Life expectancy in developed countries is higher than conventionally estimated. Implications from improved measurement of human longevity

Dalkhat M. Ediev [1]

[1] Vienna Institute of Demography, Austrian Academy of Sciences, Wohllebengasse 12-14, 6th fl., 1040 Vienna, Austria, dalkhat.ediev@oeaw.ac.at.

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Conventional indicators of human lifespan[1,2] are based on a hypothetical synthesis of the mortality conditions of different cohorts with (as yet) incomplete life histories. There is considerable ongoing debate about improvements to the traditional methodology under changing mortality rates.[3-8] Improved measurement of the human lifespan is crucial for estimating prospects of longevity[9-13] and for understanding the implications of population ageing.[13-16] Here we show that both the centuries-long tradition of conventional lifespan indicators and the more recent criticism to 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 a 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 20% in low-mortality countries. The 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.

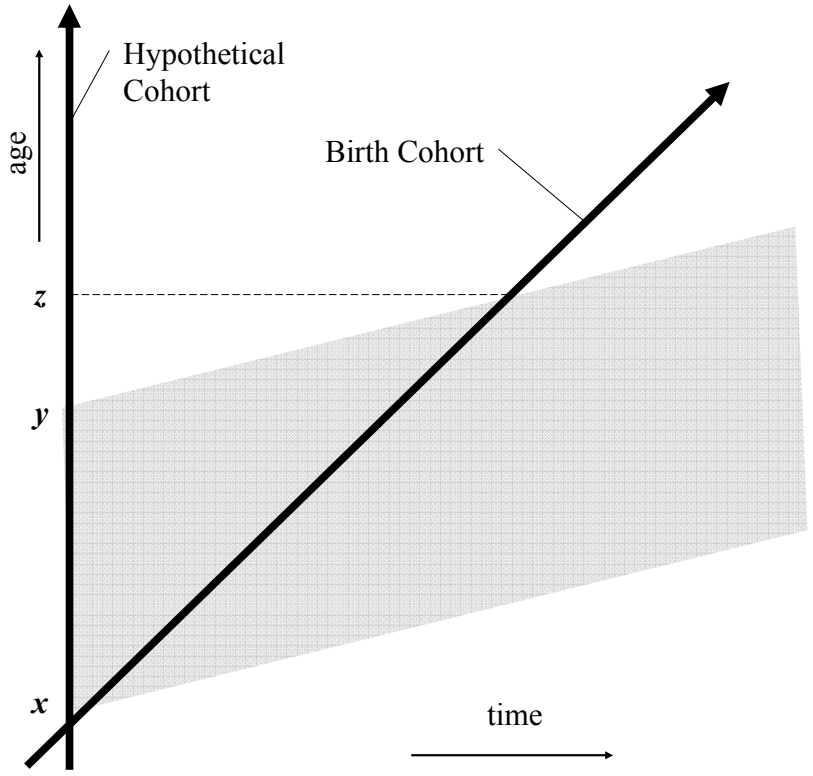
1. Introduction

The mean duration of human life can only be estimated after observing the whole life span of a given birth cohort, which is not yet possible for cohorts who are still living. Therefore, conventional estimates are obtained by calculating the *period life table*[1,2] 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 tempo effect in fertility,[3] which generated a remarkable debate.[4-8] As argued by the proponents of the tempo effect in mortality, with increasing lifespans the deaths to birth cohorts are underestimated 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.

Figure 1. Illustration to the tempo effect



As we argue, however, a recent interpretation[17] 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. 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.)

We present an alternative approach that is based on the assumption that the hypothetical cohort experiences observed mortality rates over exposure periods of the same duration as birth cohorts do. These are combinations of rates and of exposures to them, not just of the rates alone, which characterise the experience of real people. Our indicator of period life expectancy shows how long on average people would live were they exposed to

the currently observed mortality levels over the same durations of time as currently observed individuals are.

