Life Expectancy in Developed Countries Is Higher Than Conventionally Estimated. Implications from Improved Measurement of Human Longevity

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Abstract

Conventional indicators of human lifespan (Graunt 1661; Chiang 1984) are based on a hypothetical synthesis of the mortality conditions of different cohorts with (as yet) incomplete life histories. There is a considerable ongoing debate about improvements to the traditional methodology under changing mortality rates (Bongaarts and Feeney 2002; Wilmoth 2005; Barbi et al. 2008). Improved measurement of the human lifespan is crucial for estimating prospects of longevity (Wilmoth 1998; Tuljapurkar et al. 2000; Oeppen and Vaupel 2002; Robine et al. 2006; Olshansky et al. 2009) and for understanding the implications of population ageing (Olshansky et al. 2009; Sanderson and Scherbov 2005; Lutz et al. 2008; Council of the European Union 2009). Here we show that both the centuries-long tradition of conventional lifespan indicators and the more recent criticism of them ignore the true exposures of individuals to prevailing mortality levels. These exposures form a genuine part of a more comprehensive picture of the prevailing mortality conditions. In low-mortality countries, our estimated duration of human life is about 95 years, which exceeds the conventional estimates by 15 years. This difference is crucial for health care, long-term care and pension systems. Our theory implies that mortality dynamics are characterised by considerable inertia. This is used to develop new effective methods of forecasting, leading to a more optimistic outlook for future mortality. Even if there were no further change in mortality conditions, conventional life expectancy at birth will rise to 90 years by 2050, while the probability to survive beyond age 100 will reach 30% in low-mortality countries. Conventional longevity indicators still provide a useful summary of the observed mortality rates which, in turn, are essential for population projections. However, they do not give the full picture of current mortality conditions and mislead about the prospects of human longevity.

1 INTRODUCTION

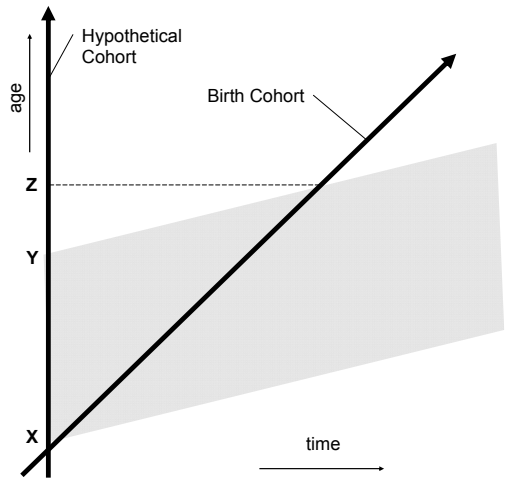
The mean duration of human life can only be estimated after observing the whole lifespan of a given birth cohort, which is not yet possible for cohorts that are still living. Therefore, conventional estimates are obtained by calculating the *period life table* (Graunt 1661, Chiang 1984) which is a combination of currently observed age-specific mortality rates (each of which characterises the mortality of a different birth cohort). The life table is an important tool in population projections, actuarial statistics, epidemiology and biology; it is used to examine social, geographical and temporal variations in mortality.

Common logic behind the conventional calculations was challenged by building on ideas imported from studies on the so-called *tempo effect* in fertility (Bongaarts and Feeney 2002), which generated a remarkable debate. As argued by the proponents of the tempo effect in mortality, the deaths to birth cohorts are underestimated with increasing lifespans because they are stretched beyond the period when they would 'normally' be observed. Such distortions are corrected by special adjustments, which inflate the observed mortality rates to their expected 'normal' level. Somewhat counter-intuitively, such adjustments imply that mortality rates may stabilise only after a significant jump, when mortality conditions suddenly stop improving.

As we argue, however, a recent interpretation (Ediev 2008) of the tempo effect as being caused by the different exposure of birth cohorts and of the conventional hypothetical cohort to similar life stages indicates that both conventional and tempo-adjusted period life tables mislead about the current mortality conditions. Consider the typical case when adult mortality increases with age and decreases with time. In this case, same levels of mortality will be experienced at higher and higher ages by successive cohorts. An illustration to this situation is presented in Figure 1. The grey strip represents the area in the age period (Lexis) surface with a given level of mortality. The strip has a positive slope as the same level of mortality is

observed at more and more advanced ages. Mortality is higher above the strip and lower below it.

Figure 1 Illustration of the tempo effect.



The conventional hypothetical cohort (represented by the vertical line in the Lexis surface) is 'exposed' to the given mortality level during the period indicated by age interval **XY** in the figure. But the actual birth cohorts (represented by the bisector), experiencing what the period life table is supposed to be a combination of, are exposed to the same mortality level over a longer period of time, as indicated by age interval **XZ**. Conventional life tables neglect the real exposures of birth cohorts, cutting off the part of cohorts' experience indicated by age interval **YZ** in Figure 1. This leads to an overestimation of mortality, as the conventional hypothetical cohort is exposed to a higher mortality in the interval **YZ**. The usual adjustments for the tempo distortion in fact even exaggerate this bias by compressing all deaths occurring to the birth cohort during the interval **XZ** into the interval **XY**, thereby inflating the mortality rate. (Usual tempo adjustments assume a somewhat different picture, describing mortality conditions by standardised

death counts; this difference is not relevant to logic of our discussion though.) A better approach, which would also reconcile some mutually exclusive aspects of both traditional theories, would be to assume that the hypothetical cohort experiences observed mortality rates over exposure periods of the same duration as birth cohorts do (see the Methods section). These are combinations of rates and of exposures to them, not just of the rates alone, which characterise the experience of real people. (See more on this in the Discussion section below.)

2 WE MAY LIVE CONSIDERABLY LONGER THAN CONVENTIONAL LIFE EXPECTANCY INDICATES

Most recent conventional and exposure-adjusted life expectancies averaged over selected countries (data source: the *Human Mortality Database*[1]) are presented in Table 1 and Fig. 2.

On average, the exposure-specific calculations produce period life expectancy at birth of about 90 years, which exceeds the conventional estimates by ten years. Excluding countries in transition (the former Eastern block), which still have considerably high mortality levels, average exposure-adjusted life expectancy at birth of more than 95 years are produced. Estimates based on a correct account for exposures to the prevailing mortality levels reveal a twice-as-high variation in life expectancy as compared to the variation suggested by the conventional method.

