), are used for proportions of survivors from exact age x to exact age x + 1. Similarly, in the computation of present values of annuities, for example, a cohort perspective is necessary. In that case, the more relevant concept is the remaining life time of a person alive at exact age x≥0, at time t, which equals

$$c_x(t) = \int_0^\infty \exp(-\int_0^y \mu(x+u,t+u)du)dy.$$

Since mortality has typically declined, we expect that $e_x(t) \leq c_x(t)$. We note that even if life expectancies $e_x(t)$ have considerable descriptive value, they are of limited direct usefulness in population forecasting.

Taken together the values of $e_x(t)$ do determine the hazards $\mu(x,t)$ for a given t, but if only $e_0(t)$ is known, then infinitely many patterns $\mu(x,t)$'s would produce the same value $e_0(t)$. In special cases, such as a proportional hazards model ($\mu(x,t) = \mu(x)g(t)$ with $\mu(x)$ known) or a log-bilinear model of the Lee-Carter type ($\mu(x,t) = a(x) + b(x)g(t)$ with a(x) and b(x) known), a one-to-one correspondence exists (e.g., Alho 1989). In these cases forecasting $e_0(t)$ leads directly to estimates of age-specific mortality, but the assumption of known multipliers is strong. Given that the multipliers may change over time, it is not clear that this would, in practice, lead to a more accurate forecast of mortality hazards than forecasting the latter directly.

On the other hand, $e_0(t)$ might perform as an "auxiliary measure" if it behaves in a more time-invariant manner (e.g., Törnqvist 1949) than the age-specific series themselves. The recent finding of Oeppen and Vaupel (2002), in which the so-called best-practice life expectancy, i.e., the life expectancy of the country that is the highest at any given time, was shown to have evolved almost linearly for 160 years, points to this possibility. The first purpose of this paper is to establish the empirical relationship of the best-practice life expectancy to country-specific life expectancies in selected industrialized countries, during the latter part of the 1900's. Simple regression techniques will be used. The second purpose is to examine the statistical underpinnings of using best practice life expectancy as an auxiliary series for the prediction of the country-specific life expectancies.

Changes in Life Expectancy in 19 Industrialized Countries in 1950-2000

Oeppen and Vaupel (2002) show that the best practice life expectancy for females has followed remarkably well ($R^2 = 0.99$) the model:

$$\tilde{e}_0(t) = 45 + (t - 1840)/4,$$

for $t \geq 1840$. Could this "invariant" be used as an auxiliary series to improve accuracy?

To examine this question empirically we have collected data on female life expectancies for 14 European countries, Australia, Canada, Japan, New Zealand, and the United States, for the periods 1950-55, 1955-1960,..., 1995-2000 (United Nations 2000). For ease of exposition, we denote the five year periods as t = 1953, 1958,..., 1998. Denoting life expectancy at birth in country i = 1, 2,..., 19 by $e_{0,i}(t)$ we define the variables of interest as:

early life expectancy $LE53(i) = e_{0,i}(1953)$;

later life expectancy $LE78(i) = e_{0,i}(1978)$;

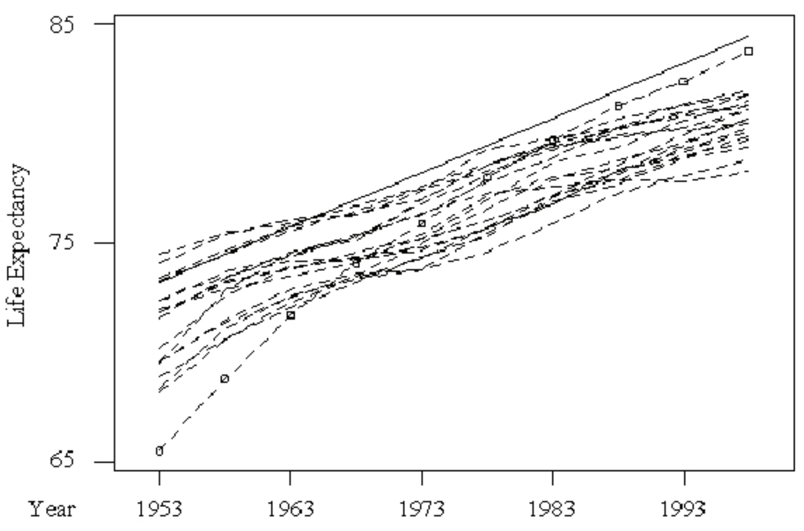
deviance $Dev(i) = \tilde{e}_0(t) - e_{0,i}(t)$,

early annual improvement $Early(i) = (e_{0,i}(1978) - e_{0,i}(1953))/25$,

later annual improvement $Later(i) = (e_{0,i}(1998) - e_{0,i}(1978))/20$.

Figure 1 shows the life expectancies of the 19 countries together with the best practice line. Two facts stand out. First, Japan has behaved in a radically different manner from the rest of the countries. A formal test using Mahalanobis' distance (e.g., Afifi and Azen 1979, 282) also suggests that Japan is an outlier with a P-value < 0.001. Second, all other countries appear to gradually veer off below the line. It is this set of 18 countries that we will be primarily concerned with in this paper.

Figure 1 **Life expectancies in 19 countries (Japan with a circle), and the best practice life expectancy (solid)**



To quantify the latter effect the following descriptive statistics were calculated for the 18 countries (Japan omitted):

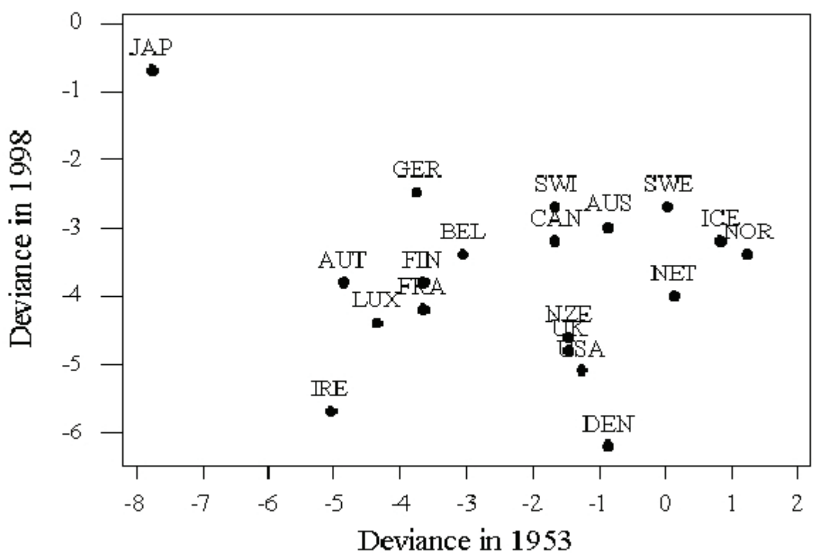
Variable	N	Mean	Median	StDev
Dev53	18	-1.956	-1.550	1.942
Dev98	18	-3.928	-3.800	1.050

Thus, the 18 countries that were an average of 2 years behind the best country in the early 1950's (the best country being a member of the set of 18!), have fallen 2 years further behind in approximately 45 years. We also see that the spread among the 18 countries has decreased by a half.

For reference later, we note that *had* one forecasted life expectancy 45 years ahead in the first part of the 1950's, by assuming that life expectancy will increase at the same rate as best practice life expectancy, then the average error in the 18 countries would have been 2 years.

Figure 2, which includes Japan, illustrates how different Japan is. However, it also reveals other interesting changes. For example, Denmark that was just under the best-practice line in the early 1950's has fallen a full *six* years behind. The neighboring countries of Iceland, Norway and Sweden also fell behind, but by "three years only". Thus, Denmark has, during a half a century, gradually distanced itself from the neighbors.

Figure 2 Deviances in 1953 and 1998



To examine country-specific changes more closely, we regressed the early improvement (Early) on life expectancy in the early 1950's (LE53), among the 18 countries. The estimated coefficients are:

Predictor	Coef	SE Coef	T	P
Constant	1.4708	0.3257	4.52	0.000
LE53	-0.017432	0.004537	-3.82	0.002

with R^2 = 47.7%. Regressing later improvement (Later) on life expectancy in the late 1970's (LE78) yielded:

Predictor	Coef	SE Coef	T	P
Constant	2.5127	0.6091	4.13	0.001
LE78	-0.030312	0.007909	-3.83	0.001

with R^2 = 47.9%. Figures 3 and 4 illustrate the same phenomenon. We find that in both cases the countries that had high life expectancy grew, on average, slower than those with low life expectancy. The well-known phenomenon of "regression to the mean" explains part of the changes, but we cannot ignore the possibility that there would be a tendency of having a lower rate of improvement when starting from a high value.

Figure 3 Early annual improvements as a function of life expectancy in 1953

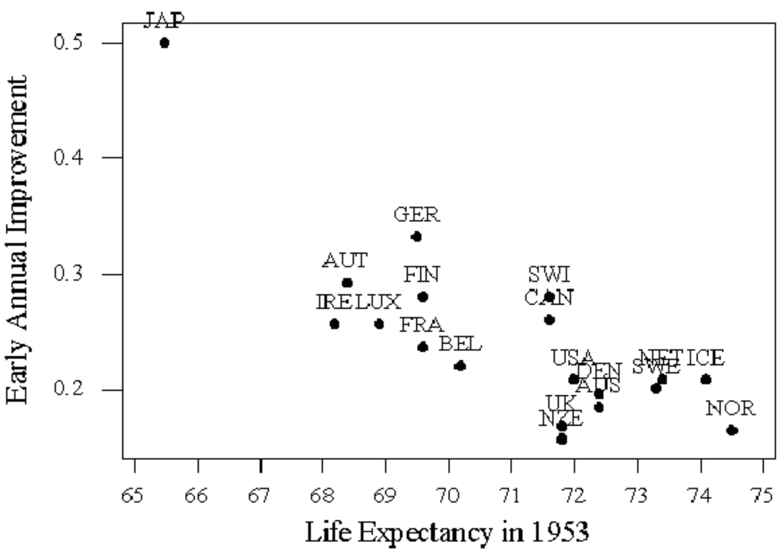
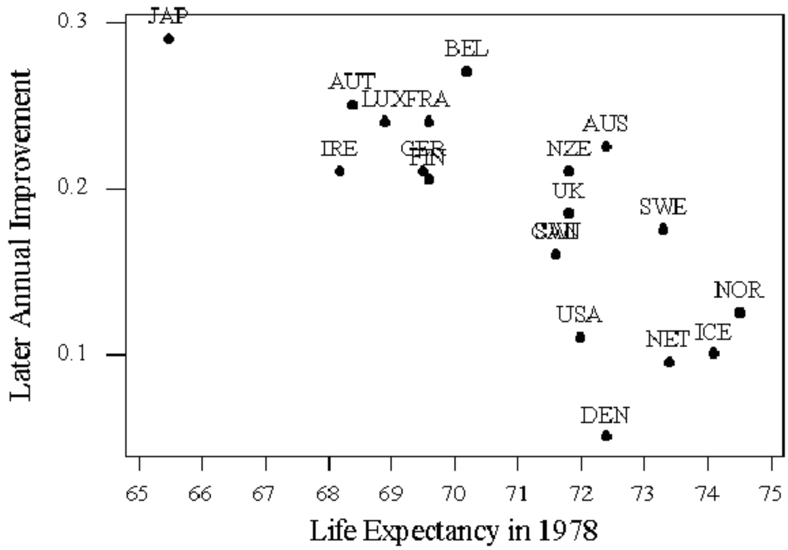


Figure 4 Later annual improvements as a function of life expectancy in 1978



We then examined the persistence of improvement among the 18 countries. Correlations (with P-values for the hypothesis of zero correlation in parenthesis) between Later, LE78, and Early were (Japan omitted):

	Later	LE78
LE78	-0.692 (0.001)	
Early	0.342 (0.165)	-0.081 (0.748)

This suggests that there may be some persistence. However, when Later is regressed on LE78 and Early, the coefficients are

Predictor	Coef	SE Coef	T	P
Constant	2.3514	0.5855	4.02	0.001
LE78	-0.029288	0.007525	-3.89	0.001
Early	0.3617	0.2163	1.67	0.115

with R^2= 50.2% (adjusted for the number of explanatory variables). While the regression is marginally better than the one not including Early (with R^2 = 47.9%), the effect of Early is small and not significant. The regression is compatible with the notion that current level rather than past improvement has had a systematic association with the later development.

Descriptive statistics on early and later improvement among the 18 countries are as follows (Japan omitted):

Variable	N	Mean	Median	StDev
Early	18	0.2280	0.2140	0.0490
Later	18	0.1789	0.1950	0.0618

Had these statistics been used to forecast life expectancy in the late 1970's for the late 1990's, the average error would have been 20 (0.2280 - 0.1789) = 0.982, as opposed to the average error of 20× (0.25 - 0.1789) = 1.422 years that would have resulted from the use of the best practice line. I.e., the error of the latter forecast would have been about 50% higher.

We conclude that during 1950-2000, as life expectancy has increased, its annual improvement has gradually decreased. Based on Figures 3 and 4 this holds for Japan, as well. The 18 countries have also come closer together, and they have fallen further behind Japan.