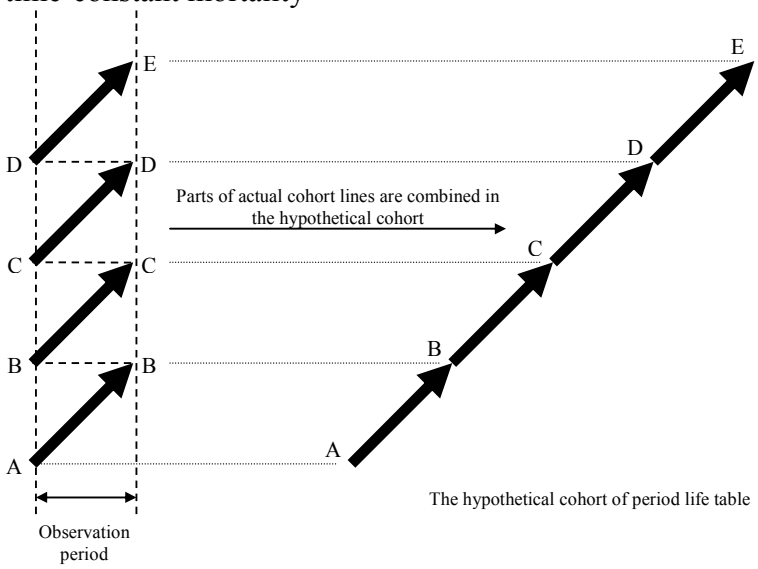
The work is structured in the following way. We first strengthen the motivation for the new method by continuing to expose limitations of the conventional period life table in the next section; this is followed by some formal basics of our method and supporting empirical evidence on durations of exposure to selected mortality levels and cohort life expectancies; then, estimates of lifespan based on the new method are presented for 37 national populations; a final discussion forms the conclusion.

2. Built-in paradoxes of the conventional period life table model

To see that the exposure distortions imposed by the period life table model 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 additional schematic illustrations in this section.

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 schematic in figure 2.

Figure 2. Illustration to the hypothetical cohort of period life table in the case of time-constant mortality

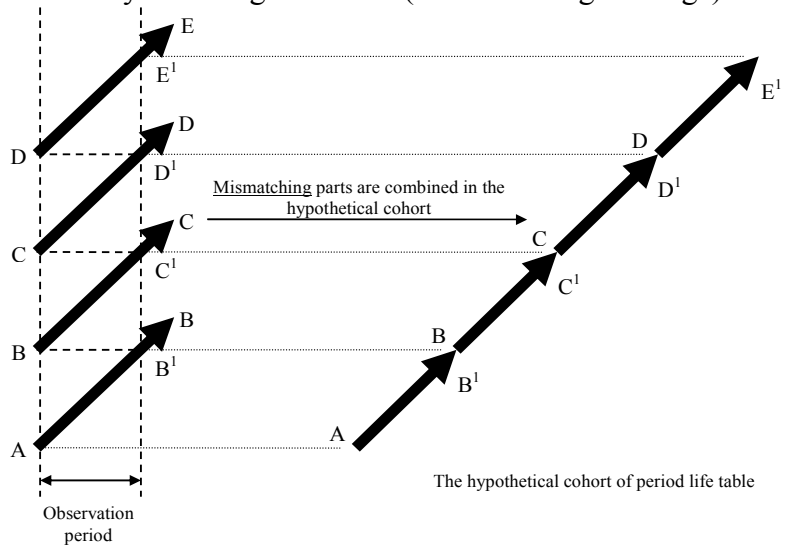


Note: Arrows depict parts of life span of birth cohorts in the Lexis surface (age goes along the vertical axis). Capital letters denote different levels of mortality.

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). 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.

Figure 3. Illustration to the hypothetical cohort of period life table in the case of mortality declining with time (but increasing with age)



Note: Arrows depict parts of life span of birth cohorts in the Lexis surface (age goes along the vertical axis). Capital letters denote different levels of mortality.