For some populations, exposure-adjusted life expectancy at birth is almost 100 years (Australia, Austria, Canada, France, West Germany, Ireland, New Zealand, Norway, Portugal, Sweden and Switzerland). Among countries in transition, only in East Germany does exposure-adjusted life expectancy at birth approach the average for the low-mortality countries. In

[1] The *Human Mortality Database,* sponsored by University of California, Berkeley (USA) and Max Planck Institute for Demographic Research (Germany), www.mortality.org or www.humanmortality.de.

Belarus, Latvia, Lithuania, Russia and Ukraine, exposure-adjusted estimates are close to, or even lower than, the conventional ones.

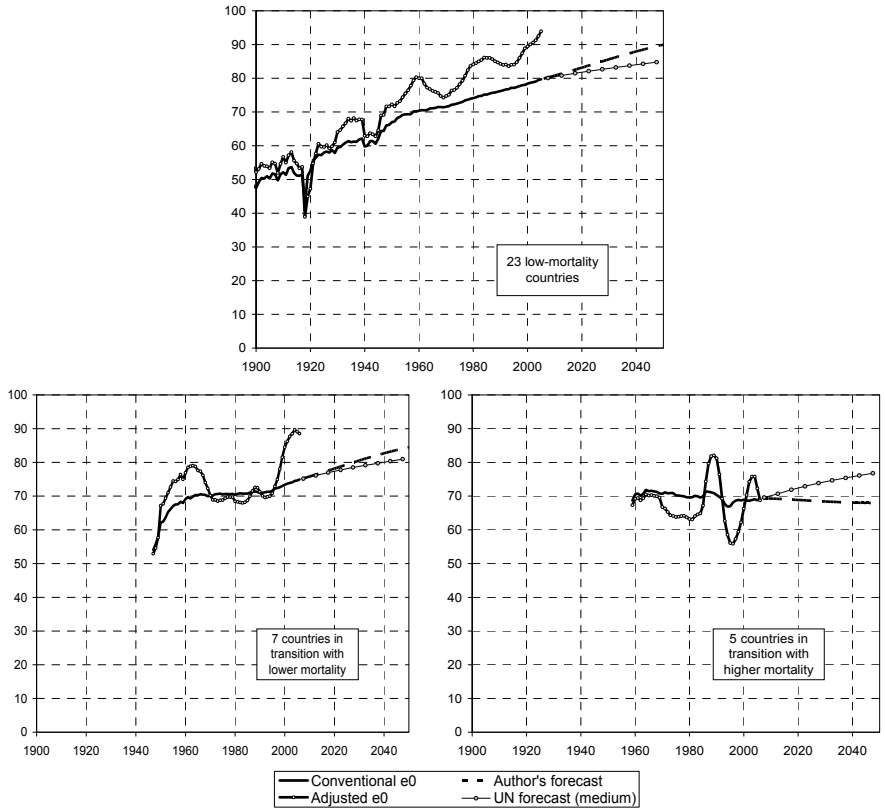
Another optimistic outlook is indicated by exposure-adjusted estimates of the probabilities to survive beyond a certain age. According to these estimates, in low-mortality countries up to 30% of people may survive beyond age 100 in the future. A projection based on the assumption of constant mortality conditions (see the method below) implies that such probabilities of conventional period life tables could already be observed by 2050. The probability of surviving to age 100 may well repeat the dynamics of the probability of surviving to age 90, which has already increased from rather low levels to 20%. Meanwhile, according to our projections, the proportion of people surviving beyond age 90 in low-mortality countries may exceed 60% in the coming half-century.

Table 1 Conventional and exposure-adjusted life expectancy at birth and at age 65.

	Life expectancy at birth, e_0 (years)		Life expectancy at age 65, e_{65} (years)		
	conven-tional	adjusted	conven-tional	adjusted	adjusted - for those aged 65
Average over 35 countries	77.5	89.6	17.9	29.8	21.1
Standard deviation	*4.2*	*10.2*	*1.9*	*7.8*	*3.2*
Average – excluding CIT [a]	80.0	94.7	19.1	33.6	23.0
Standard deviation	*1.2*	*3.8*	*0.7*	*3.3*	*1.2*
Average over CIT [a]	72.7	79.9	15.7	22.6	17.5
Standard deviation	*3.6*	*11.7*	*1.3*	*9.0*	*2.8*

[a] Countries in transition include 12 populations of the former Eastern block

Figure 2 Conventional and exposure-adjusted life expectancy at birth (years). Selected countries.



3 MORTALITY CHANGE SHOWS INERTIA. NEW APPROACH TO MORTALITY FORECASTING

The difference between the period 'exposures' and actual cohort exposures, even assuming constant mortality conditions (by which we understand a combination of rates and exposures), implies that the future age pattern of mortality will be different from the one currently observed. It will be decompressed in the upper part of the age scale and compressed for child mortality. This built-in prospect of transformation may be interpreted as the

mortality inertia: once observed, the change of mortality will tend to continue until mortality complies with the exposure-adjusted pattern.

The dynamics of age-specific mortality rates associated with the mortality inertia may be used in forecasting. The technique is relatively straightforward, albeit principally different from conventional extrapolations (see Methods section). The efficiency of the forecasting method is illustrated by forecasts assuming constant mortality conditions since 1980 (Table 2).

An examination of results country by country reveals that it was exclusively countries in transition which outperformed the would-be forecast by five years or more. Given profound changes in those countries, such an outcome does not seem all that unnatural. A good performance of the method indicates that the mortality inertia may be a characteristic feature of mortality dynamics. It also indicates that the widespread mortality decline in recent decades could have been, to a large extent, a mere result of continuation of the same mortality conditions as in 1980. However, mortality conditions have also improved since then, as shown by the exposure-adjusted estimates above. This indicates a further decline of mortality.

A comparison of our forecasts based on recent data to the medium-variant UN projections (United Nations Statistics Division 2009) (Table 3, Fig. 1) reveals that our method, though assuming constant mortality conditions, results in an approximately 1.5 times higher forecast increase of the conventional life expectancy at birth by 2050 (nearly twice as high when countries in transition are excluded). Only for high-mortality countries in transition does the UN assume a higher increase of life expectancy which, however, may still seem unrealistic in view of past trends. A comparison to other traditional forecasts also shows that they may significantly underestimate the future mortality decline (Tuljapurkar et al. 2000; US Census Bureau 2009). Only unconventional forecasts based on extrapolating life expectancy at birth provide results that are similar to ours (Mamolo and Scherbov 2009).

Table 2 Extrapolations of the conventional life expectancy at birth and at age 65 assuming time-invariant mortality conditions since 1980 as compared to observations (years).