Conditions on the Usefulness of an Auxiliary Series

The model for the best-practice life expectancy says that (female) life expectancy at birth increases by 0.25 years every calendar year, but the 18 countries have fallen from 1.5 years behind in the 1950's to nearly 4 years behind in the late 1990's, on average. The deviance for the average of the 18 countries is a roughly linear function of time (R^2= 86.1%), and we estimate that the deviance has increased by about 0.05 years each calendar year. In 50 years time the best-practice line would imply an increase of 12.5 years, but if the average of the 18 countries continues to fall behind, the increase would be less, or 12.5 - 0.05×50 = 10.0 years. In general, we might wish to establish an empirical relationship between the best practice line and the measure of interest, which we take here to be the average of the 18 countries.

Suppose there are some functions $f_j(t)$, j = 0,1,2,..., such that an invariant g(t) is of the form

$$g(t) = \sum_{j=0}^{m} \alpha_j f_j(t).$$

Suppose the series of interest, say e(t), is related to the invariant via

$$e(t) - g(t) = \sum_{j=0}^{n} \beta_j f_j(t) + \in(t)$$

Where $\in(t)$ is random with expectation $E[\in(t)] = 0$. If $n \geq m$, then the *same* (e.g., generalized least squares) forecast for e(t) is obtained by (a) modeling the difference e(t) - g(t) and adding the result to g(t) that is assumed to be known, or (b) by modeling e(t) directly with the same explanatory variables $f_j(t)$, j = 1,..., n, but with modified coefficients $\gamma_j = \beta_j + \alpha_j$ (take $\alpha_j = 0$ for j > m). This follows from the fact that if the result of (a) is known, then the result of (b) can be deduced, and *vice versa*. Thus, in this case the knowledge of the invariant provides no help.

On the other hand, suppose m > n, or the invariant g(t) behaves in a more complex manner than the deviance e(t) - g(t). In this case, if the future values of the invariant can be assumed to be known for all t, we can reduce the dimensionality of the problem to m explanatory variables by modeling the deviance from the invariant. This can be of important practical use, especially if the future values of some of the functions $f_j(t)$, j = n + 1,..., m, are unknown. From this perspective having a linear invariant (with m = 2 only) is, paradoxically, the least helpful!

An alternative point of view is that *if* there is information about the difference e(t) - g(t) that has not been reflected in the past values of the series e(t), then such information can be introduced *via judgment* into forecasting. In the example at hand, suppose one believes that there is a feedback mechanism in operation such that if the life expectancy of a country falls sufficiently far behind the best-practice life expectancy, then corrective action will be taken by the society to reduce the deviance, in the future. This is a reasonable hypothesis, and presumably such an effect could manifest itself in the future. For example, even though Denmark has distanced itself from its neighbors for a half a century, perhaps later it will recoup some of the loss. More generally, if the 18 countries that have fallen behind Japan transform their life style in such a way that it resembles more that of Japan in terms of nutrition, job-security, attitude to leisure etc., then maybe they will begin to catch up. However, as this is a strong judgmental assumption that has to be defended by means other than statistical analysis, we will next pursue a number of alternatives that a statistical analyst might consider.

Model Choice

Figure 5 Average annual improvement in average life expectancy during five-year periods, of the 18 countries (Japan excluded), in 1950-2000, and four forecasts based on historical average (*), last observed value (·), exponential trend (×) and linear trend (+)

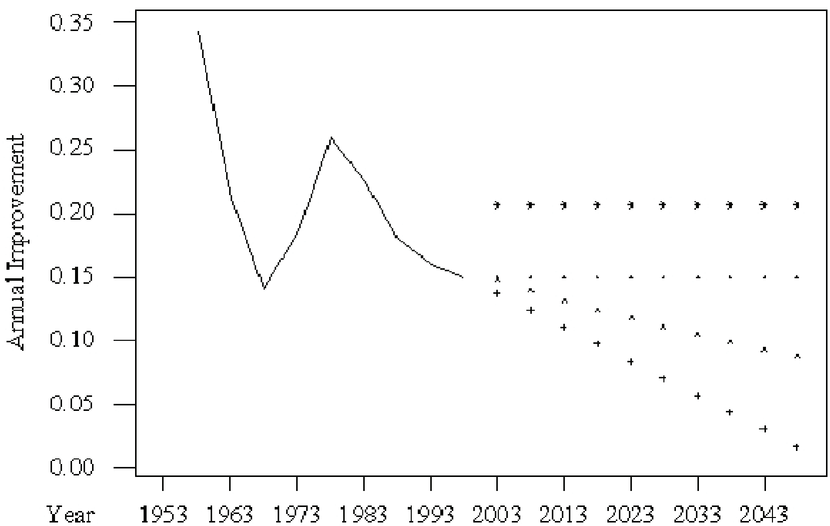


Figure 5 shows, in accordance with the earlier analyses, that the average improvement was higher in the early part of the observation period than in the later part. If the intention is to forecast until, say, 2050, the observation period is rather short, and alternative ways of viewing the trend are plausible. (a) Disregarding the first appearance, if we assume that the series is actually stationary, then the mean (*) is approximately the best predictor after a few years. (b) If we think that the series is a random walk, then the last observation (·) is the best predictor. (c) If we think that there is an exponentially linearly declining trend in the series, then the best prediction also declines exponentially (×). (d) If we think there is a linear trend, then the best predictor is the estimated linear line (+).

Forecasting as far as 2050, a choice between (a) - (d) can make a tremendous difference (this was pointed out in a more general context by Whelpton et al. 1947, already):

- using the historical average we expect to gain 50×0.2062 = 10.3 years;
- using the latest value we expect to gain 50×0.15 = 7.5 years;
- using the exponential trend we expect to gain 5.9 years;
- using linear trend we expect to gain 4.0 years.

All values are below the expected gain of 12.5 years derived from the linear model for the best practice life expectancy.

To distinguish between the models we can first examine the estimated variance of the residuals under models (a) - (d) and the best practice line model that assumes a constant rate of increase of 0.25 years per calendar year. The number of data points is n = 10 (from ten 5-year periods), and the number of estimates of annual increase is n - 1 = 9. The residual degrees of freedom in models (a) - (d) are 8, 8, 7, and 7, respectively. The best practice line model has 9 degrees of freedom, because it has no estimated parameters. Compared in this manner we find that the estimated variances of the residuals in the five models are 0.0041, 0.0042, 0.0031, 0.0031 and 0.0056. In view of Figure 5, it is not surprising that the two regression models lead to the best fit. Similarly, it is not surprising that the last model with a rate coming from the outside of the data set fits the worst. The fact that the random walk model is not among the best is informative. Although the regression models fit the best, we recognize that the data period is short and one cannot take results of this type as decisive.

Another possibility is to try to find supporting evidence based on alternative approaches to the same problem. Here the “rates-to-life expectancy” comparison is available. The life expectancy of the Finnish women in 2000 was 81.0 years, or essentially the same as the average of 80.6 for the late 1990’s, of the 18 countries. A stochastic forecast (Alho 2002) that assumed the decline in age-specific mortality to continue in each age at the rate of the most recent 15 years lead to a median of female life expectancy in 2050 of 86.7, indicating a gain of 6 years. This agrees with the assumption of an exponential decline model (c). We will examine this model further.

Consider a function e(t) such that e(0) = A and $e'(t) = e^{\alpha - \beta t}$, $\beta > 0$, for $t \geq 0$. It follows that

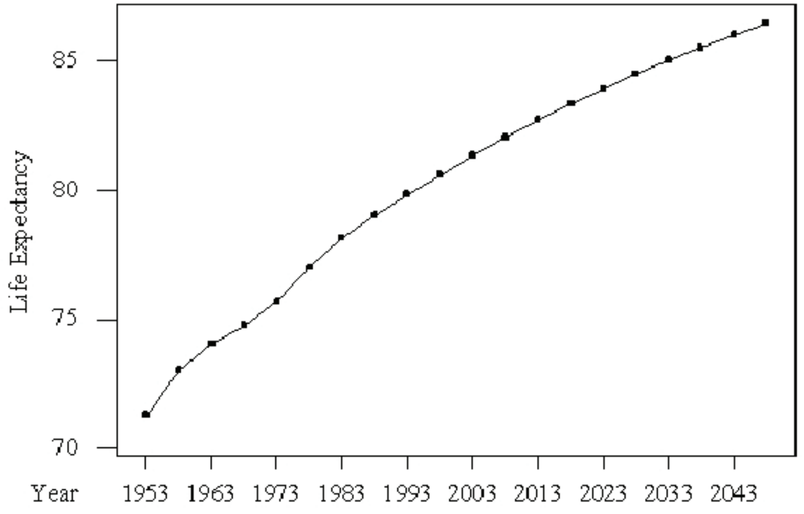
$$e(t) = A + B(1 - e^{-\alpha t}),$$

where $B = e^{\alpha}/\beta$. Taking t = 0 to correspond to the late 1990's, we have A = 80.6 and our empirical estimates can be translated to values $\alpha = -1.8472$ and $\beta = 0.01151$, which imply that B = 13.7. Under this model the average life expectancy of the 18 countries would never exceed 80.6 + 13.7 = 94.3 years. For the year 2050 we would get the value 80.6 + 6.2 = 86.8, for example. (The increase here is slightly larger than the 5.9 years given above, because the starting period is earlier.)

To complement the above point estimates we note that by using the so-called delta-method (e.g., Rao 1973, 385-6) we can compute a standard error for the estimate of B, as 9.4 years. Thus a 95% confidence interval for the additional improvement is quite wide, approximately 13.7 ± 18.4 years. From this, the 95% upper limit for the average life expectancy of the 18 countries would be about 94.3 + 18.4 = 112.7 years. Of course, even under this model, individual people can live much longer.

Figure 6 has a graph of the past data together with a point forecast until the late 2040's. Visually, the slight concavity smoothly continues from the past data to the point forecast.

Figure 6 Average life expectancy of the 18 countries in 1950-2000 continued with a forecast based on an exponential trend in annual improvements for 2001-2050



Concluding Remarks

We have investigated statistically the possible use of the best-practice life expectancy as an aid in forecasting the life expectancy of industrialized countries. The evidence shows that during the past 50 years this would have been overly optimistic. The results do not preclude the possibility that in the longer term a comparison to the best practice line might prove to be useful, but beliefs concerning this cannot be based on statistical analyses of the type we have conducted. Instead, arguments concerning processes, whose effects have not manifested themselves yet, are required.

Better fits would have been provided by models that incorporate the slowing down of improvement in life expectancy, among the countries studied. A model that assumed a geometric slowing down leads to an absolute upper bound for life expectancy, but estimates about this upper bound are statistically quite uncertain. The validity of such a model cannot be ascertained based on the short data period we consider.

Independently of whether life expectancy turns out to be approximately linear or concave (or convex!) in the long run, there may well be other periods besides the latter part of the 20th century, in which groups of countries veer off the trend for decades. From the perspective of individual countries this possibility would have to be allowed in the construction of prediction intervals.

In case one is not willing to choose an appropriate model at all, one can try to assign probabilities to each model, and do model averaging (Draper 1995). This approach has the advantage of leading to more honest prediction intervals, as it does not condition on a particular choice, but the disadvantage is that it requires the assignment of probabilities. It may be difficult to achieve a consensus on the latter.

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Life Expectancy Convergence among Nations since 1820: Separating the Effects of Technology and Income*

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Limits and Convergence in Life Expectancy

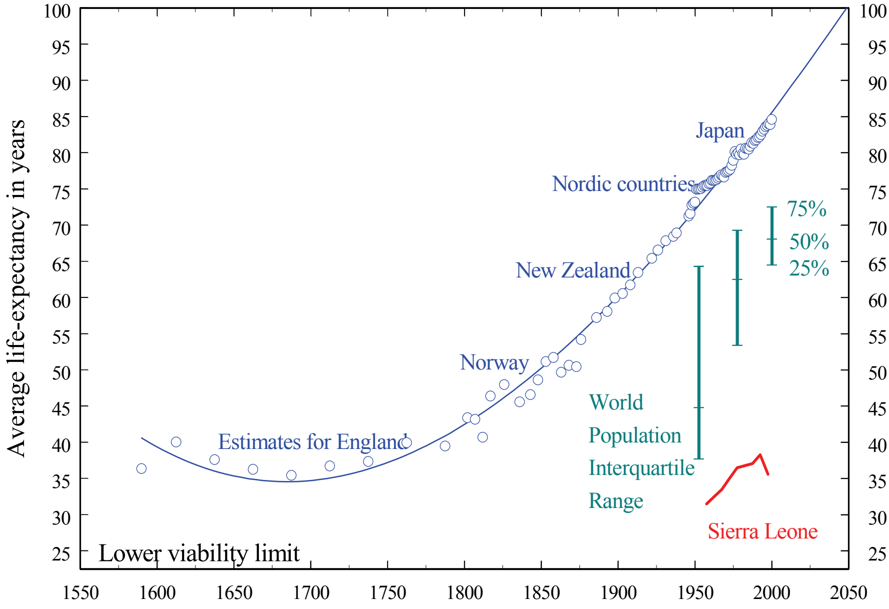
Figure 1 shows some details of the probable trajectories of limits and convergence for average life expectancy over the past four centuries. The curved line is an attempt to define the upper bound, or "best practice", average life expectancy that could be achieved at any one time.[1] We can think of this as an evolving upper bound to the "technophysio" evolution of the human population, in the sense proposed by Fogel and Costa (1997). The bottom limit of the graph is drawn at an average life expectancy of 22.5 years, to approximate the lowest level that a population could experience and still be viable in the long term.[2] Today, even a country like Sierra Leone, with one of the lowest life expectancies recorded by the U.N., is close to the upper limit for a pre-1800 population.