To illustrate the consequences of the traditional period life table methodology in the case of systematically changing (in our example, decreasing with time and increasing with

age) mortality, let us improve the illustration by assuming mortality (static prior to the observation year) to decline in all ages in the observation period (figure 3). 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 $\mathbf{B^1}$ 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 $\mathbf{B^1}$ and then suddenly jumps on to the higher-mortality level **B** and so on, continually skipping parts of the natural sequence of mortality rates.

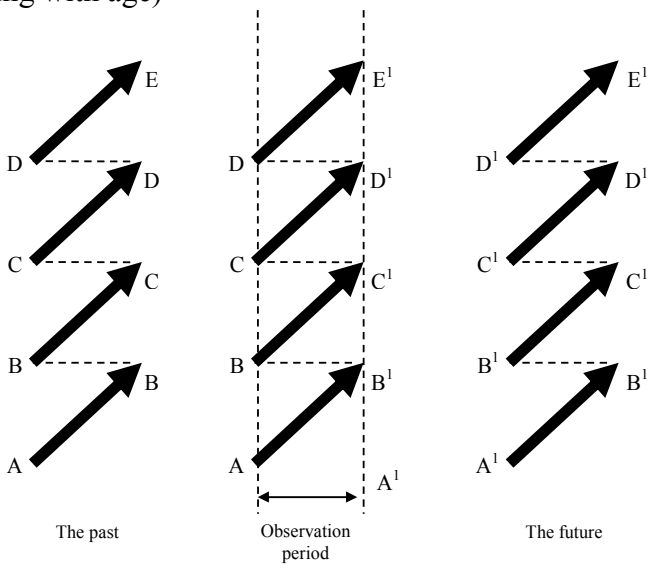
This unnatural discontinuity of mortality in the hypothetical cohort also *misrepresents empirical mortality conditions*. In the period life table, a person who ages to the point at which his or her mortality is $\mathbf{B^1}$ immediately proceeds to mortality level **B**, while current data indicate 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 individuals. 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 **C**[1]. Since the procedure is already discrete, the interruptions presented in the illustration above would not be apparent.

Figure 4. Illustration to the conventional 'constant mortality conditions' scenario in the case of mortality declining within the observation period (but increasing with age)



Note: Arrows depict parts of life span of birth cohorts in the Lexis surface (age goes along the vertical axis). Capital letters denote different levels of mortality. The panel to the left depicts stagnant mortality prior to the observation period, the one in the middle depicts declining mortality during the observation period and the panel to the right depicts the conventional 'constant mortality' scenario of the future.

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 frontier time line of the 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 in figure 4. 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 and mortality compression 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 $\boldsymbol{x}$ of one cohort and age $\boldsymbol{y}$ 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.

An alternative interpretation may also 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.

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 [18-23]. 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 when mortality tends to decline.

3. The alternative model for period mortality conditions: the exposure-adjusted period life table

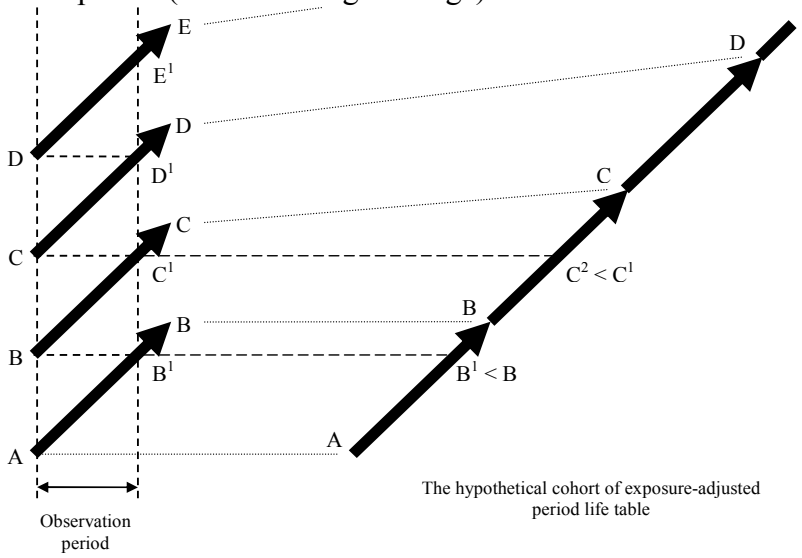
Our alternative hypothetical cohort assumes a different synthesis and takes complete account for cohorts' exposures to different mortality levels. An illustration based on our simplified schematic is presented in figure 5.