	Conventional life expectancy at birth					Conventional life expectancy at age 65		
	1980		1990	last year		1980	last year	
Population	obser-ved	obser-ved	fore-cast	obser-ved	fore-cast	obser-ved	obser-ved	fore-cast
Average over 34 countries	72.7	74.3	73.5	77.4	74.6	15.1	17.9	16.7
Standard deviation	*2.4*	*3.0*	*3.8*	*4.2*	*6.4*	*1.1*	*1.9*	*3.9*
Average – excluding CIT [a]	74.2	76.3	76.0	80.0	78.8	15.7	19.1	19.2
Standard deviation	*1.3*	*1.2*	*1.7*	*1.1*	*2.7*	*0.8*	*0.7*	*2.2*
Average over CIT [a]	70.0	70.7	69.0	72.7	67.0	14.1	15.7	12.1
Standard deviation	*1.2*	*1.1*	*1.8*	*3.6*	*3.2*	*0.7*	*1.3*	*1.2*

[a] Countries in transition include 12 populations of the former Eastern block

Conventional extrapolations of mortality tended to underestimate the nearly linear growth of life expectancy in the past (Oeppen and Vaupel 2002; Sanderson and Scherbov 2004; Bengtsson 2006). Our model, by contrast, provides results which are consistent with the mortality dynamics in the past and produces more optimistic projections into the future. There is a rather simple explanation to this. Usual mortality projections rely on extrapolating mortality rates age by age. In that way, it is impossible to foresee the onsets of the mortality decline which, as was usually the case at advanced ages, are anticipated by periods of mortality stagnation. This does not apply to our method, which involves decompressions of the age pattern of mortality and therefore 'shifts' the mortality conditions observed at younger ages to older ages. Somewhat similar ideas of shifting the mortality

age schedule upwards have been proposed in the literature (Bongaarts 2005) and also applied for projecting mortality in Japan (Kaneko 2007). This resulted in the forecast life expectancy at birth, which is still below our estimates by about four years.

Table 3 Extrapolations of the conventional life expectancy at birth and at age 65 assuming time-invariant mortality conditions in the future (years).

	Conventional life expectancy at birth				Conventional life expectancy at age 65		
Population	2015	2025	2050	UN 2045-50	2015	2025	2050
Average over 35 countries	79.1	81.1	85.7	82.9	19.3	21.0	25.6
Standard deviation	*4.9*	*5.9*	*8.3*	*3.3*	*2.4*	*3.2*	*5.7*
Average – excluding CIT [a]	81.9	84.4	90.0	85.0	20.7	22.9	28.5
Standard deviation	*1.2*	*1.4*	*2.3*	*1.1*	*0.7*	*1.0*	*1.9*
Average over CIT [a]	73.7	74.9	77.6	79.2	16.6	17.5	20.0
Standard deviation	*4.8*	*6.4*	*9.6*	*2.8*	*2.0*	*3.1*	*6.6*

[a] Countries in transition include 12 populations of the former Eastern block

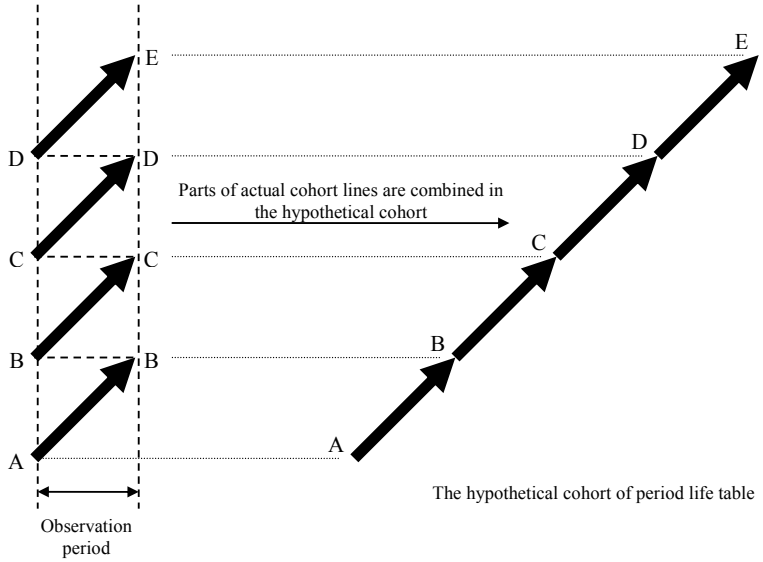
4 DISCUSSION

In the following, I discuss links to the tempo theory, inconsistencies of the conventional period life table and lines of further research.

The approach presented was inspired by the previous work on tempo theory (Ediev 2008) and clearly fits into the discussion on mortality tempo. Two differences of our adjustment to those in the literature may be noted here. First, similar to the 'tempo-sceptic' approach, we do not describe mortality conditions by death counts or cohort survival proportions. Instead, following conventional practice, we use age-specific mortality rates (theoretically, the force of mortality). The death counts are a product of the prevailing rates and population exposed; therefore, they are considered as mixing up current mortality conditions and the cumulated effect of the conditions in the past on current population numbers. Second, studies on mortality tempo so far—similar to the traditional no-tempo approach and unlike ours—have not considered *durations of exposures* to different mortality levels as part of the story. Therefore, those works implicitly assume the 'complete' death counts (partially stretched or postponed beyond the observation period) to be allocated within traditional exposure periods equal to the duration of the observation period, thus distorting, in our view, the mortality rates. The basic balance $Deaths = Exposure \times Rate$ makes inevitable such substitution of distorted exposure duration by distorted rate given the distorted deaths count.

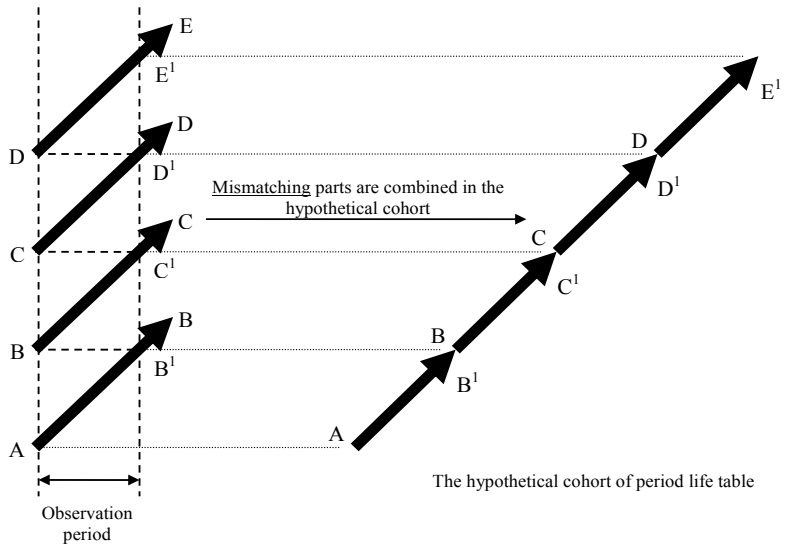
To see that the adjustments presented here are not related to how technically we estimate the mortality rates, to the usage of rates computed for quadrangles as opposed to triangles in the Lexis surface, etc., we present several schematic illustrations in the following text. Let us assume that we have full knowledge about birth cohorts' experiences and that births in each cohort are not spread over the whole year but rather cumulated on a single birth date, e.g., 1 January. Consider, first, the static situation of time-invariant mortality. The logic of the conventional period life table may be

illustrated by the following schematic (see explanation below the illustration):