* I should like to gratefully acknowledge the enormous help I have received, from a large number of kind individuals and institutions, in building the demographic data-series for this paper. A full list of their names and the sources used will appear in the longer version of this paper. It is also clear that this topic could not have been addressed at all without the economic data published by Angus Maddison.

1 For details of its definition, and particularly its linearity after 1840, see Oeppen and Vaupel (2002) and associated Web material.

2 The lower limit to viability is somewhat uncertain as it depends on assumptions about age-specific mortality patterns and about the dependence between mortality and reproductive health.

Figure 1 Limits and convergence for national average female life expectancy at birth



If these two limits are plausible, then the history of average life expectancy over the last four centuries must lie between them. It is immediately apparent that the scope for absolute divergence after 1850 is much greater than before. Since the middle of the twentieth century, data on life expectancy or U.N. estimates are available for most countries and convergence has been generally apparent, although there has been recent concern about sub-Saharan Africa and the former communist bloc. A particularly effective way of depicting this convergence was published by Wilson (2001).[3] He weighted national averages by populations to estimate the concentration of life expectancy for the World population at three dates. The vertical bars show the inter-quartile range of life expectancy for countries containing half the World's population.

The bars emphasise three massive changes: rapid improvement in life expectancy, greater symmetry in the distribution, and the globalisation, or compression, of mortality experience. It also becomes clear that the years from 1850 to 1950 were probably the period of maximum diversity in the history of human mortality. After 1950 cross-sectional, or sigma, convergence is

3 This article contains similar analyses of fertility.

apparent, with compression from below, but the gap between the 75th percentile and the national "best-practice" limit seems to be growing.[4] This might be interpreted as evidence of a new period of divergence. Today's highest levels of life expectancy can only be achieved by reducing the mortality of the elderly and it may be that some countries will find this harder to achieve than the gains they made at younger ages.

So how do we explain these broad patterns of rising and converging life expectancy, bounded by one fixed and one evolving limit? Many economists have assumed that survival improvements follow automatically from economic development. This is supported by the observation that the rank ordering of countries across both variables is broadly similar and persistent over time, although the ratio of highest to lowest in income is massively bigger than that for mortality, suggesting a non-linear relationship.[5] Thus rising world life expectancy could be a simple function of rising real incomes, but what role should be assigned to technology transfers?

A second problem is that while the mortality range is compressing across nations over time, the consensus seems to be that the same is not true for income, although this is a subject of debate among economists. One might seek to explain it as the approach to a fixed biological upper bound to average life expectancy, resulting in diminishing returns to wealth, but this common idea of a fixed and imminent limit receives no support in two recent investigations (Oeppen and Vaupel 2002; White 2002). We have also seen that the World population does not seem to be converging on the evolving upper bound.

For insights into the roles of wealth and technology in determining the levels and convergence of life expectancy we turn to the classic article in the field.

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[4] Of course, it is possible that this process began before 1950.

[5] The stability over time of the rankings for survival is a curious phenomenon because there has been a massive "sectoral" redistribution since 1820 in the pattern of deaths by age. Why should a country like Norway maintain its position close to the top of the list, regardless of whether mortality is concentrated among infants, adults or the elderly – perhaps the equivalent of changing from an organic, to a mineral, to an information economy?

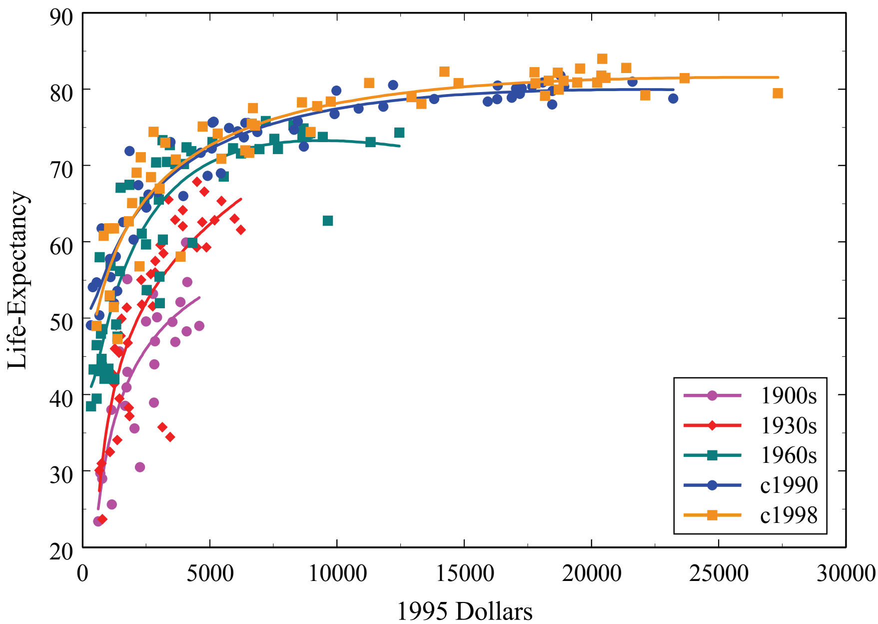
The Classic Article: Preston (1975)[6]

Speculation and assumption regarding the link between income and health persist. The first concrete, macro-level, study seems to have been undertaken by Preston (1975). In this article, Preston partitioned an historic fall in mortality into two factors: modern economic growth, and improvements in health technology. The first step was to find a function linking national income per head and life expectancy. Figure 2 is an updated version of Preston's graph – the original included cross-sections for the 1900s, 1930s, and 1960s, with logistic functions fitted to the latter two.[7] The idea is that there is a level of technology, or universal production function, that links input (National Income *per capita)* to output (average life expectancy) at any one moment in time, but that these functions are subject to temporal shifts. For example, an input of five thousand dollars per head "produced" an average lifetime of fifty years with the technology prevailing in the 1900s, but the same amount of money realised about seventy years in the 1960s. The addition of data for the 1990s does not alter the basic finding and shows that the curve is still shifting upwards in the wealthier countries.

[6] Slightly longer versions detailing cause-of-death effects are contained in Preston 1976 and 1985.

[7] The data shown are for female life expectancy and GDP per capita, expressed in 1995 international Geary-Khamis dollars. Preston used life expectancy for the sexes combined and national income per head in 1963 U.S. dollars, truncating the horizontal axis below the income level reached by the four richest countries in 1960. His list of countries grows over time, and by 1960 overlaps heavily with the one used here, but is not an exact match, especially among the poorer nations. Preston fitted logistic curves to the un-truncated data with an *a priori* asymptote of 80 years and scaled each cross-section's income from 0 to 100. The lines shown here are polynomials in the log of GDP per capita. The 1960s outlier with poor survival but high income is Venezuela.

Figure 2 Female life-expectancy at birth and GDP per capita



Easterlin (1996) has pointed out the similarities between Preston's approach and a pioneering study of modern economic growth by Solow, who divided growth in output into two components: (1) input growth with fixed technology, and (2) shifts in the production function due to technological change. In between technological shifts, countries could still make gains by increasing inputs. Easterlin describes Preston's study as "done independently of Solow's work and no less deserving of classic status" (1996, p. 75).

Preston calculated the rise in life expectancy that would have occurred if health technology had been fixed at the 1930s curve, but real incomes per head had risen as observed. Subtracting the hypothetical gain due to income change from the total gain led to the conclusion that about 80% of the rise in life expectancy from 1930 to 1960 could not be attributed to increases in income. This model of mortality treated changes in health technology as an unidentified, exogenous component expressed as a function of time. In subsequent papers, Preston (1980) included variables measuring literacy and nutrition, showing that 70% of the mortality decline in LDCs (excluding China) between 1940 and 1970 could not be accounted for by changes in income. For the period 1965 to 1979, again for LDCs, he has estimated that the technology share has fallen to 30% (Preston 1985).

Extending the Analysis

Preston's model of the linkage between health and national income offered a new way of looking at an old problem, but it still leaves some questions unanswered. The two cross-sections enclose a period of rapid technological change in health, including the introduction of antibiotics, so we have to question whether the dominance of technological change over income change is a long-term phenomenon. The "best-practice" line in Figure 1 suggests that these cross-sections enclosed the only marked "step" in survival over the last century. The rest of the period suggests stable change at the top level. For countries lower down the list, some authors have suggested that the period of inter-war retrenchment in international trade may have deferred demographic innovations, accentuating "catch-up" in the immediate post-war period (see e.g. Bloom and Williamson 1998).

Another important question is whether the dynamics of the model are well specified. Is health technology simply scalable with income? The "sectoral" changes in the age-distribution of deaths required to move from a life expectancy of 50 to one of 80 have been associated with major shifts of emphasis; changes in the importance of infectious versus chronic diseases, public health measures versus medicine, and the changing share of responsibility between the individual and the state. It seems unlikely that every country will experience these changes in the same way. We should expect persistent, "national" effects within the overall relationship.

For this paper on convergence, Preston's major result is that if we assume a fixed and universal health technology function then the curves show that rising real incomes will lead to convergence in life expectancy, without the requirement that the real income distribution should itself converge. But since Preston argues that technological change dominated between the 1930s and the 1970s, a mechanism based only on income offers little insight into the full mechanisms of long-run convergence. Today there is a considerable literature on economic convergence, but almost no formal analyses of demographic convergence (Wilson 2001). Demographers have concentrated on transition models, with time-scale compression for the late-entrants. The discussion favours technology transfer rather than economic growth, and emphasises the countries that have achieved high life expectancy with relatively low incomes. As with economic growth, late-entrants are recognised to have experienced rates of life expectancy increase never seen in the pioneering countries, but this is not framed in an analysis of the lower costs of imitation compared with innovation.[8]

This paper tries to expand the wealth of results that Preston's article generated into three new areas. Firstly, the temporal range of the data can be extended. Secondly, new statistical methods may allow us to learn more about the precise roles of time/technology and income. Finally, these same methods may provide more insights into country-level patterns, treated as residuals in the Preston model.

New Data

The desire to look at change in life expectancy over the long course of the health transition is severely restricted by the available data, and thus the resulting model will be unsatisfactory in many ways.[9] Time and GDP *per capita* are poor proxies for the things we would really like to know.

This paper takes advantage of the collection of national time-series for 56 countries published by Maddison (1995)[10]. GDP per capita is used here, expressed in 1990 Geary-Khamis dollars to remove the effects of inflation and currency. The series were made comparable using a Purchasing Power Parity (PPP) approach rather than relying on exchange rates, which are often distorting.[11] For most advanced capitalist countries, there are estimates for 1820, 1850, and then annually from 1870 to 1994. For other countries, the starting dates and continuity are variable.

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8 For an economic approach, see van Elkan 1996.

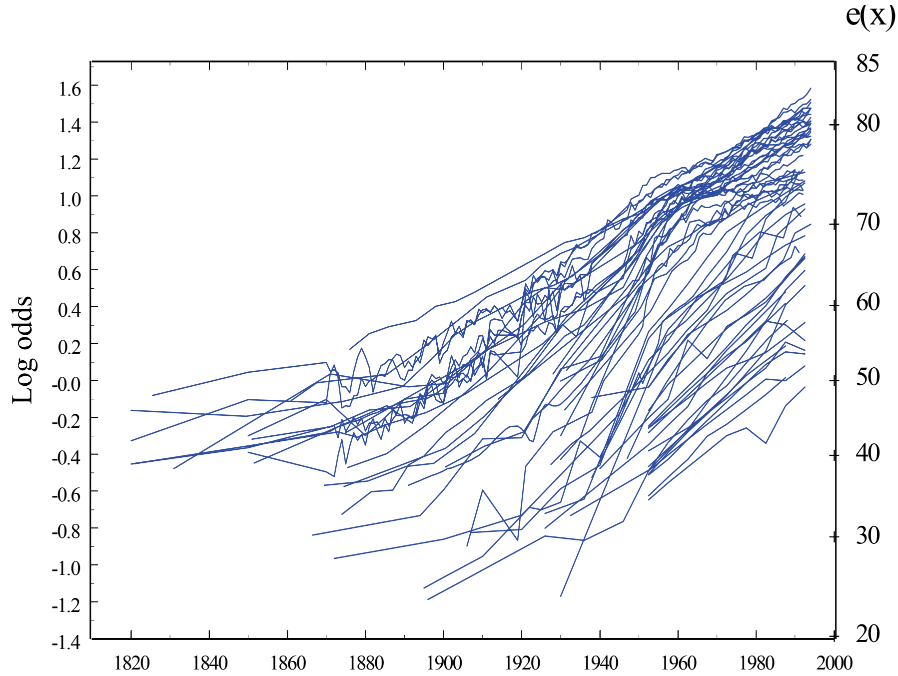
9 For the years after 1950, a much richer selection of socio-economic variables is available. See Jonathan Temple's website at http://www.bris.ac.uk/Depts/Economics/Growth/ for a guide to data and literature.

10 The data extends over 56 countries and from 1820 to 1994. A more extensive set of countries from 1950 to 1998 is contained in Maddison 2001. The additional countries will allow this analysis to extend to the poorer nations of Africa, Asia, and Central and South America and it is being revised to incorporate these new data.

11 PPP attempts to compare currencies by their power to buy similar products. Preston switched to PPP after his first article. Non-traded items are typically cheaper in poor countries and thus PPP adjusted wealth estimates are usually higher than those based on exchange rates for poor countries. This may explain why Preston found that a log model did not fit the low-income range.