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 hypothetical cohort (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 conditions' scenario does no longer exist: in the future, people enter the second age group at lower mortality $\mathbf{B^1}<\mathbf{B}$ than the currently observed cohort and, accordingly, end up with a lower mortality $\mathbf{C^2}<\mathbf{C^1}$ by the end of the age group.

Figure 5. Illustration to the exposure-adjusted period life table and 'constant mortality conditions' scenario. Mortality is declining within the observation period (but increasing with age)



Note: Arrows depict parts of life span of birth cohorts in the Lexis surface (age goes along the vertical axis). Capital letters denote different levels of mortality.

The examples above are also helpful in illustrating what we call *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 may be used to forecast mortality (see examples further down in the text). However, they 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.

By contrast to the conventional theory, our hypothetical life table assumes a stretch of the period mortality schedule and uncompressed shifts of exposure intervals along the age scale. In reality, such a process may be checked by mortality compression if the chronological age as such did matter for biological ageing (e.g., if there were strict biological limits to the human lifespan). In principle, such prospects would not undermine the basis of our method, which is a pure period theory and only provides a summary of current mortality conditions including the currently observed durations of exposure to different mortality levels. Our method does not necessarily predict exposure durations to the same levels in the future. However, empirical evidence indicates that our basic assumption about the hypothetical cohort, i.e. an unchecked shift of mortality levels and of

exposure durations along the age scale, might be a good model of mortality in low-mortality populations.

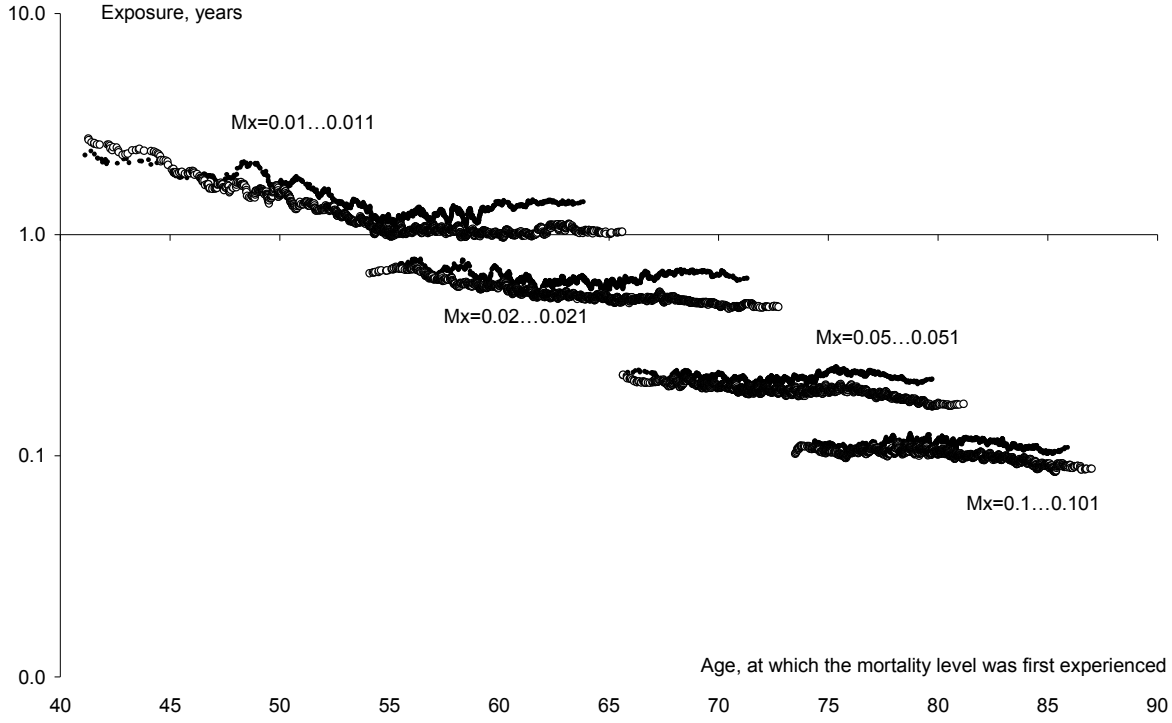
First, we note in this respect that recent works on mortality compression[21,23] point to a shift or an expansion, but not a compression, of mortality at older ages. Those works, however, were primarily based on period analysis and dealt with compression indicators that were only indirectly related to shifts of mortality conditions as assumed by our hypothetical cohort model.