The arrows in the left part of the illustration correspond to four selected birth cohorts, which fall under observation in the current period (which we assume for simplicity to have a duration of one year, although this may be arbitrarily short; we also consider the case of mortality increasing with age). The youngest cohort enters into the observation period with a mortality level labelled ‘A’ and by the end of the year its health deteriorates and mortality reaches level ‘B’. Since we assume the static mortality situation, the next cohort, which enters the observation period at the same age at which the first cohort exits from the observation period, must also have mortality level ‘B’ when entering the observation period. In a similar way, the second cohort exits the observation period at mortality level ‘C’ equal to the initial mortality for the third cohort, etc. For the lack of data on cohorts’ future and past and for the need to reflect on contemporary mortality conditions only, the period life table technique piles up the

observed parts of cohorts' experience to produce a hypothetical cohort following at each age the same mortality rates as the cohort which is passing through the same age in the observation period. This is a natural synthesis of the time-invariant mortality conditions and the outcome of it has a clear interpretation in terms of life-long mortality experience of a birth cohort following the same conditions as currently observed. It also provides a correct reconstruction of mortality experience of all cohorts observed provided there was no change in mortality. This may have been the case for pre-20th century mortality, when mortality was showing only modest systematic temporal changes (and when the life table methodology was established). It was not, however, the case for 20th century mortality, nor is the static situation relevant to contemporary mortality dynamics. To illustrate the consequences of the traditional period life table methodology in the case of systematically changing (in our example, decreasing) mortality, let us improve the illustration by assuming mortality (static prior to the observation year) to decline in all ages in the observation period:



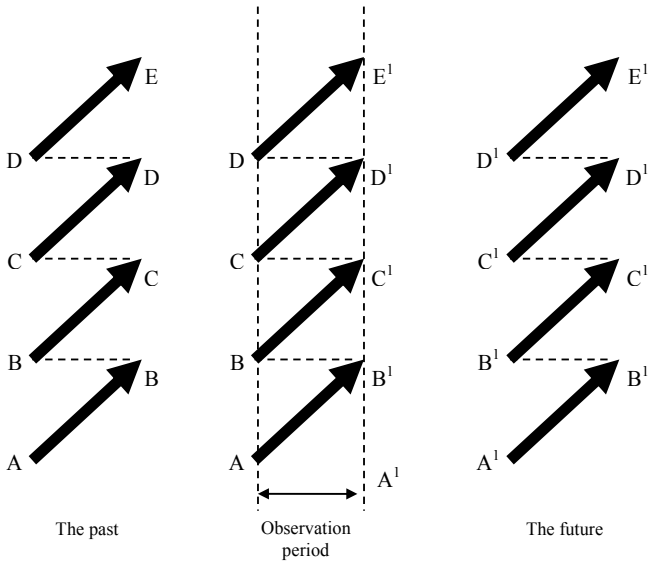
The important difference to the previous example is that now each cohort ends up by a better health condition (lower mortality level) by the end of the observation period as compared to what was the experience of cohorts in the past. Hence, the first cohort shown in the illustration reaches mortality level $\mathbf{B}^{\mathbf{1}}$ by the end of the observation period, which (the level) is lower than the entrance mortality level of the older cohort (**B**). The older cohort has lived through the first age group shown in the illustration under the past (worse) mortality conditions and, therefore, has naturally appeared in the observation period at higher mortality than the younger cohort of respective age. The same applies to other cohorts. Each cohort will take more than one year to reach the mortality level that was observed for a one-year older cohort at the beginning of the observation period. The traditional period life table disregards those differences and piles up the parts of cohorts' mortality experiences which fall within the observation window (see the right-hand side of the illustration). Doing so, it produces a hypothetical cohort with an interrupted mortality schedule: the hypothetical cohort starts at mortality level **A** (as the youngest cohort in the observation period), moves to mortality level $\mathbf{B}^{\mathbf{1}}$ and then suddenly jumps on to the higher-mortality level **B** and so on, continually skipping parts of the natural sequence of mortality rates. This unnatural discontinuity of mortality also misrepresents empirical mortality conditions. In the period life table, a person who ages to the point at which his or her mortality is $\mathbf{B}^{\mathbf{1}}$ immediately proceeds to mortality level **B**, while current data indicate that such a person must still enjoy a period of lower mortality before reaching level **B**.

Another way to appreciate the bias of conventional period life tables as representations of the current mortality is to consider what would happen if mortality conditions—as depicted by these life tables—were assumed to be constant in the future. The logic of the conventional life table implies that such a scenario simply means constant age-specific mortality rates in the future. Despite its appealing simplicity, this scenario brings counter-intuitive developments of mortality conditions for real people. Consider, for example, the youngest cohort in the illustration. Next year, the cohort ages by one year

and—as a consequence of the constant mortality rates assumption—must have the same mortality as the second cohort had in the observation period, i.e., its mortality must change from level **B** to level $\mathbf{C}^{\mathbf{1}}$. However, the cohort we look at has already been observed to have mortality level $\mathbf{B}^{\mathbf{1}}$ by the end of the current year. In other words, people from the younger cohort have only reached mortality level $\mathbf{B}^{\mathbf{1}}$ by 31 December, of this year, while the naïve 'constant mortality' scenario implies that this cohort should have had the higher mortality level **B** already on 1 January. Such a scenario can by no means be labelled to show 'constant mortality conditions'. Instead, it assumes—at each and every age—a mortality that is worsening overnight between the end of the current year and beginning of the next year. (Such an outcome of the conventional 'constant mortality' scenario also applies to the realistic case of cohorts evenly spread over all possible birthdates.)