Despite the recent increase in the number of countries with annual life-table series, much of the life expectancy data is sporadic and covers varying periods.[12] The GDP data has been averaged to match the time spans of the life expectancy estimates, which are shown for females in Figure 3. The nineteenth century has few low-survival countries and is largely confined to countries in Europe, or of European origin. Some Asian and Latin American estimates start in the first half of the twentieth century, but the U.N. estimates for African countries only begin in 1950. This results in a very unbalanced design with discontinuous data, and places a limitation on the kinds of models that can be used. Initial experiments in modelling showed that the 1918 flu epidemic created problems with the residuals, as did wars. An attempt has been made to identify the years when countries were subject to the direct and indirect effects of war and these, together with data for 1918, have been omitted.

Figure 3　　Female life-expectancy at birth



[12] Collections of mortality data can be found by following the links at http://www.demogr.mpg.de/

The income data used in the model is log GDP *per capita* in real dollars, and the life expectancy data is expressed as the log-odds of survival assuming an upper limit on life expectancy of 100 years.[13]

Equation 1: Log odds of life expectancy at birth

$$\ln odds\ (e_0) = \ln(e_0 / (100 - e_0))$$

The average number of years lived is divided by the average number of years "lost" assuming an upper limit on average life expectancy of 100 years. Taking the natural log means that the measure is unbounded on the positive and negative sides. This has the advantage of linearising the life expectancy data and removing any ceiling effect – something that Preston did with a logistic transform.

National Effects: A Shopping Analogy

Although economists would be quick to point out that there is no real market, Preston introduced us to the idea of an international price/technology/quantity relationship for life expectancy. We can hold any one constant and think about the other pair. Five thousand dollars in 1960 "bought" 70 years of life expectancy, but the same money in 1900 could only buy 50 years. Most people are familiar with this from buying personal computers and other electrical goods. A thousand dollars today buys a greater quantity of computing power than it did five years ago because technology has shifted the supply curve upwards.

Is a model based on an international relationship sufficient to reproduce the data? Preston considered that there were also national relationships hidden within the international model, but he didn't integrate them and treated them as residuals. He observed, for example, that Japan seemed to have very high life expectancy in the 1900s, relative to its income per head, and cites Taeuber's explanation of "personal cleanliness and the assumption of health responsibility by government organizations as important factors in counteracting the adverse effects of poverty"(Preston 1975, n. 22, p. 236).

To extend the shopping analogy, suppose that technology is always a year ahead in Japan compared to the U.S. – as a result you get a better PC at any given price in Japan, because the technology/price relationship is higher.

[13] This transformation is probably unnecessary and may be dropped in the final analyses.

Similarly, if delivery costs are high in a country, then the quantity/price ratio is pulled down for any given technology. Thus there may be persistent technological leads and lags, and pricing discounts and surcharges at the national level.

This viewpoint prompts new questions. For example, Norway seems to have always been close to the top of the life expectancy rankings, yet it was relatively poor by European standards at the start of the nineteenth century. Has it always been able to "buy" its life expectancy at a discount, perhaps because an egalitarian society gives a real meaning to "*per capita*" income, and more easily translates this into health for all the population? Or have they always had a technological lead, perhaps because literacy was so high, not gender specific, and created a tradition of investment in human capital? (Graff 1987, p. 375; Houston 1988, p. 135). Maybe both factors were at work and they were lucky? When they were poor, they knew how to control infant mortality at little cost. By the time mortality reduction required expensive items, like advanced health care for all and State support for the elderly, they had become rich.

Preston's analysis was for the sexes combined, but we can also consider who is doing the "shopping" – a man or a woman? Why, in the modern era, do women seem to be able to buy more? Each discipline that addresses this question – from evolutionary biology to sociology – has its own explanation.

Multilevel Models[14]

In Preston's original paper, the model was fitted to cross-sectional data. This raises a number of familiar estimation problems. We can illustrate this in an intuitive way by examining the points in Figure 1. It is likely that had lines been plotted for countries rather than cross-sections, a very different impression of the data would have been gained. Each country's data can be thought of as a number of repeated measures on a single unit or group. Preston's plot shows us the between-groups picture at three points in time, but we also need to understand the within-group change.

This paper uses a multilevel model to go beyond Preston's "series of cross-sections" approach. Multilevel models are designed to respect the hierarchical nature of both data and explanations. The textbook examples often use

[14] For information on multi-level models, in increasing order of complexity, see Kreft and de Leeuw 1998, Snijders and Bosker 1999, and Goldstein 1995.

school data. Pupils may be tested several times; they are grouped within classes and by teachers, which are grouped within schools, districts, and so on. Historical demographers are used to seeing nested data on regions, villages, families, parents, siblings, and individuals. Treating the hierarchy explicitly solves a number of problems. Factors may be significant at one level and not at another, or they may work differently at two levels. For example, the income of a family may have one effect on infant mortality and the average income of the village may have another. One may reflect familial access to resources, and the other may affect community provision of health infrastructure. Many studies ignore the hierarchy and force all the variables to one level. Thus we might see person-level regressions of infant mortality, with population density, a higher level measure, as an explanatory variable.

Equation 2 shows a naïve regression model that we can use as a means of introducing the concepts of multilevel models.

Equation 2: Regression model

$$\ln oddsf_{j,t} = \beta_0 + \beta_1 \times t + \beta_2 \times \ln GDP_{j,t} + \varepsilon_{j,t}$$

This equation models the log odds of female life expectancy in all countries, indexed by j, and for all time periods t, as the sum of a constant, a function of time, a function of log GDP *per capita* in the country at time t, and an error term. This is a "one size fits all" model, and it probably wouldn't work very well, judging by the plots of the data. A standard method of extending such a model is to fit a separate intercept term, or constant, for each country. In bivariate regression, this results in a series of parallel lines, one for each country. In this regression, it leads to a family of parallel planes. The model is usually referred to as Analysis of Covariance, or ANCOVA. The intercepts are really weighted means of the extent to which a particular country differs from the international model. A similar model is RANCOVA, or Random ANCOVA, shown in Equation 3. In this model, we have a global intercept $\beta_{0,0}$ and an additive term, $\beta_{0,j,}$ for each country j. The additive terms are estimated as a sample from a normal distribution with mean zero. They sum to zero, so they can also be regarded as a "national" residual that doesn't vary with time.

Equation 3: RANCOVA model

$$\ln oddsf_{j,t} = (\beta_{0,0} + \beta_{0,j}) + \beta_1 \times t + \beta_2 \times \ln GDP_{j,t} + \varepsilon_{j,t}$$

This idea of national offsets, or residuals, about an international model can be extended to the other parameters. Equation 4a shows a multilevel model with country-specific offsets for all parameters - $\beta_{1,j}$ for time, and $\beta_{2,j}$ for income.

Equation 4a: Multilevel model

$$\ln oddsf_{j,t} = (\beta_{0,0} + \beta_{0,j})$$
$$+ (\beta_{1,0} + \beta_{1,j}) \times t + (\beta_{2,0} + \beta_{2,j}) \times \ln GDP_{j,t} + \varepsilon_{j,t}$$

Rearranging the terms to Equation 4b reveals another view of the model and exposes its levels. The first line is an international model (or *fixed part* in mutilevel model terminology); line two is a country-specific level expressed as offsets or residuals from the higher level (level 2); and finally there is a lowest level residual term (level 1). We now have a model that is interpretable at the international and national levels. It can also be forecast, in both the international and national components.[15]

Equation 4b: Multilevel model separated into a fixed part and two residual levels

$$\ln oddsf_{j,t} = \beta_{0,0} + \beta_{1,0} \times t + \beta_{2,0} \times \ln GDP_{j,t}$$
$$+ \beta_{0,j} + \beta_{1,j} \times t + \beta_{2,j} \times \ln GDP_{j,t} + \varepsilon_{j,t}$$

To make the interpretation easier, Equation 5 illustrates such a model, which we will pretend is for Finland, country number 6 in this dataset. The international intercept for the log odds is .45, but *ceteris paribus,* Finland always seems to lag behind by a factor of -0.01. Overall, the measure of survival rises 0.15 for each additional unit of time, but Finland lags a little behind by -0.07, with a combined effect giving a rise of +0.08 per year. On the other hand, Finland seems to be "buying" its survival at a discount of 0.26. Instead of the international gain of 0.19 per additional unit of income, it gets 0.45 for each extra income unit.

Equation 5: Illustrative multilevel equation for country number 6

$$\ln oddsf_{6,t} = 0.45 + 0.15 \times t + 0.19 \times \ln GDP_{6,t}$$
$$- 0.01 - 0.07 \times t + 0.26 \times \ln GDP_{6,t} + \varepsilon_{6,t}$$

[15] This assumes that GDP forecasts are available. We might also use the model to back-project, or interpolate.

Turning back to Equation 4a, we can interpret the combined effects on the explanatory variables. $\beta_{1,j}$ results in a growing lead when it is positive, and a growing lag when it is negative. Similarly, $\beta_{2,j}$ is a discount when it is positive, and a surcharge when it is negative. As with the intercept in the regression model, we don't really know how to interpret a particular $\beta_{0,j}$ parameter. It could represent a fixed lead (lag), independent of time. Or if it were associated with income, then it is a stable rebate (cost). In practice, these two fixed possibilities cannot be logically differentiated.

This is a very simplified introduction to the use of the model in this context. It would take too long to recount the full properties of multi-level models here, but a number are particularly relevant. Firstly, the model recognises that the structure of the data is hierarchical. Each country's data is a set of repeated measures over time which share certain implicit factors that cannot be ignored. Secondly, the model does not require that the time points are evenly spaced, or that the data are known for all countries. This allows us to use unbalanced data.

Model Results

As expected, the model represented in Equation 4 does not work very well. Examination of the residuals shows that they have significant patterns. The strategy adopted for this paper, which concentrates on the national effects, is to make the fixed or international part of the model as flexible as possible. This is an attempt to avoid having the failures of the fixed part interpreted as national effects. Conversely, the national component of the model has been kept as simple as simple as possible, and the form used in that part of Equation 4 is retained.

The final form of the international model uses a polynomial in time because the log transforms do not fully linearise the data. It is also clear that there are epochs in the data. For this reason, the data has been partitioned into pre-World War I, Inter-War, and post World-War II epochs for both time and income. Even then, the post-World War II reconstruction decade presents significant problems. This is an extremely important period in the diffusion of antibiotics and other health technologies, and a time of rapid economic change, so rather than delete the data points, affected countries have been identified and a special component fitted in the model. Finally, even with this expanded model, it was clear that the variance in the level 1 residuals seemed to be a negative function of income, so the model was expanded to allow complex level 1 variation to remove this heteroscedasticity (Goldstein 1995).

The parameter estimates for the fixed, or international, part of the model are shown in Table 1.[16]

Table 1 Multilevel model for log odds of life expectancy

Variable	Female	Male
Intercept	-2.3420	-1.954
Time	-0.1073	-0.0961
Time squared	0.0179	0.0185
Time cubed	-0.0004	-0.0005
Inter-war dummy	-0.7258	-0.9735
Post-war dummy	0.9255	0.7637
Ln GDP pre-war	0.1999	0.1173
Ln GDP inter-war	0.2892	0.2403
Ln GDP post-war	0.1122	[0.0486][a)]
Post-war reconstruction dummy	-2.0817	-1.6653
Time * Post-war reconstruction dummy	0.1349	0.1082
-2 * log likelihood	-5635	-4938

[a)] Bracketed parameters are not significant.

This model suggests that the long-term upward trend in survival was depressed in the inter-war period, but jumped up after 1945. In both periods men seem to be in a worse position. Income terms for females are positive, particularly so in the inter-war period, but there is evidence for a post-war diminution in the effect of income, and this contrasts with Preston's conclusions for combined male and female life expectancy in LDCs. The inter-war period does seem to show a period of retrenchment – temporal gains slowed and wealth became more important. For men, income seems to be less important than for women and is not statistically significant after 1945. Broadly speaking, the parameters for females and males show similar patterns, although the model is less successful in explaining the male data.

[16] 1810 has been subtracted from the Time variable in these models, to limit the scale of the polynomial terms.

National Patterns

The nation-specific component of the model for country *j* is

The nation-specific component of the multi-level model

$$\beta_{0,j} + \beta_{1,j} \times t + \beta_{2,j} \times \ln GDP_{j,t}$$

and this can be interpreted as the national "offset" that can be added to the international prediction to get the full prediction for any country. [17] It tells us how one country is performing after controlling for the functions of income and time common to all countries. Figure 4 plots the three elements that sum to the national component for the USA and Japan. Because it is controlled out, the international level can be thought of as the horizontal line at zero years. The first panel shows the country-specific constants. Multilevel models are usually fitted to grand-mean centred data so that the variance of the intercept has meaning. The second panel shows the temporal components. Japan's offset relative to overall temporal change seems to be fixed and approximately zero. The USA has a broadly similar "health technology", if we can interpret it this way, which is not surprising. The real difference in their contemporary position is shown in the third panel. The US has become progressively unable to translate log dollars into health. It is now about 10 years behind the position we would expect based on income alone, a figure slightly offset by a small advantage of about two years in technology. The American pattern is typical of the countries of Northwest European origin, but only the southern European countries come close to Japan's position of combining a high income with a good conversion rate. The sums of the three components that make up the national offset from the international model are shown in the fourth panel. The USA has regressed to the mean, but Japan shows some strengthening of a long-term advantage.