More explicit evidence on durations of exposure to four selected mortality levels in low-mortality countries is presented in Table 1 and Figure 6. (The estimates are based on the cohort and period life tables available from the Human Mortality Database[24] excluding Iceland and Luxembourg, due to small their population sizes, as well as eastern European countries.) The table consists of exposure durations averaged over all countries in three selected calendar periods. The graphs depict how exposure durations changed as functions of age when the mortality levels were experienced (random variation of individual estimates is eliminated by a moving average.) Artificial compressions of the exposure durations suggested by the period life table are evident from the gaps between cohort and period estimates. Because of these distortions, period life tables would indicate compression as a universal feature of declining mortality, while individuals' actual experience (as described by cohort estimates) would not support this view. In the more recent period, stagnant or expanding exposure durations would have been a better model than the compressing ones. These observations support building the exposure-adjusted period life table on the currently observed exposure durations without subsequent adjustment for a possible compression at older ages.

Table 1. Durations of exposure of birth cohorts (left panel) and period life tables (right panel) to the selected mortality levels in low-mortality countries averaged over selected periods of time (years)

Mortality level (range of the death rate)	Birth cohorts' actual exposure to the selected mortality levels in periods:			Exposure estimates from the period life tables		
	1900-1909	1960-1969	1997-2006	1900-1909	1960-1969	1997-2006
0.01-0.011	2.47	1.09	1.44	2.15	1.00	1.04
0.02-0.021	0.68	0.55	0.70	0.63	0.52	0.49
0.05-0.051	0.23	0.21	0.23	0.22	0.20	0.18
0.10-0.101	0.11	0.11	0.11	0.11	0.10	0.09

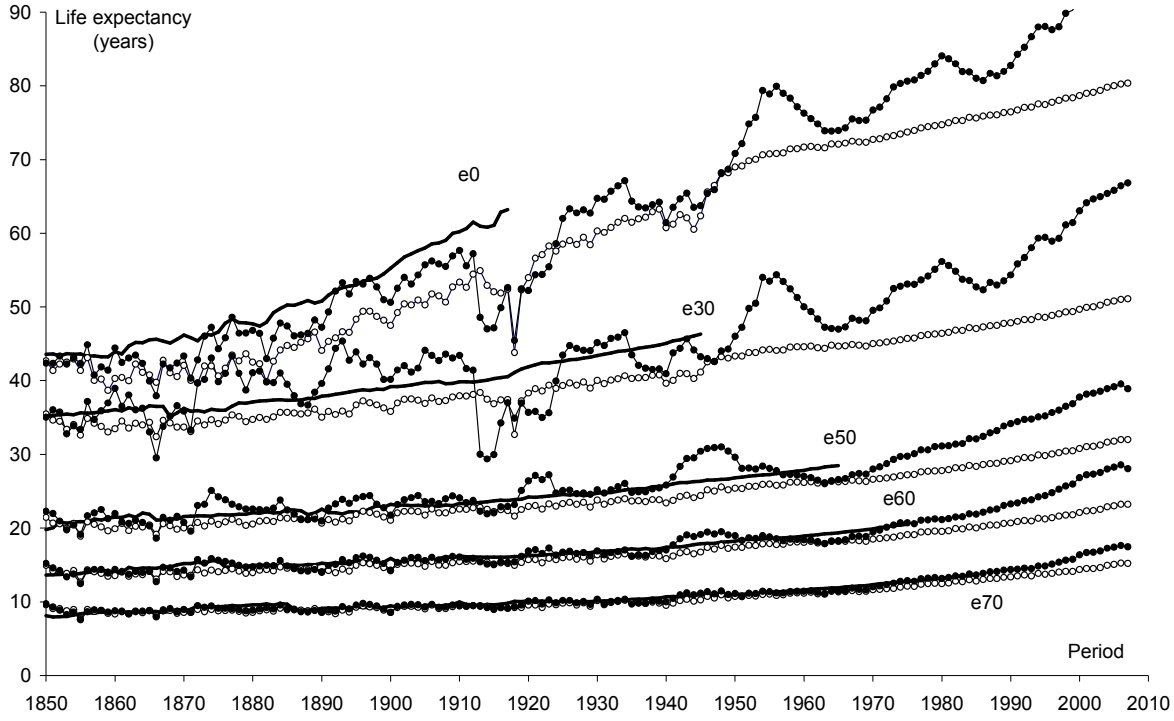
Figure 6. Dynamics over age of durations of exposure of birth cohorts (dots) and period life tables (circles) to the selected mortality levels in low-mortality countries smoothed by moving average over 19 adjacent points. (Logarithmic scale for the exposure.)