In practical life tables, the problems illustrated above are concealed because we do not have exact knowledge about instantaneous mortality rates. Instead of tracing how mortality changes from level **A** to level $\mathbf{B}^{\mathbf{1}}$, we would normally estimate their average, assign it to the first age group and then move to the next age group, where the mortality estimate would be the average of levels **B** and $\mathbf{C}^{\mathbf{1}}$. Since the procedure is already discrete, the interruptions presented in the illustration above would not be apparent.

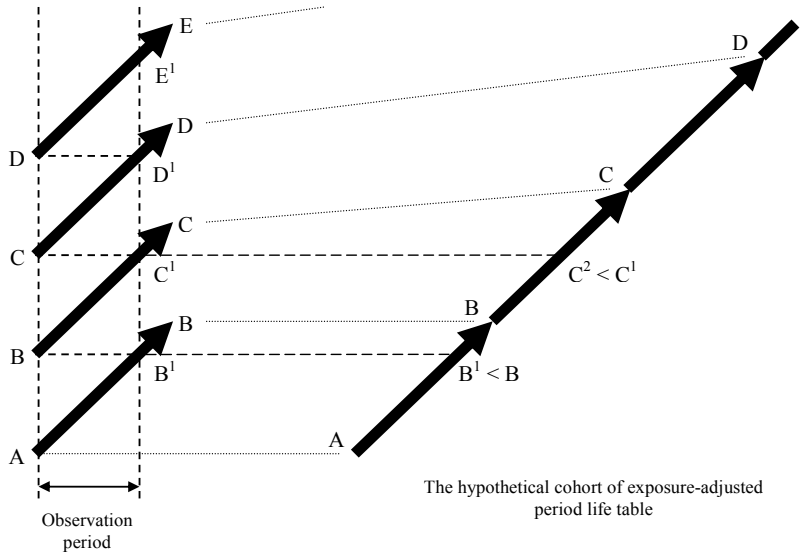
One may suspect that the problem illustrated above is because we consider an unfortunate constant-mortality scenario copying discrete observation periods into the future. Perhaps we should have considered a scenario in which future force of mortality is a smooth function of age, time-invariant and copied from the very last observation moment of the current year, i.e., from the boundary line between the current and next observation period? After all, there is no mathematical problem in assuming a scenario $\mu(x,t) \equiv \mu(x,t_1)$ at $t \geq t_1$, where t_1 is the very last moment of the current observation period. Such a scenario is illustrated below:



Indeed, this might be a scenario for the future, though it is by no means consistent with intuitive expectation. Consider, for example, the second age group. In the future, our scenario assumes people to pass from mortality level $\mathbf{B^1}$ to the level $\mathbf{C^1}$ while passing through the age group under consideration. Already in the current year, however, the second youngest cohort in the illustration has moved from the higher mortality level **B** to the same eventual mortality level $\mathbf{C^1}$, all the while being in the same age group. Hence, against intuition, in the future individuals' health will deteriorate faster than it happens for those currently observed: although they start off with better health conditions (as indicated by lower mortality), they do not end up being healthier than the current population by the end of the age group. Paradoxically, time-invariant death rates in the future imply a sudden acceleration of health deterioration for individuals if the time-invariant phase is precluded by a period of mortality decline. The 'ideal' conventional period life table, skimming forces of mortality along a vertical (time) line in the Lexis surface, mistakes the difference between the age when an individual experiences a force of mortality $\mathbf{B^1}$ and the age when another individual

experiences mortality level $\mathbf{C^1}$ for the duration of *time* over which an individual moves from level $\mathbf{B^1}$ to level $\mathbf{C^1}$. However, a difference between ages may indicate time intervals only within the same cohort. Difference between age **X** of one cohort and age **Y** of another cohort is not a time duration at all. Only in the case of constant mortality may we consider age to tell the same story irrespective of the cohort to which it refers, and take differences between the ages of different cohorts as durations of time over which people move from one condition to another.

Our alternative hypothetical cohort assumes a different synthesis and takes complete account for cohorts' exposures to different mortality levels. An illustration based on our simplified schematic is presented below.



In the exposure-adjusted synthetic cohort, the duration of exposure to any given mortality level is taken as it is estimated for the birth cohort currently observed at that level. Take for example the youngest cohort. According to current observations, the cohort 'ages' from mortality level **A** to mortality level **B** over a period estimated to be longer than one year (for

simplicity of illustration, we do not assume observations for younger cohorts and therefore do not introduce a lowered mortality level $\mathbf{A^1<A}$ as a starting point for future cohorts). As this is the cohort who most recently experienced the levels of mortality mentioned above, we imply a similar exposure period to mortality varying from **A** to **B** in the future. Once the hypothetical cohort reaches mortality level **B**, we move to the next cohort, which experienced that level most recently, implying that the hypothetical cohort will 'age' until mortality level **C** at the same pace as we have recently observed for the second youngest birth cohort. The procedure continues in a similar way for other mortality levels. In our method, we make sure that people's fragility in the future (reflected by their death rate) is worsening by age at exactly the same speed as currently observed. The paradox described above for the conventional 'constant mortality' scenario does no longer exist: in the future, people enter the second age group at lower mortality $\mathbf{B^1<B}$ than the currently observed cohort and, accordingly, end up with a lower mortality $\mathbf{C^2<C^1}$ by the end of the age group.

An alternative interpretation of our adjustments may be developed in terms of mortality change within the observation period and not in terms of exposures. In the illustration above, the mortality of the second cohort has increased by $\mathbf{B/C^1}$ times in one year. The conventional period life table, mistaking the age difference for a time period, implies mortality to increase, at that same age and time interval, by $\mathbf{B^1/C^1}$ times, which is against empirical knowledge about what actually happened during the observation period. In fact, adjustment coefficient (1) presented in the Appendix, is exactly the ratio of the change rate of mortality rate along the time line (i.e., in the conventional period life table) to that along the cohort line (i.e., how it actually changes for the individuals observed).

The examples above are also helpful in illustrating mortality inertia: assuming constant mortality conditions for individuals does imply the existence of a transitory period in the future, when age-specific mortality rates *must* change if they have changed in the observation period. During the transitory period, currently younger cohorts will enter older ages where,

having better starting health conditions, they will show a lower mortality than the currently older cohorts. These transient dynamics must not be mistaken for the usual mortality extrapolation. At old ages, where mortality was stagnant in the past, extrapolation would predict stagnation in the future as well, while mortality inertia implies mortality to be eventually declining at those ages because of better health conditions shifting from younger age to older ones. On the other hand, extrapolation would assume an endless mortality decline, while mortality inertia is bound to cease once new cohorts following the new mortality schedule have replaced all old cohorts.