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[17] Normally, intercepts are estimated setting all the explanatory variables to zero. For most social science data, this leads to intercept values outside the plausible range of the data. For these data, it is not so extreme for the variable t, as 1810 was subtracted from the year, but the general position holds for GDP. In multilevel models, it is customary to centre the variables that are used at this level and this has been done here. Kreft and de Leeuw (1998) give an excellent description of the role of centring data in conventional regression, and multilevel models.

Figure 4 Components of national level life-expectancy estimates

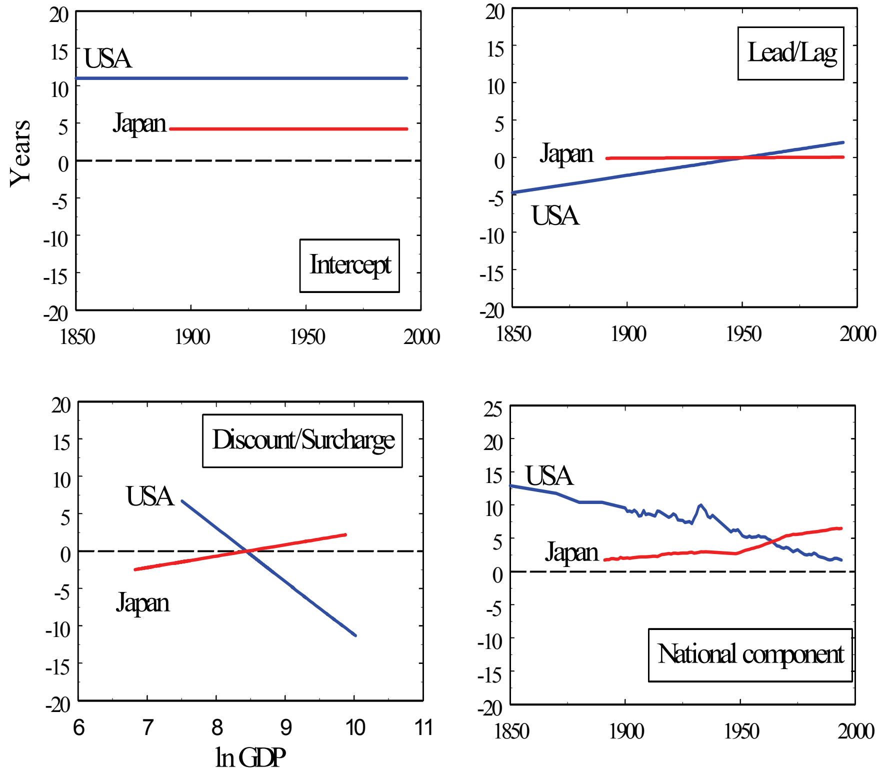


Figure 5 shows the raw data for Japan and the USA, together with dashed lines showing the life expectancy we would expect if they had zero offsets from the international model. As we might expect from the previous graph, this model fits quite well for Japan but overestimates US life expectancy for women today by about five years. The full model fits the US data quite well by setting diminishing returns to log GDP *per capita*. Figure 6 shows the same data plotted against income. The slope of the US response to log GDP seems to have changed around 1950, but it could be argued that both Japan and the US may now be back on the long-term path.

Figure 5 Female life expectancy – model and data against time

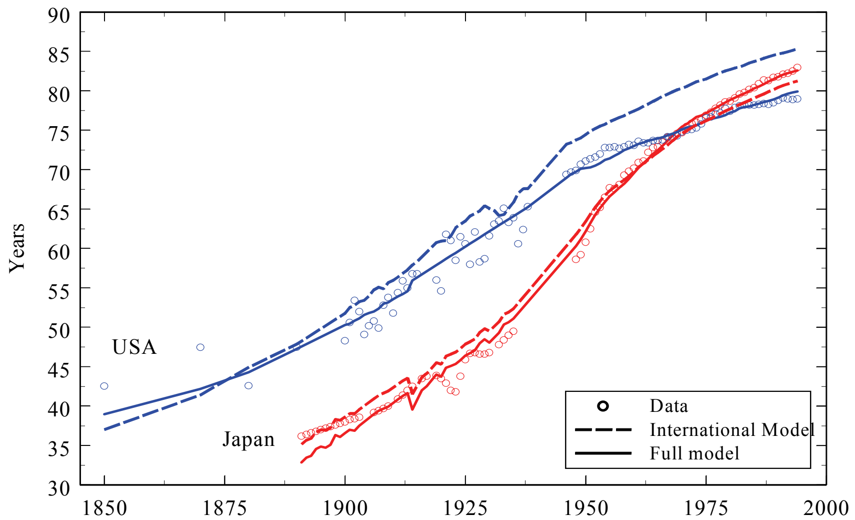


Figure 6 Female life-expectancy: model and data against per capita income

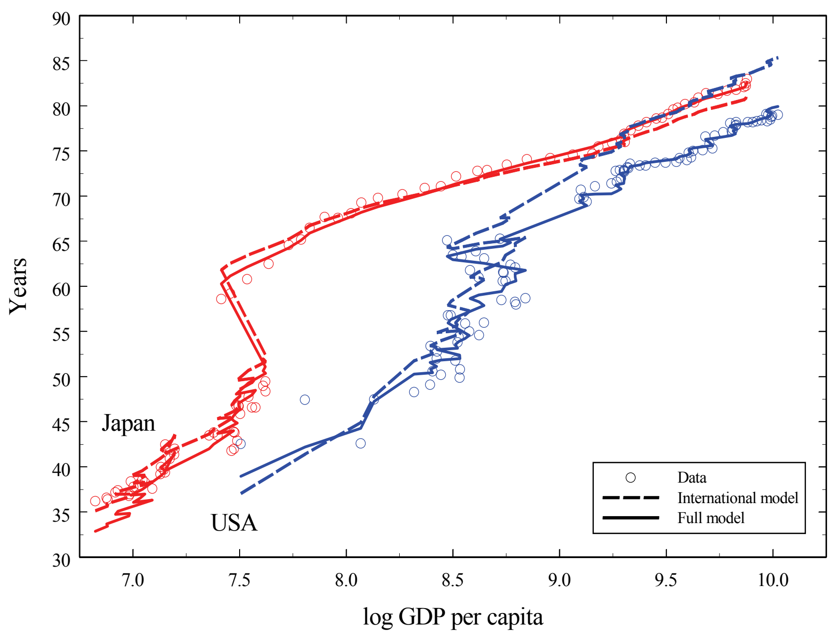
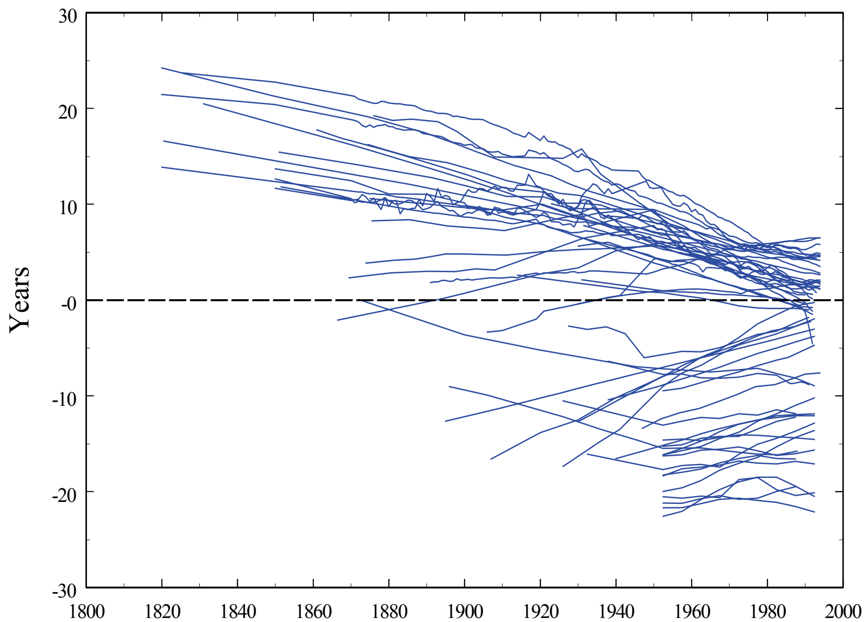


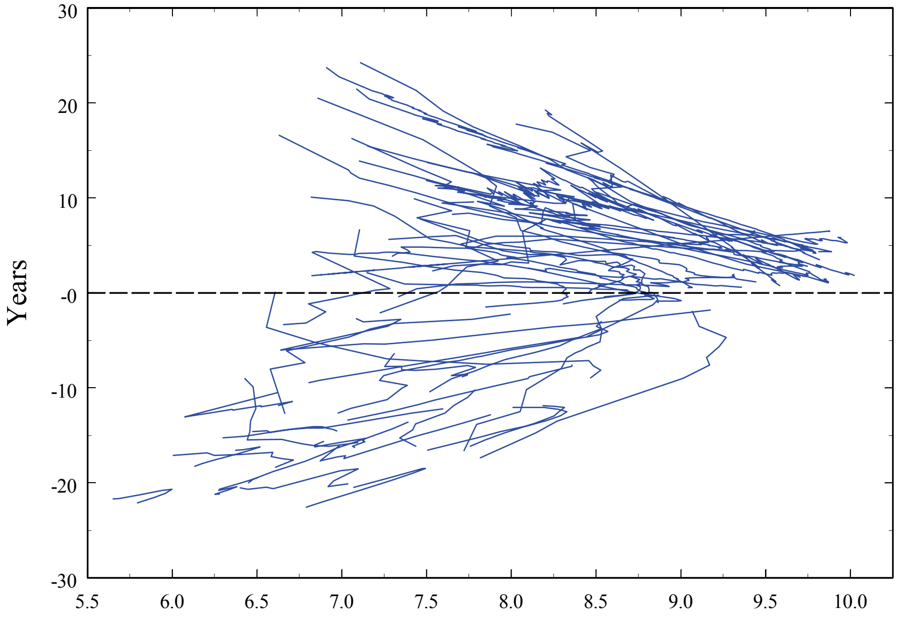
Figure 7 shows these offsets for all the countries, plotted against time. It is immediately apparent that the model is estimating convergence. The fixed part of the model predicts an overall life expectancy in the low twenties for 1820. This is both viable and plausible, and suggests that countries like Norway had a female life expectancy about 25 years above the international prediction. Over time they have progressively lost this advantage, until today it is less than five years. It also seems clear that some of the low life expectancy countries are also converging, although perhaps not at the same temporal pace when the disadvantage is greater than ten years. It should also be noted that these data stop in 1994 and do not show the recent effects of the AIDS epidemic.

Figure 7 National level female life-expectancy estimares against time



Plotting the same data against GDP in Figure 8 is even more striking. Now it seems much clearer that there is overall convergence in life expectancy as income increases. There doesn't seem to be much evidence that there are different points of convergence for some countries, although the poorest ones are not well represented in Maddison's data.

Figure 8 National female life-expectancy estimates against GDP per capita



In general, examination of the level 1 residuals shows that the fits for each country are very good, but there is temporal autocorrelation that has not been removed.[18] An exception to the encouraging results concerns the former communist countries of central and Eastern Europe. Paradoxically, the model gives better fits in the 1990s during and after the transition problems than it does in the 1960s. There is a consistent pattern of under-estimation in that period. One plausible possibility is that the economies were difficult to quantify and the GDP estimates are too low. The alternative explanation is that command economies really could deliver good health at lower cost when the challenge was to keep infants, children, and adults alive. Perhaps it was the shift of focus to the elderly population that created difficulties.

[18] Autocorrelation is ignored in this presentation, although the MlwiN software used is capable of dealing with autocorrelation in irregularly recorded time-series. See Goldstein et al. 1998.

Convergence

Many researchers have commented on the apparent convergence in life expectancy over time, and also identified a significant number of countries where the progress in health easily outruns their economic performance (Caldwell 1986). Despite this, there seems to have been no attempt to address convergence in a formal way, although there is an extensive literature in Economics on estimating convergence across countries (Jones 1998; Barro and Sala-I-Martin 1995). Among the many insights this provides for demographic studies is the distinction made between "sigma" and "beta" convergence. The former, as the name suggests, is assessed by calculating cross-sectional standard deviations (sigmas). Their evolution over time is then examined. If the trend is towards lower dispersion, it may be interpreted as convergence.[19] Sigma convergence is a measure of what actually happened, but calculating it is difficult with the demographic data before 1950 because they are unbalanced and sporadic.

Beta convergence exists if the slope of a regression line over time is negatively related to the intercept. For example, if a country has a high starting position, or intercept, and a negative slope over time relative to the average, then it is an indication that this country may eventually converge towards the mean. Beta convergence is really a measure of the propensity to converge, holding other effects constant. While it may lead to sigma convergence, it may also be overtaken by changes in other variables or random shocks.

The multilevel model facilitates the estimation of beta convergence, because of the explicit national-level intercepts and slope parameters, but two departures from the conventional intercept-slope regression approach should be borne in mind when interpreting the results. Firstly, all the "national" parameters are estimated from zero-mean normal distributions, so they can be thought of as offsets from the fixed or international model. Secondly, the intercepts in this paper are estimated at the grand means of the data. This is not a requirement of the method, although conventional in multi-level modelling, but it means that the variance of the intercept distribution has meaning within the scales of the data. This allows one to compare the variances across parameters and convert the parameter estimates into z-scores for comparative purposes.