Although our period estimates of lifespan do better than the conventional ones in indicating the cohort life expectancy (Figure 7; calculation details are coming in the next

section), they do not necessarily predict the actual cohort survival. That is subject to varying future mortality conditions and therefore may deviate from the exposure-adjusted estimates, which only take into account the current conditions. (Actual cohort life expectancies may be interpreted as averaging period mortality conditions.)

Figure 7. Remaining cohort lifespan (solid lines) at selected ages (both sexes combined) as compared to the conventional (circles) and exposure-adjusted (dots) period life expectancy at that same averaged over 12 low-mortality countries with cohort data available from HMD [24].



4. Calculation procedures and formal relations

In practical calculations, one approach could be to directly count the exposure durations of cohorts in the recent past to given ranges of the mortality rate in order to build the exposure-adjusted life table in the way illustrated above. Such an approach, while being

absolutely practical, nonetheless involves computations and annual updates of incomplete cohort tables and graduation procedures. A simpler approach, which we use here, might be based on general analytical relations between period and cohort exposures in case of time-varying mortality. If age x, at which the given mortality level is observed, increases at rate $r(x;t)$ years per year in the period of observation (t), than the general theory[17] tells us that the conventional period life table exposure to that level of mortality will be compressed by

$$k(x;t)=\frac{1}{1+r(x;t)} \tag{1}$$

times as compared to the actual exposure of individuals. An equivalent form of this relation makes use of age- and time-variation of the mortality rate[17, Eq. 11]:

$$k(x;t)=\frac{a(x;t)}{a(x;t)+b(x;t)}, \tag{2}$$

here $a(x;t)=\frac{\partial}{\partial x}\mu(x;t)$ is the derivative over age of the mortality rate $\mu(x;t)$ observed at age x at time t; $b(x;t)=\frac{\partial}{\partial t}\mu(x;t)$ is the rate of the temporal change of the mortality rate. Given its typically negative rate, (2) implies mortality compression, $k>1$, at old ages and decompression, $k<1$, at young ages.

Intuition may be provided to Eq. (2): ratio $\frac{b(x;t)}{a(x;t)}$ of the temporal and age change of the mortality rate yields a tangent slope $r(x;t)$ of the contour line corresponding to that level of mortality in the Lexis surface. The adjustment coefficient (2) 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).