Apart from its consequences for measuring longevity and assessing its prospects, the effect of an artificially accelerated worsening of mortality implied by the conventional period life table has consequences for the discussion of the rectangularisation of the survival curve (e.g. Fries 1980; Wilmoth and Horiuchi 1999; Kannisto 2000; Canudas-Romo 2008; Thatcher et al. 2010). The above 'paradoxes' show that the usual way of studying that process based on period life tables may be misleading, because the period life table—by its very design—compresses the life experience of individuals at each age group when mortality tends to decline.

Our hypothetical life table assumes a decompression of the mortality schedule and unchecked shifts of exposure intervals along the age scale. In reality, such a decompression may be limited if the chronological age as such does matter for biological ageing (e.g., if there are strict biological limits to the human lifespan). However, the consistency of mortality inertia with the recent mortality dynamics suggests the possible validity of our period life table assumptions for actual cohort mortality, so the exploration of this problem (also in relation to mortality rectangularisation) seems promising.

Indicators of life expectancy summarise the set of prevailing mortality rates in the easily interpretable form of an indicator of longevity measured in years, not in percentages dying. Several such summaries have been proposed in the literature, and we provide another one. Therefore it is worthwhile comparing their substantive interpretations. Life expectancy may

be interpreted in two ways: as an expected duration of life and as a mean age at death. CAL (Brouard 1986; Guillot 1999, 2003, 2006; it is the sum over all cohorts of proportions survived to the observation period), for instance, may be interpreted as the mean age at death during the observation period in a population with time-invariant number of births (Wilmoth 2005). It is a useful indicator of the effect of past mortality conditions on the contemporary age distribution of deaths. CAL is also helpful in assessing the role of past mortality on current population size and population momentum (Guillot 2003) and on actual longevity of cohorts observed at the moment (Wilmoth 2005; Goldstein 2006; Rodriguez 2006). However, CAL is not informative about mortality conditions in the very period of observation; after all, the proportions of individuals who survived up to the present moment (which CAL is the sum of) are not likely to say much about the currently prevailing mortality. Other tempo-adjusted measures are also similar to CAL; in a sense, CAL is the most general tempo-adjusted longevity indicator (Wilmoth 2005; see also in Bongaarts and Feeney 2002). The exposure-adjusted life expectancy (EAL) at a certain age, on the other hand, is oriented forward, reflecting implications of current mortality conditions only for the expected duration of life of those at that same age, assuming that they live the rest of their life under current mortality conditions. Unlike CAL, EAL gives no information about the mean age at death in the observation period. (That would depend on how the past mortality has shaped contemporary numbers and health conditions of individuals at different ages.) The traditional period life expectancy provides a compromise between the two measures. On the one hand, it does not reflect how mortality in the past has shaped current population numbers; unlike CAL, it provides the period mean age at death for a standardised population not according to past mortality but according to the current mortality rates which are used to produce the so-called stationary or life-table population. On the other hand, conventional life expectancy does reflect some of the effects of past mortality: it assumes that in the stationary population, by every age, the health will deteriorate to the same level as it

did for contemporary individuals, who were subject to the past mortality conditions different from the contemporary ones. For the youngest cohort, it estimates the lifespan assuming the same mortality levels as currently observed at older ages, although the youngest cohort experiencing current mortality conditions would have aged more slowly and had a lower mortality at each age as compared to older cohorts if the mortality conditions in the past were not as good as at present. When mortality conditions do not change, both the (standardised) mean age at death and people's lifespan coincide and are well captured by the conventional life expectancy. When mortality conditions change systematically, however, the conventional life expectancy provides no correct estimates for either of the two aspects of age at death; it provides an average between the two, which are better described by CAL and EAL, respectively.

The approximation used here is based on relating the cohort exposure to derivatives of the mortality rate over age along period and cohort lines in the Lexis surface (Eq. (1); see also the interpretation above). There are situations when such approximation will not work. Consider for example the situation where the derivative of the mortality rate equals zero when taken along the cohort line (this happens with minimum mortality ages at 10-30 years). In such case, our adjustment (1) would turn infinite, which would suggest that cohorts are infinitely exposed to the same level of mortality. Similar problems may arise when the derivative of the mortality rate is zero when taken along the vertical (time) line in the Lexis surface (in that case, adjustment (1) would turn zero). Such situations would indicate a failure of the first-order linear approximation of mortality rate as a function of age and the need for higher-order approximations (if polynomial approximation is possible at all). Even though theoretically possible, higher-order approximations might be not very practical to use, not least because of their lesser stability. Another alternative could be to directly count the exposure durations of cohorts and periods in the recent past to given ranges on the mortality rate, thereby avoiding indirect estimation. In this work, we avoid such complications by imposing restrictions to the adjustment

coefficient and not applying adjustments at certain ages, as described in the Appendix.

The new approach to mortality forecasting presented here may need some improvements. Firstly, the considerable deviations of the adjusted life expectancy from the general upward trend even for low-mortality countries needs further explanation, possibly by socio-economic conditions, health care system developments, cohort effects, etc. It may also require some smoothing and extrapolating the trend into the future and using extrapolated adjusted life tables for mortality forecasts. Also, the higher variance of conventional life expectancies suggested by the mortality inertia as compared to the variance of observed conventional life expectancies indicates the necessity to assume an inter-country convergence of adjusted mortality schedules in the projection.

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APPENDIX: METHODS AND DETAILED TABULATIONS

Exposure-adjusted life expectancy

A birth cohort aged x at time of observation is exposed by

$$k(x) = \frac{a(x)}{a(x) + b(x)} \tag{1}$$

times longer to the same mortality rates as the conventional hypothetical cohort; here $a(x) = \frac{\partial}{\partial x}\mu(x)$ is the derivative over age of the mortality rate; $b(x)$ is the age-specific rate of the temporal change of the mortality rate. We use a robust procedure based on approximating the graduated logarithmic mortality as a polynomial of age and time in the 15x11 years subset of the Lexis surface covering the point for which the rates are computed. We neglect exposure effects for the age groups 0 and x_m-30 (x_m is the age at minimal mortality). To avoid occasional outliers due to limitations of the approximations used, we impose limits $0.001 \le k \le 2$ to the correction coefficients.

The conventional life expectancy at birth is given as

$$e(0) = \int_0^\infty e^{-\int_0^x \mu(y)dy} dx. \tag{2}$$

Taking into account true exposures to the mortality rates yields:

$$e^*(0) = \int_0^\infty k(x) e^{-\int_0^x \mu(y)k(y)dy} dx. \tag{3}$$

The integrals above are approximated by summation over single-year-long age intervals.