[19] There is a debate in the Economics literature on the difference between convergence and regression to the mean, see Friedman 1992 and Quah 1993.

Returning to a consideration of Equation 4b, the national parameter estimates $\beta_{0,j}$, $\beta_{1,j}$, and $\beta_{2,j}$ may reveal correlation. Suppose that the intercept terms, the $\beta_{0,j}$, are negatively correlated with the lead/lag parameters, the $\beta_{1,j}$. In this case a high (low) intercept will be associated with a falling (rising) national offset over time, and the country will tend to converge on the international model. The same applies to the $\beta_{0,j}$ and $\beta_{2,j}$ parameters. Negative (positive) correlation means that a country with a good starting discount will have a falling (rising) response with respect to income. Finally, if $\beta_{1,j}$, and $\beta_{2,j}$ are negatively (positively) correlated, then relative gains with respect to one variable may be offset (reinforced) by the other.

Before examining convergence in the life expectancy data, we need to consider whether the income data are converging, although the Preston model reveals that this is not a necessary condition for convergence. If there were a simple linkage between income and survival, then economic convergence might be driving mortality convergence directly. Economic convergence is a subject of great debate and the general opinion seems to be that there is no unconditional convergence (Jones 1998). Some groups of countries seem to be converging within their own "club", but it has been argued that this is conditional on the structures of their economies.[20] My own very simple attempts to look at convergence in the full Maddison GDP dataset, using a multilevel model without covariates, also indicate that there is no evidence of global convergence. In fact, divergence is suggested.

Figure 9 plots the national intercepts, $\beta_{0,j}$ against the parameters on Time, $\beta_{1,j}$, after they have been converted to z-scores. There is a negative correlation of -0.38, which indicates a slight but statistically significant tendency for countries with high intercepts to decline against time, and *vice versa*, leading to convergence.[21] There is some evidence of clustering by geographic areas and economic types. On this time scale, advanced economies with high life expectancies seem to be progressing faster. These correspond to the economies that Sachs and Warner identified as "open" to international trade in 1960 (Sachs and Warner 1995). By 1992, the few remaining "closed" economies are confined to a peripheral arc running from China to Egypt. The former communist countries are making slower progress.

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[20] As an epidemiological example, we might speculate on whether the malarial and non-malarial nations could converge on different trajectories.

[21] The country abbreviations are shown in Table 2 at the end of the chapter.

Figure 9 National level parameters for female life expectancy

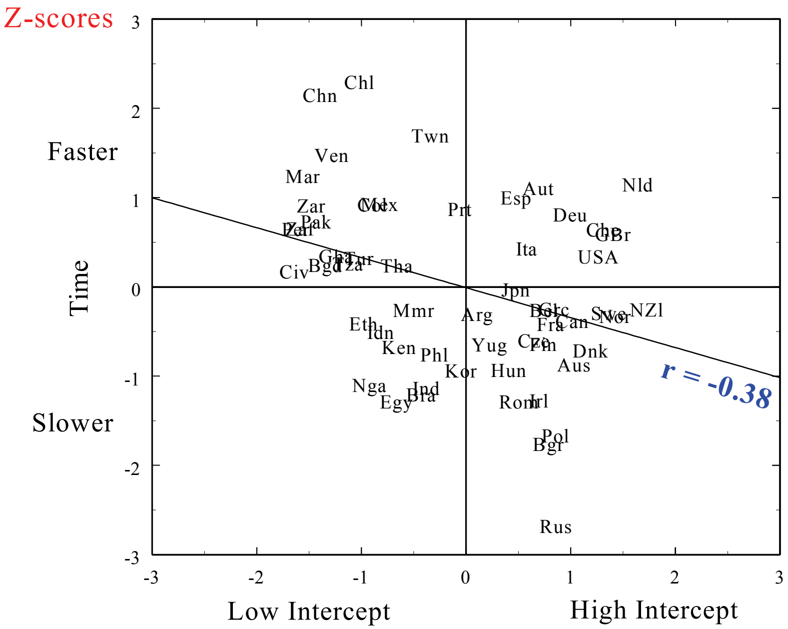


Figure 10, with a correlation of –0.63 shows that income is the major factor driving beta convergence. As incomes rise, laggard countries are adding years faster than the leaders. Countries of north-west Europe, and their wealthier former colonies, seem to be doing badly, with Britain, the Netherlands, and New Zealand in the worst position. Figure 11 shows that the correlation between the time and income parameters, $\beta_{1,j}$ and $\beta_{2,j}$ is also negative and significant at –0.39, indicating that the effects are offsetting to some degree. Two countries are worth highlighting across all three graphs. Japan is the only wealthy country that is close to the origin on all three scales. Ireland seems to be associated with the countries of the former communist bloc!

Figure 10 National level parameters for female life-expectancy

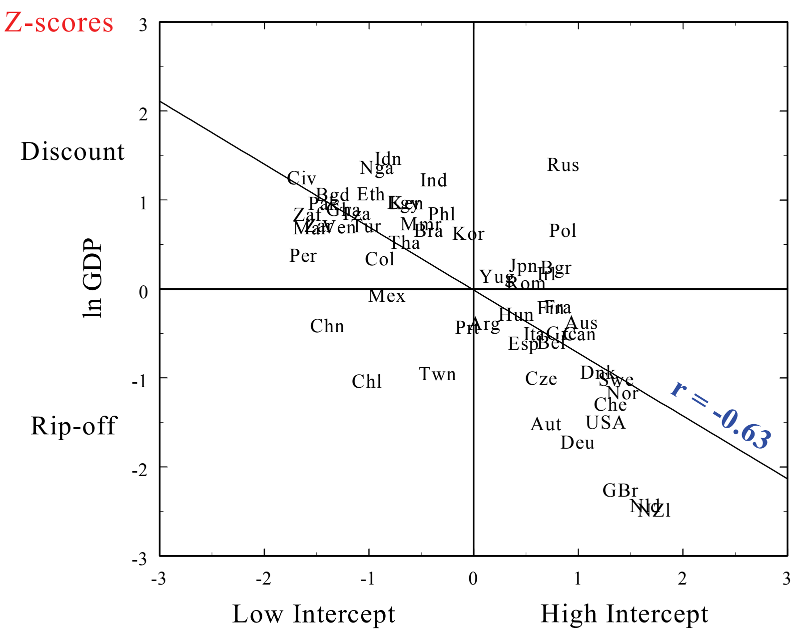
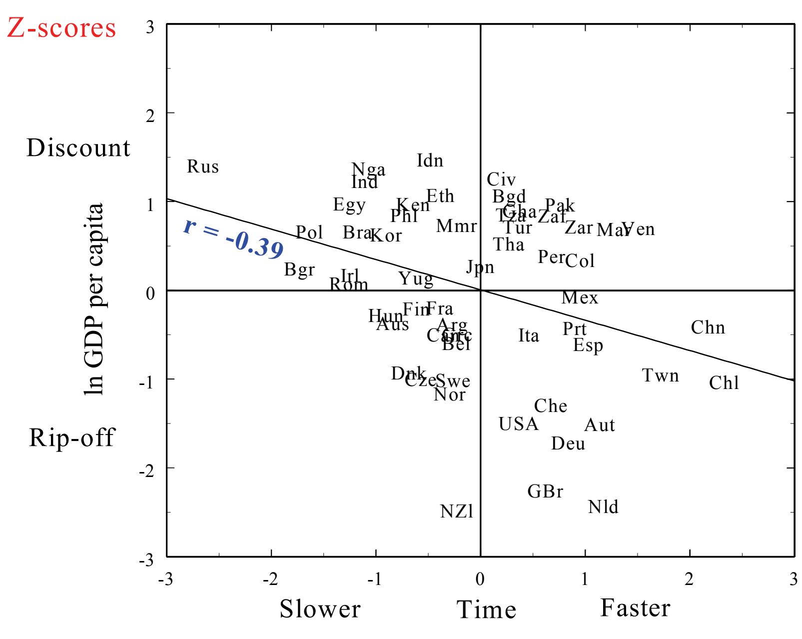


Figure 11 National level parameters for female life-expectancy



The full possibilities of this model are not covered here, but some work has been done. For exploratory purposes one can treat the parameter estimates as data. The intercept for females is strongly related to educational attainment as measured in 1985, so the broad ranking may be a long-run feature. There is some evidence that countries with mid-range average education of between five and nine years have the positive time-parameters that indicate "catch-up". The GDP parameter is strongly and negatively associated with education. It seems that the educated countries are in a phase when additional years of life expectancy are "expensive".

The effect of income inequality on life expectancy has been a subject of debate (Wilkinson 1998). It could be that, with the international parameter controlling for the broad effect of GDP, the national parameter might be associated with the income distribution of the country. Countries where there is high inequality may have below par conversion of income into health. Using contemporary data from the World Bank on the share of income held by the lowest twenty percent, there seems to be no relationship with the GDP parameters. However, the more egalitarian countries do seem to have higher intercepts, but they also have lower rates of change over time. No relationships are significant when the data are restricted to the 17 countries described by Maddison as "advanced capitalist", although the hypothesis is only expected to apply to richer countries.

Because the model is parameterised at the "national" level it would be possible to use country-specific GDP forecasts to forecast life expectancy. Another experiment is to enter the US GDP time-series into each country's equation. I expected that this would lead to impossible values, but they looked plausible. For example, the model suggests that in the post-Independence era, Indian women would have had US life expectancy if they had had US incomes. The only forecast that exceeded the "best practice" line in Figure 1 was for Russian women. In general, there seemed to be little evidence that there were "structural" limits in the fitted equations that would prevent life expectancy approaching the best levels if incomes grow. One of the insights from this exercise was that some countries have trajectories that are independent of GDP. Chile and China, for example, have national parameters that are approximately equal to the international parameter on GDP, but with a negative sign, so that changing GDP has no effect at all.

Conclusion

Multilevel models offer considerable scope for disentangling effects in collections of unbalanced, repeated-measures data. These results are preliminary and designed to explore what can be done, rather than suggesting final interpretations. Preston's finding that time seems to be becoming less important in LDCs is contradicted in the international component of this model, where it is the income effects that seem to have diminished in the post-war era, particularly for men. On the other hand, changes in income seem to be more important than health technology in explaining survival convergence. Breaking down the national level effects into their constituent components suggests that countries of Northwest European origin have translated a diminishing proportion of their gains in income into gains in health. Combined with the "catch-up" opportunities for the laggard countries, this has led to rapid convergence. Japan and the Southern European countries seem to be the exceptions to this diminishing return to log income.[22] They seem to have emerged from the "pack" by maintaining a small long run advantage over the international position. The story of why women's patterns are different from men's will have to wait for another day.

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[22] Measurement problems of the "black economy" in southern Europe should also be considered.

Table 2 56 countries

Country	Abbreviation	Country	Abbreviation
Argentina	Arg	Korea	Kor
Australia	Aus	Mexico	Mex
Austria	Aut	Morocco	Mar
Bangladesh	Bgd	Myanmar	Mmr
Belgium	Bel	Netherlands	Nld
Brazil	Bra	New Zealand	NZl
Bulgaria	Bgr	Nigeria	Nga
Canada	Can	Norway	Nor
Chile	Chl	Pakistan	Pak
China	Chn	Peru	Per
Colombia	Col	Philippines	Phl
Cote d'Ivoire	Civ	Poland	Pol
Czechoslovakia	Cze	Portugal	Prt
Denmark	Dnk	Romania	Rom
Egypt	Egy	Russia	Rus
Ethiopia	Eth	South Africa	Zaf
Finland	Fin	Spain	Esp
France	Fra	Sweden	Swe
Germany	Deu	Switzerland	Che
Ghana	Gha	Taiwan	Twn
Greece	Grc	Tanzania	Tza
Hungary	Hun	Thailand	Tha
India	Ind	Turkey	Tur
Indonesia	Idn	UK	GBr
Ireland	Irl	USA	USA
Italy	Ita	Venezuela	Ven
Japan	Jpn	Yugoslavia	Yug
Kenya	Ken	Zaire	Zar

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Linear Increase in Life Expectancy: Past and Present

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Improvements in human stature, real income and life expectancy have taken place at an unprecedented speed during the last two hundred years. In the case of life expectancy at birth, the record has been broken at an amazingly constant pace since 1840. Females have continuously gained 2.92 months per year, males slightly less (Oeppen and Vaupel 2002). While the increase is considerable, with improvements in life expectancy of some 8 years from parent to child, it is the regularity of the advancement that is remarcalbe, not the speed as such. The reason is that the countries entering the mortality transition at a later stage in history tend to exhibit an even faster improvement. Japan, for example, experienced improvements of 6 months per year in life expectancy during its catch-up in the twentieth century. In China the corresponding figure was well above one year in the 1960s and 70s. Thus, while the increase of best-practice countries is not astonishing in itself, the linearity of the improvement certainly is. This raises obvious questions: What are the causes of this linear increase and how long can it be sustained? Other questions concern whether the observed linear increase in life expectancy can be used in forecasting life expectancy both for countries lagging behind and countries in the lead.