Forecasting mortality

The age $y(x)$ in the eventual exposure-adjusted age schedule of mortality, which corresponds to age x in the initial schedule is determined by decompression coefficients (1):

$$y(x) = \int_0^x k(u)du \,, \tag{4}$$

For UK females in 2006, e.g. $y(60) \approx 66$. That means that eventually, assuming constant mortality conditions, mortality at age 66 will be the same as at age 60 in 2006. This transition may be modelled on a cohort basis. Let us take, for instance, the same cohort aged 60 in 2006. One year later, the cohort ages 61. If it experiences the exposures of the base year, its mortality will correspond to that of a 67 years old from the exposure-adjusted life table. The method may be supplemented by the extrapolation of exposure-adjusted mortality rates, which may in particular facilitate accounting for the convergence of countries with regard to their mortality conditions.

Table A.1 Selected conventional and exposure-adjusted estimates of life expectancy at birth and at age 65 (years).

Population	Year	Life expectancy at birth		Life expectancy at age 65		
		Conventional	Adjusted	Conventional	Adjusted	Adjusted - for those aged 65
Australia	2007	81.3	99.9	20.0	38.5	25.1
Austria	2005	79.5	97.9	18.8	36.8	23.2
Belarus	2007	70.3	72.0	14.6	16.4	15.2
Belgium	2006	79.3	94.2	18.8	32.9	22.1
Bulgaria	2007	73.0	81.8	14.9	22.7	16.3
Canada	2005	80.0	96.4	19.3	35.0	22.6
Czech Republic	2008	77.2	91.0	17.0	30.1	20.5
Denmark	2007	78.3	94.9	17.8	33.5	21.2
East Germany	2006	79.0	97.2	18.5	36.5	23.1
West Germany	2006	79.7	98.6	18.7	36.7	22.4
Estonia	2007	73.1	89.3	16.3	31.9	18.9
Finland	2007	79.3	94.2	19.1	33.4	24.0
France	2006	80.5	97.4	20.1	36.5	24.3
Hungary	2006	73.4	88.4	15.9	29.0	18.2
Iceland	2007	81.5	93.5	19.5	31.4	22.9
Ireland	2006	79.6	100.9	18.4	39.6	25.1
Italy	2006	81.3	94.8	19.7	33.4	24.4
Japan	2007	82.4	91.5	20.9	30.2	24.7
Latvia	2007	71.2	75.6	15.4	19.4	16.2
Lithuania	2007	70.9	67.5	15.8	12.5	15.8
Luxembourg	2006	79.5	91.3	18.7	30.6	22.8
Netherlands	2006	79.7	92.8	18.5	31.0	21.5
New Zealand	2003	79.2	96.5	18.6	35.9	22.4

Table A.1 continued on the next page

Table A.1 (continued)

Population	Year	Life expectancy at birth		Life expectancy at age 65		
		Conven-tional	Adjust-ed	Conven-tional	Adjust-ed	Adjusted - for those aged 65
Norway	2007	80.5	98.2	19.1	36.4	22.9
Poland	2006	75.2	87.9	16.8	28.9	20.4
Portugal	2007	79.0	95.1	18.5	34.5	22.2
Russia	2006	66.6	60.6	13.9	8.9	13.9
Slovakia	2006	74.4	82.9	15.6	23.5	17.2
Spain	2006	80.7	91.3	19.6	30.2	22.7
Sweden	2007	80.8	97.7	19.2	35.2	21.7
Switzerland	2007	81.6	97.5	20.1	35.7	24.2
Taiwan	2008	78.3	89.5	18.5	30.2	22.3
Ukraine	2006	67.9	64.4	13.9	11.2	14.1
United-Kingdom	2006	79.3	89.6	18.6	29.1	22.9
United States	2006	77.9	85.5	18.8	26.2	21.1
Average		77.5	89.6	17.9	29.8	21.1
Standard deviation		*4.2*	*10.2*	*1.9*	*7.8*	*3.2*
Average - excl. CIT [a]		80.0	94.7	19.1	33.6	23.0
Standard deviation		*1.2*	*3.8*	*0.7*	*3.3*	*1.2*
Average - CIT [a]		72.7	79.9	15.7	22.6	17.5
Standard deviation		*3.6*	*11.7*	*1.3*	*9.0*	*2.8*

[a] Countries in transition include 12 populations of the former Eastern block

Table A.2 Extrapolations of the life expectancy at birth and at age 65 based on assuming time-invariant mortality conditions since 1980 as compared to actually observed dynamics (years).

	Conventional life expectancy at birth					Conventional lie expectancy at age 65		
	1980	1990		last year		1980	last year	
Population	observed	observed	forecast	observed	forecast	observed	observed	forecast
Australia	74.5	76.9	77.3	81.3	82.0	15.9	20.0	22.1
Austria	72.7	75.7	74.2	79.5	76.4	14.9	18.8	18.0
Belarus	71.1	71.2	68.9	70.3	65.0	15.4	14.6	11.1
Belgium	73.2	76.0	74.8	79.3	76.9	15.0	18.8	18.4
Bulgaria	71.1	71.3	70.5	73.0	69.4	13.6	14.9	12.4
Canada	75.0	77.3	76.7	80.0	79.4	16.6	19.3	19.7
Czech Republic	70.3	71.4	70.8	77.2	71.9	12.9	17.0	13.5
Denmark	74.1	74.8	74.5	78.3	74.9	15.7	17.8	16.4
East Germany	71.9	72.9	72.3	79.0	72.3	13.8	18.5	14.3
West Germany	73.4	76.0	75.2	79.7	77.9	15.1	18.7	18.9
Estonia	69.5	69.9	67.9	73.1	64.7	14.2	16.3	11.1
Finland	73.6	75.0	76.4	79.3	81.0	15.1	19.1	20.8
France	74.2	76.8	75.9	80.5	78.7	16.3	20.1	20.0
Hungary	69.1	69.4	67.6	73.4	64.9	13.2	15.9	10.7
Iceland	76.6	78.4	79.3	81.5	83.5	17.3	19.5	23.1
Ireland	72.6	74.9	73.5	79.6	75.3	14.1	18.4	15.6
Italy	74.0	76.9	75.2	81.3	77.5	15.4	19.7	17.5
Japan	76.1	78.9	79.3	82.4	85.1	16.2	20.9	24.1
Latvia	69.1	69.5	67.4	71.2	64.1	14.5	15.4	10.9
Lithuania	70.7	71.3	69.3	70.9	66.3	15.4	15.8	12.9
Luxembourg	72.8	75.6	74.9	79.5	78.3	14.5	18.7	18.7
Netherlands	75.7	76.9	77.3	79.7	79.9	16.2	18.5	19.3

Table A.2 continued on the next page

Table A.2 (continued)

	Conventional life expectancy at birth					Conventional lie expectancy at age 65		
	1980	1990		last year		1980	last year	
Population	observed	observed	forecast	observed	forecast	observed	observed	forecast
New Zealand	72.9	75.4	74.2	79.2	76.2	14.9	18.6	16.8
Norway	75.6	76.3	76.7	80.5	78.8	16.2	19.1	18.0
Poland	70.2	70.7	69.5	75.2	67.5	14.1	16.8	12.9
Portugal	71.6	74.1	73.3	79.0	75.9	14.9	18.5	18.3
Russia	67.4	69.2	65.8	66.6	62.9	14.2	13.9	11.2
Slovakia	70.4	70.8	70.3	74.4	70.0	13.7	15.6	13.1
Spain	75.4	76.9	77.5	80.7	81.0	16.4	19.6	20.7
Sweden	75.7	77.5	76.3	80.8	76.9	16.2	19.2	17.2
Switzerland	75.6	77.3	77.5	81.6	80.5	16.4	20.1	20.6
Taiwan	(n.a.)							
Ukraine	69.6	70.4	67.9	67.9	65.0	14.3	13.9	11.3
United Kingdom	73.6	75.7	74.6	79.3	76.3	15.0	18.6	16.8
United States	73.7	75.3	76.2	77.9	80.5	16.3	18.8	21.4
Average	72.7	74.3	73.5	77.4	74.6	15.1	17.9	16.7
Standard deviation	*2.4*	*3.0*	*3.8*	*4.2*	*6.4*	*1.1*	*1.9*	*3.9*
Average - excl. CIT [a]	74.2	76.3	76.0	80.0	78.8	15.7	19.1	19.2
Standard deviation	*1.3*	*1.2*	*1.7*	*1.1*	*2.7*	*0.8*	*0.7*	*2.2*
Average - CIT [a]	70.0	70.7	69.0	72.7	67.0	14.1	15.7	12.1
Standard deviation	*1.2*	*1.1*	*1.8*	*3.6*	*3.2*	*0.7*	*1.3*	*1.2*

[a] Countries in transition include 12 populations of the former Eastern block

Table A.3 Selected results of extrapolating the conventional life expectancy at birth (e_0) and at age 65 (e_{65}) assuming constant mortality conditions in the future (years).

Population	Base year	Conventional life expectancy at birth				Conventional life expectancy at age 65		
		2015	2025	2050	UN 2045-50	2015	2025	2050
Australia	2007	83.3	86.1	93.0	86.2	21.7	24.3	31.2
Austria	2005	82.1	85.0	91.7	85.0	20.8	23.2	30.1
Belarus	2007	70.8	71.3	72.0	76.2	14.9	15.4	16.4
Belgium	2006	81.0	83.2	88.4	85.0	20.1	21.8	26.6
Bulgaria	2007	74.2	75.8	79.5	79.5	15.8	16.7	20.0
Canada	2005	82.1	84.4	90.1	85.2	21.0	22.8	28.3
Czech Republic	2008	78.8	81.3	86.8	81.9	18.3	20.3	25.5
Denmark	2007	80.1	82.6	88.7	83.0	19.2	21.2	26.8
East Germany	2006	81.5	84.6	91.5	84.4	20.6	23.3	30.4
West Germany	2006	81.7	84.4	90.9	84.4	20.3	22.4	28.6
Estonia	2007	75.3	78.1	84.3	80.0	17.6	19.5	26.0
Finland	2007	81.2	83.7	88.9	84.5	20.8	22.8	27.7
France	2006	82.5	85.0	90.8	86.0	21.8	23.8	29.3
Hungary	2006	75.6	78.2	83.8	79.6	17.2	18.8	23.7
Iceland	2007	83.2	85.6	91.0	86.0	20.9	23.1	28.8
Ireland	2006	82.8	86.5	94.5	84.5	21.1	24.6	32.8
Italy	2006	83.4	86.1	92.2	85.4	21.5	24.0	30.6
Japan	2007	83.9	85.8	89.7	87.2	22.3	24.2	28.3
Latvia	2007	71.9	72.8	74.7	79.1	15.8	16.3	18.2
Lithuania	2007	70.3	69.3	67.7	78.7	15.7	14.9	12.8
Luxembourg	2006	81.6	84.1	88.8	84.6	20.5	22.7	27.8
Netherlands	2006	81.5	83.7	88.7	84.2	19.9	21.8	26.6
New Zealand	2003	82.3	85.1	91.6	85.2	21.2	23.8	30.7
Norway	2007	82.4	85.0	91.6	85.2	20.6	22.8	29.4
Poland	2006	77.4	79.9	84.7	80.9	18.6	20.6	25.2

Table A.3 continued on the next page

Table A.3. (continued)

Population	Base year	Conventional life expectancy at birth				Conventional life expectancy at age 65		
		2015	2025	2050	UN 2045-50	2015	2025	2050
Portugal	2007	80.8	83.4	89.2	83.2	19.9	22.2	28.1
Russia	2006	65.1	63.3	60.7	74.9	13.7	12.8	9.2
Slovakia	2006	75.9	77.6	81.1	80.3	16.6	18.0	21.4
Spain	2006	82.3	84.2	88.5	85.5	21.0	22.7	27.2
Sweden	2007	82.2	84.3	89.9	85.2	20.2	21.8	27.1
Switzerland	2007	83.4	85.9	92.1	86.6	21.6	23.7	29.9
Taiwan	2008	80.0	82.4	87.0	-	20.1	22.4	27.4
Ukraine	2006	67.3	66.5	64.6	75.1	14.0	13.8	11.6
United Kingdom	2006	81.3	83.6	87.9	84.1	20.4	22.8	27.3
United States	2006	79.2	80.7	83.6	83.3	19.9	21.3	24.0
Average		79.1	81.1	85.7	82.9	19.3	21.0	25.6
Standard deviation		*4.9*	*5.9*	*8.3*	*3.3*	*2.4*	*3.2*	*5.7*
Average - excl. CIT [a]		81.9	84.4	90.0	85.0	20.7	22.9	28.5
Standard deviation		*1.2*	*1.4*	*2.3*	*1.1*	*0.7*	*1.0*	*1.9*
Average - CIT [a]		73.7	74.9	77.6	79.2	16.6	17.5	20.0
Standard deviation		*4.8*	*6.4*	*9.6*	*2.8*	*2.0*	*3.1*	*6.6*

[a] Countries in transition include 12 populations of the former Eastern block