To Oeppen and Vaupel, the linear development of life expectancy suggests that the process of mortality reductions “should not be seen as a disconnected sequence of unrepeatable revolutions but rather as a regular stream of continuing progress” (Oeppen and Vaupel 2002:1029), referring to Lee and Carter (1992), and Tuljapurkar, Li and Boe (2000). Still, in the next sentence Oeppen and Vaupel state, with reference to Riley (2001), that mortality improvements are the result of a complex process of “advances in income, salubrity, nutrition, education, sanitation, and medicine, with the mix varying over age, period, cohort, place, and diversity” (Oeppen and Vaupel 2002:1029). Thus, on the one hand the advance in life expectancy is a regular stream of continuous progress but on the other it is also an intricate interplay of a mixture of social, economic and medical factors, which sounds almost like a paradox that calls for further clarification. As starting point, I will take a closer look at the countries that are the leaders in life expectancy: a very small number indeed, consisting of nine countries altogether. What mixture of factors varying over *age, period, cohort, diversity of diseases,* and *place* has made them the global leaders of life length? I will then turn to the issue of causality.

Descriptive Overview

Starting with *age and period*, to quote Oeppen and Vaupel (2002:1029), “most of the gain in life expectancy was due to large reductions in death rates at younger ages. In the second half of the 20th century, improvements in survival after age 65 propelled the rise in the length of people’s lives”. This is indeed one of the most well-known and universal facts regarding the historical mortality transition. It holds true both for countries that have experienced the mortality decline recently and for those where it started hundreds of years ago. In Sweden, an example of the latter, the level of infant mortality dropped almost without interruptions from the mid-eighteenth century onwards. The other Nordic countries showed a similar development (Bengtsson and Lundh 1999). England and other parts of Western Europe, as well as North America, initially followed the same pattern of infant mortality decline in the eighteenth and the beginning of the nineteenth century but after that point in time, the decline levelled out. Alfred Perrenoud (1984) consequently differentiates between a Nordic model, with continued decline, and a West-European model, with an interrupted decline. From around the end of the nineteenth century to present day, however, all countries in the industrialized world have exhibited the same development of rapid decline in infant and child mortality, which was the main reason for the rise in life expectancy. Though death rates for the elderly started to drop already in the latter part of the nineteenth century, it was not until the mid-twentieth century that life expectancy was largely *propelled* by falling mortality at age 65 and above. Since the change from infant and child mortality to mortality among the elderly as the major explanation of the observed improvements in life expectancy has not yet occurred in many countries, most of the increase in life expectancy during the twentieth century in these countries has still been due to the decline in infant and child mortality.

Another striking and commonly-shared pattern is the change over time in the *diversity of diseases*. Here Oeppen and Vaupel refer to Bongaarts and Bulatao’s volume *Beyond Six Billion* (2000) and Riley’s book *Rising Life Expectancy: A Global History* (2001). In turn, Riley’s way of reasoning is much in line with the Epidemiological Transition Theory, according to which the pestilences and famines are followed by receding pandemics, and later by degenerative and man-made diseases (Omran 1971). This line of theory argues that the changes are mainly the result of man's control over his environment. How mortality patterns change over time is not the object of much controversy; more so the causes behind these changes. General agreement prevails that decline in infant and child mortality starts off in the form of reduced mortality in highly virulent infectious diseases but is upheld by a decline in less virulent infectious diseases. The role of famines in this process is more debated but it is unlikely that it has influenced trends in infant and child mortality to any significant degree (Wrigley and Schofield 1981). Thus, it was a reduction in the mortality among children in highly virulent diseases, primarily a drop in smallpox mortality, together with further reductions in mortality in low virulent infectious diseases, which brought the best-practice countries to the lead in 1840.

The second crucial change came after the mid-twentieth century and consisted of the fall in mortality in ages 65 years and above. This decline was largely caused by reductions in chronic diseases (cardiovascular, cerebrovascular and some cancer diseases), possibly in combination with a general health amelioration due to improvements of conditions in early life in the beginning of the twentieth century. In fact, when the great mortality decline of Western Europe was first analysed by Derrick (1927) and Kermack, McKendrick, and McKinley (1934), they clearly advocated the role of *cohort factors*. They believed that the decline in adult mortality in England, Wales, and Scotland, as well as in Sweden, to a large extent was the result of improved conditions in childhood. This argument later lost ground as the Demographic Transition Theory evolved and the process of modernization and other *period factors* came into focus (UN 1953). It was not until the late seventies that Preston and van de Walle (1978), Fridlizius (1989) and later Barker (1994) and Fogel (1994), brought these issues into play again. Today, there is an extensive and lively debate on the importance of early-life factors on mortality in later life vis-à-vis period factors

Regarding *place,* it is striking that so few countries have been record-holders in female life expectancy over the past 160 years, as shown in Table 1. The linear line is based on the experience of only nine countries, starting off with Sweden and Norway in the first two decades after 1840, and followed by Australia in the 1860s. New Zealand came into the lead in 1876 and almost monopolised this position until 1941, with the exception of a brief period between 1916 and 1919 when first Sweden and then Denmark surpassed all others. During the Second World War, Norway and Sweden, now in company with Iceland, showed the best-practice levels in life expectancy and

Table 1 The nine world record holding countries

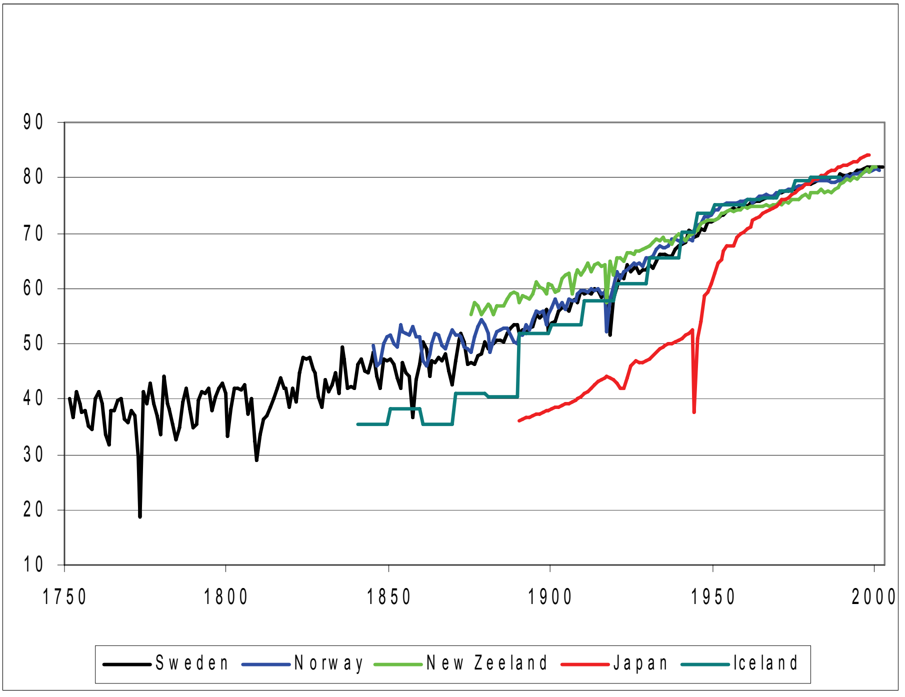
Country	*Years in lead*	*Starting year*	*Last year*
Sweden	10	1840	1973
Norway	48	1841	1969
Australia	8	1861	1920
New Zealand	57	1876	1947
Denmark	2	1918	1919
Iceland	19	1941	1984
The Netherlands	1	1964	1964
Switzerland	1	1985	1985
Japan	15	1986	2000

Source: Oeppen and Vaupel (2002, Supplementary Material, Table 2)

remained leaders until 1986 when Japan took over the lead position. Except for two years, during which the Netherlands and Switzerland respectively out-performed all other countries, Japan has continued to hold the world record until the present day. Thus, three of the nine countries demonstrate outstanding life expectancy figures for very limited periods, i.e. a year or two, and for one of these, Australia, annual data is in fact lacking. Only two single values are used for Australia, of which one is used to cover a 7-year period in the 1860s and 1870s (Oeppen and Vaupel 2002, Supplementary Material, Table 2).[1] That leaves five countries which among them share the world record for 148 out of the 160 years that the analysis covers: Sweden, Norway, New Zealand, Iceland, and Japan. The focus will hence be placed on these five leading nations.

[1] The data that Oeppen and Vaupel use stems from Rowland and cover periods between nine to sixteen years in length. The value for 1861-63, 1867-68, and 1874-75, when Australia is in lead, is based on the average of the period 1860-1875, in which the value is lower than for Norway. Since we don't know if it in the lead in any of these particular years or not, we leave Austriala out of the following discussion.

Figure 1 Female life expectancy 1751-2001



Sources: The Human Mortality Database, University of California, Berkeley (USA), and Max Planck Institute for Demographic Research (Germany), available at www.mortality.org or www.humanmortality.de (data downloaded on 7 October 2005); *Hagskinna. Icelandic Historical Statistics* (1997). Jónsson G. and M.S. Magnússon (eds.); and Nanjo and Kobayashi (1985).

Sweden and Norway have the highest levels of life expectancy from 1840 until data become available for New Zealand in 1876. For a decade, the New Zealand level exceeds the two Nordic countries with almost 5 years. However, the improvement is somewhat faster in the two Nordic countries than in New Zealand, which means that they converge and finally catch-up in the beginning of the 1940s, as shown in Figure 1. This is the period in which the decline in infant and child mortality drives up life expectancy. It is also the period when mortality in low virulent infectious diseases declines. Thus, the question is what makes these three countries stay ahead of all others as regards mortality in infectious diseases among infants and children during this 100-year period. Further, if comparing the three, why is New Zealand unable to improve as fast as Sweden and Norway and keep its superiority?

In the period after the Second World War, in the countries that started the mortality decline in the nineteenth century, life expectancy was mainly driven by reductions in mortality among the elderly due to a reduction in chronic diseases. Up until 1985, when Japan took over the lead, Iceland, and for some years Norway and Sweden, exhibit the highest life expectancy rates. It is noticeable that while New Zealand, Norway, Sweden, and also Iceland, level off as they come into the phase where life expectancy no longer mainly is driven by reductions in infant and child mortality, Japan does not. Once again, the question is what factors make these five countries more successful than the rest of the world.

Causes

Beyond Six Billion by Bongaarts and Balata (2000:117-123), which Oeppen and Vaupel refer to as regards changes in lethal diseases, not only gives an overview of the diversity of diseases during various phases but also supplies an explanation much in line with Riley (2001) and Omran (1971) and which can be summarised as follows:

1st stage 1700-1800
Reduction in volatility/epidemics due to

1. more stable consumption (better storage and transportation) giving higher resistance
2. decline in virulence of pathogens

2nd stage 1800-1900
Reduction in infectious diseases (influenza, pneumonia, bronchitis, TB, and smallpox) due to

1. increasing standard of living through improved health behaviour
2. public health measures including smallpox vaccination

3rd stage 1900-1960
Reduction in infectious diseases due to

1. reduced exposure
2. reduced transmission

4th stage 1960-1996
Reduction in chronic diseases (cardiovascular, cerebrovascular and some cancer diseases) due to

1. early detection and prevention
2. improvement in surgical procedures
3. refinement of medical therapies

Table 2 GDP per capita in 1870 (in 1990 international dollars)

Country	*GDP/capita*
United Kingdom	3 191
Netherlands	2 753
United States	2 445
New Zealand/Australia/Canada	2 339
Sweden	1 664
Norway	1 432

Source: Maddison (2001, Table B-21)

The question is whether these factors explain why the five countries are in the lead and why the development of female life expectancy is linear. How well did Norway, Sweden and New Zealand do in terms of standard of living, improved health behaviour, and public health measures in comparison to other countries up until the Second World War?

Regarding Norway and Sweden, they did not perform well in terms of living standards in the latter 1800s. GDP per capita in 1870 (in 1990 international dollars) was low compared with the US, the Netherlands and England, as shown in Table 2.

While real wages for workers in Sweden increased after 1870 (Bengtsson and Dribe 2005; Jörberg 1971), we are less certain of the development prior to that. In fact, during the first part of the nineteenth century, the majority of people might even have been worse off than during the eighteenth century (Bengtsson and Dribe 2005). GDP per capita for Norway was even lower than for Sweden. In New Zealand, GDP per capita was well above the Nordic countries, to the extent that it was almost on a par with the most advanced European countries. While the ranking of New Zealand versus the two Nordic countries correctly reflects their position regarding life expectancy, the rest is contrary to what we could expect given the countries' economic performance.

The Nordic countries are today known for their flat income distribution. Historically, though, this has not been the case. The income distribution in the beginning of the nineteenth century – a period of commercialization of agriculture and rapid economic transformation – was most likely spread. Several indicators show that while the income for landowners increased, it decreased for non-landed groups making the latter more vulnerable to variations in food prices (Bengtsson 2004; Bengtsson and Dribe 2005).

Turning to *health behaviour*, we have no evidence that Norwegians and Swedes were better-off than other Europeans; rather the opposite. Malthus, for example, reports from travelling in Scandinavia that Swedes were dirty and poorly fed (James 1966:67). They did not even have proper inns for travellers. Malthus statement refers to the beginning of the nineteenth century but similar depictions can be found well into the 1930s, when the deprecia-tory concept *Lortsverige* (Dirty-Sweden) was coined (Nordström 1938).

Riley claims that Sweden was very successful in terms of public health measures (Riley 2001). He states that the vaccination campaigns eradicated smallpox. While it is true that Sweden experienced rather few deaths in smallpox mortality after vaccination started in 1801, most of the decline in smallpox mortality, nevertheless, took place before this time (Bengtsson 1998, 2001; Sköld 1996). Smallpox vaccination was not the only public health improvement undertaken. Other measures include breast-feeding campaigns, education of midwives, disease control, investments in water supply and sewage systems, and promotion of improved personal hygiene.

Without doubt, investments in water supply and sewage control did have effects on mortality in urban areas after c. 1880, even more so in more urbanized countries than Norway and Sweden, both of which both were predominantly rural countries at this time. In fact, most cities in both Norway and Sweden in the mid-nineteenth century, when the two were in the lead, were small; no more than large villages by contemporary West European standards. By the same standards, only the two capitals could rightly be defined as cities, which gave Norway and Sweden a comparative advantage at a time when water supply and sewage control still were insufficient in most urban regions. The urban toll was thus less heavy in less urbanized countries, like Sweden and Norway, than in the more developed parts of Western Europe.

As for other public health measures, such as the breast-feeding campaigns that took place in Sweden from the 1830s and onwards, a certain local impact in areas where breast-feeding was uncommon was reported (Brändström 1984), but the influence on national levels of infant mortality was slight. Incidentally, childhood mortality in fact went up in Sweden during the period when these campaigns started (Fridlizius 1984). Other measures, like the training of midwives, commenced about the same time as the breast-feeding campaigns. Taken together, it is likely that they had some impact on the infant mortality decline from around the 1830s onwards.

The question of improved storage of food and other undertakings aimed at stabilizing consumption which, according to Bongaarts and Bulatao (2000) were important for the mortality reduction in the eighteenth century, constitutes a controversial issue. Firstly, we have no evidence of such measures being taken in the Nordic countries and secondly, it is unlikely that such initiatives would have influenced trends in infant and child mortality to any significant degree (Wrigley and Schofield 1981).

To summarize, Sweden and Norway had no advantage in terms of living standards or equal income distribution in the nineteenth century when they exhibited the highest level of recorded life expectancy in the world. Neither were they particularly well-organized with regard to, for example, the poor relief system. However, several public measures, like the above mentioned education of midwives and breast-feeding campaigns, were carried out in order to improve public health. They were also favoured by a low degree of urbanization. But perhaps most important of all, they were lucky to escape from highly virulent diseases, i.e. smallpox, even before vaccination programs started.

For New Zealand, which held the position of world leader in life expectancy for 57 years of the 160-year period, other factors were instrumental. In 1876, the first year data is available for New Zealand, there are indications showing that the country's white population was the most long-lived on Earth and that the level of living standard was well above the Nordic countries, as well as most other countries of the world. The situation also differed in that a large share of its rapidly increasing population was made-up by immigrants. Furthermore, not only is it reasonable to assume these immigrants to be of reasonably good health, in particular considering that they had travelled long-distance, most of them were selected for their qualities and also underwent at least one health test, for phthisis (Pool and Cheung 2005). New Zealand also became a well-organized society with an expanding public sector. It can easily be compared to Britain in terms of health organisation and institutions but without the burden of large cities and with a selected population, thus almost as a natural experiment with the UK as a point of departure.[2] Still, however, improvements in life expectancy were slower than in Norway and Sweden. Thus, the lead for New Zealand is much a result of its initial superiority: a selected, well-fed, well-organized population in combination with a low disease load.

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2 Jim Oeppen made this point during the workshop that this volume is based on. He also noticed that life expectancy on the English country side was on a par with New Zealand during the latter part of the nineteenth century.

In comparing New Zealand with Norway and Sweden, and the three of them with the rest of the world, it is difficult to distinguish any "regular stream of continuing progress" that could explain why these three specific countries on a global scale perform so outstandingly in life expectancy. It is seemingly a basket of factors, partly different in New Zealand from the two Nordic countries, which make them stay at the top. They share the low degree of urbanization and a low disease load and differ in terms of economic resources. They are well-organized in that public schooling was introduced early and that they took public measures to improve health, but so did many other countries without advancing to the lead position and without contributing to the linear development of life expectancy.

Moving on to the latter part of the twentieth century, this period is characterised by *propelled* life expectancy due to declining death rates among the elderly, mainly as an effect of mortality reduction in chronic diseases (cardiovascular, cerebrovascular and some cancer diseases). According to Bongaarts and Bulatao (2000) this is brought about by early detection and prevention of diseases, improvements in surgical procedures, and refinements of medical therapies. The question is why Iceland and, post-1986, Japan perform better than all other countries within these areas.

Starting with Iceland – the world leader for 19 years between 1941 and 1984 – it has an historical development that sets it apart from the other Nordic countries. While Iceland had a stagnant population throughout the nineteenth century, the other countries experienced steady population growth. In addition, mortality was higher and life expectancy was lower than in any of the other Nordic countries. The Icelandic life expectancy at birth during the 1880s is about 10 years less than Norway and Sweden. In the last decades of the nineteenth century and in the beginning of the twentieth century, however, mortality drops dramatically and in the 1940s, Iceland is on a par with Norway and Sweden, as shown in Figure 1. Causing the catch-up is a fall in infant and child mortality. Due to the high infant and child mortality in the latter part of the nineteenth century, the proportion surviving to ages above 65 years in the 1940s was very low compared with the countries in the lead. Thus, the population at risk in Iceland is constituted in a different way than New Zealand, Norway and Sweden since the females in older ages represented a much smaller proportion of their birth cohorts than in the other three countries. As the difference with the other countries diminishes, Iceland follows the same pattern of life expectancy as Norway and Sweden. In some of the years in the post-World War II period their life expectancy is slightly higher, in some years it is lower.

Japan differs somewhat from the other countries and had it not been for this country, the linear development would have been interrupted by the 1980s since the life expectancy in Iceland, Norway, Sweden, and New Zealand is levelling off. Japan is a country with a very high income level, attained only over the last decades. Previous to its rapid economic development from the 1960s onwards, the situation was less favourable and life expectancy was rather low. In fact, Japan is an example of one of the newly industrialized countries that have shown a tremendous development during the course of the twentieth century. Life expectancy for women rose from 60 years in 1950 to 80 years in 1984. This is not a development of life expectancy by 2.92 but by 6.00 months per year! Is this due to early detection and prevention of diseases, improvements in surgical procedures, and refinements of medical therapies causing mortality among the elderly to decline? It is surely not; rather it is an exemplary case of the catch-up of a rapidly developing country. The increase in life expectancy is not mainly driven by mortality improvements solely among the elderly but within a wider age span.

The rapid change in Japan also has some characteristics in common with Iceland that are important in making comparisons with the old leaders. The rapid transition from high to low mortality within a short period of time means fewer elderly relatively speaking. For example, while 90 percent of the women born in Sweden in 1935 have reached the age of 65 years, the corresponding figure for Japan is only 60 percent[3]. Thus the population age structure in 2000 is entirely different in Japan comparative to Sweden. This has two implications. First, the Japanese women at higher ages contributing to the period life-expectancy in year 2000 are highly selected in comparison to the Swedish older women. If the "scarring" effect is smaller than positive selection effects then the Japanese elderly would be expected to be less fragile than their Swedish counterparts[4]. Second, due it its late fertility transition, the elderly are relatively speaking fewer in Japan compared with Sweden. While the proportion 65 years and over in Sweden reached 8 percent in 1900, the corresponding figure was reached in Japan more than 70 years later. Because the Japanese elderly are fewer, relatively speaking, the costs for pensions and care are smaller for the Japanese vis-à-vis the Swedish working generation.

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[3] Based on data from *Population Statistics of Japan 2003*, complied by National Institute of Population and Social Security Research, Japan, and Befolkningsutvecklingen under 250 år (*Population Development in Sweden in a 250-year perspective*), Demografiska rapporter 1999:2, Statistics Sweden

[4] See Preston 1998, p. 1232.

Summary and Discussion

We started off by pointing out that very few countries, only nine, have held the leading position in life expectancy at birth over the last 160 years, and only five of them did so for more than a few years. Typically, new countries caught up with and replaced former best-practice countries for several decades. However, we can note that this has not only been the case for life expectancy but has also occurred in other areas of human activity, such as economic performance. The total number of leaders in GDP per capita corresponds in size to the number of leaders in life expectancy, albeit they are not the same countries. The list of GDP leaders, ranked from high to low according to years at the lead and for roughly the same period, is as follows: the USA, Australia, Switzerland, the UK, and New Zealand (Maddison 2001). The fact that this list is different from that for life expectancy, emphasizes the relevance of Easterlin's conclusions that the mortality decline since the mid-nineteenth century was not mainly driven by economic development (Easterlin 1999). Instead, there are a variety of factors that lie behind the improvements in life expectancy, economic factors constituting only one of these.

High life expectancy in Sweden and Norway in the mid-nineteenth century was due to low infant and child mortality, in particular in infectious diseases. It was not the result of private or societal investments, strong nation-states, high living standards or an equal income distribution. What favoured the Nordic countries was instead a low degree of industrial development and urbanization combined with a low disease load. When New Zealand took over the lead position in 1876 (the first year for there is data), it shared these favourable characteristics of the two Nordic countries, in addition to other favourable conditions such as high income levels and a positively selected population.

Mortality in all age-groups dropped quickly in the early twentieth century but the improvements in life expectancy were still mainly due to the decline in infant and child mortality. During this period it was largely due to societal investments of reducing disease exposure; directly through eradication programs, indirectly through water purification systems and better transportation. This was the case for the most developed countries. For example, the previously large differences between hospital wards in many US cities disappear within a few decades (Fogel 2004). The same process was at hand in countries like Singapore, Sri Lanka, Argentina, Costa Rica, Chile, Cuba, and Uruguay, which later affected the mortality transition (Bongaarts and Bulatao 2000:124). Still, none of these countries reached the highest level of life expectancy. New Zealand remained in the lead and it was instead the Nordic countries, making the same sorts of societal investments, which caught up in the 1940s. Thus, societal investments in infrastructure and high per capita income alone were not that important in determining life expectancy at birth. If this were the case, the US, the UK, Australia, and New Zealand would be at the top.

Iceland had been lagging far behind the leading nations when it started its catch-up which brought it to lead in the 1940s, and for Japan this was even more the case before it became the world leader in the 1980s. Both countries, especially Japan, had a very small elderly population when reaching the top position in terms of life expectancy. Today, life expectancy in the developed countries is not entirely the result of low infant and child mortality, as used to be the case, but instead old age mortality has become important. Medical care and private investments in health are also of greater significance nowadays. Thus Japan had the advantage of rapid improvements in living standards and societal investments in infrastructure, facilitated by access to new types of medical care, all of which they share with the most advanced countries of the world. In addition, they have a smaller group of elderly in the population. This means that the elderly are are a selected group. Since the proportion of elderly is lower in Japan due to its late fertility decline, it also means, *ceteris paribus*, that Japanese senior citizens will have access to more care resources than their equals in countries that have experienced an earlier fertility transition.

Why then has life expectancy in the flow of best-practice countries followed a linear trend for a 160 year period? It is hard to find any specific continuous process that explains such a development. It resembles more the outcome of a diversity of processes, of which some but not all are directly related to human activity. If one compares with economic performance, it is reasonable to ask why life expectancy does not follow the exponential trends of economic output, the signum of economic growth ever since Malthus wrote his first essay, but instead *only* a linear trend? As regards economic development, more resources create more resources for good investments, thus generating an exponential trend. In the Malthusian world, population expanded at an exponential rate and production at a linear rate at best. Here we are confronted with the opposite situation: The economy expands at an exponential rate while the population stagnates and life expectancy develops at a linear rate. The question is then 'why have we been less successful in investments in health than in economic growth'?

It is reasonable that the best-practice path of linearity could be used for forecasting life expectancy for countries still in the catch-up phase, assuming that they have the economic means and incentives to invest in best-practice technology. Countries with a rapid catch-up, like Iceland and Japan, also has the advantage of having a relatively smaller proportion of elderly for several decades, constituting a sort of population momentum, which works in their favour and which helps them to stay on the path of linear advancement. The momentum, however, disappears after some time and then it is likely that they, like their predecessors at the lead, face a downward bend in life expectancy. Few countries finally became world leaders, still they tend to be replaced and their life expectancy curve levels off. Thus, new countries are catching up and replacing the former leader and contributing to the linear development of life expectancy.

A parallel within economics can be drawn with the so called Cardwell's Law (Mokyr 1990) economics, which states that no country can maintain technological lead for very long. It implies turnover at the top, just as the case was with regard to life expectancy. Several other economists could be referred to, such as Alexander Gerschenkron who developed the concept of Economic Backwardness (Gerschenkron 1966). Perhaps even more to the point are the concepts of the institutional economist Torstein Veblen, who coined the phrases "the penalty of taking the lead" and "the advantage of borrowing the technological arts". Both phrases refer to the disadvantage of old investments, or in the case of human capital, "aged" capital vis-à-vis new capital. These concepts therefore seem highly relevant to apply when evaluating the significance of low proportions of elderly (i.e. "aged" capital) in populations that has more recently undergone demographic transition, as for example Japan. Will then the future pace of life expectancy in Japan slack as a result of the penalty of taking the lead (population ageing) as has be the case for previous world leaders? And will new countries take the advantage of a backward position and reach the top ranks in terms of life expectancy? My answer is 'yes' on both of these questions.

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Försäkringskassan

ISSN 1651-680x
ISBN 978-91-7500-340-5