We use the compression coefficients (2) to construct the age $y(x)$ in the exposure-adjusted life table, which corresponds to age *x* in the conventional life table. A dx-year change of age from *x* to $x+dx$ in the conventional mortality schedule corresponds to a $k(x)\cdot dx$-year change in the uncompressed schedule (for simplicity of notation, we omit the time variable). Hence, the uncompressed age $y(x)$ may be obtained by cumulating the compression coefficients (2) starting from age 0:

$$y(x)=\int_0^x k(u)du\,. \tag{3}$$

This correspondence suggests identity linking the conventional age schedule of mortality $\mu(x)$ and the exposure-adjusted schedule μ^*: $\mu^*(y(x))=\mu(x)$, i.e.,

$$\mu^*(x)=\mu\left(y^{-1}(x)\right), \tag{4}$$

where $y^{-1}(x)$ is a function inverse to (3) (we calculate it numerically).

From the adjusted mortality schedule (4), we calculate the exposure-adjusted life-table functions $p^*(x)$, $q^*(x)$, $d^*(x)$, $l^*(x)$, $L^*(x)$, $T^*(x)$, $e^*(x)$ in the conventional way.

In the exposure-adjusted life table, we produce two estimates of life expectancy at each age *x*: $e^*(x)$ for those in the radix of the life table (i.e. newborns to the hypothetical cohort who will live their entire life under current mortality conditions) and another one for those at that same age in the observation period (their starting health and remaining lifespan are affected by past mortality conditions). To produce exposure-adjusted life expectancy at age *x* for those already at that age, we use age transformation (3):

$$e^*_x(x) = e^*(y(x)). \tag{5}$$

More generally, the (hypothetical future) life expectancy and mortality rate at age *x* for those currently at age *z* may be obtained as:

$$e^*_z(x) = e^*(y(z) + x - z), \qquad \mu^*_z(x) = \mu^*(y(z) + x - z). \tag{6}$$

(Intuition: a person currently aged *z* corresponds to one aged $y(z)$ in the uncompressed age schedule; ageing by another $x - z$ years shifts him to age $y(z) + x - z$ in the uncompressed schedule.) Note identity for those in the life table radix: $e^*_0(x) = e^*(y(0) + x - 0) \equiv e^*(x)$.

We conclude the formal part by presenting an analytical relation for the exposure-adjusted life expectancy. The conventional life expectancy at birth is given as $e(0) = \int_0^\infty e^{-\int_0^x \mu(z)dz} dx$. Decompressing the age schedule in both integrals by coefficients (2) yields the formula for the exposure-adjusted life expectancy at birth:

$$e^*(0) = \int_0^\infty e^{-\int_0^x \mu(z)k(z)dz} k(x)dx. \tag{7}$$

(The formal derivation can be found in the Appendix.)

We conducted the calculation procedures presented above in a discrete manner. The integrals above are approximated by summation over single-year-long age intervals.

Annual increments of mortality rate over time and age (which would be proxies for derivatives in (2)) show high volatility when estimated over short time/age intervals. For this reason, we estimate the time and age derivatives in (2) based on approximating the logarithmic mortality as a polynomial of time and age in the 15x11 years subset of the Lexis surface covering the point for which the rates are computed. (The polynomial is

linear in time, as usual in mortality extrapolation models, and quadratic in age. Whenever possible, it is used to estimate the derivatives in the central age of the subset. However, we estimate derivatives for the last time point of the subset, in order to emulate usual situation, when the estimation period is the one most recently observed.) Such particular size of the smoothing frame was a compromise between volatility of adjustment coefficients estimated from smaller subsets and irrelevance of results produced by averaging over too wide subsets. Usual mortality extrapolations involve a much stronger graduation when estimating change of mortality over time. Our purpose here is not to reveal the long-run trend in mortality dynamics, however; rather, we apply a weakest possible smoothing to the data so as to produce estimates relevant to mortality conditions in as short a period as possible. (Other graduation methods may also be used for that purpose.)

There are situations when the linear approximation used here will not work. Consider, for example, the situation where the derivative of the mortality rate is estimated as zero when taken along the cohort line (this happens with minimum mortality ages at 10-30 years). In such cases, 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 in (3) and the need for higher-order approximations. Even though theoretically possible, higher-order approximations might be not very practical to use, not least because of their lesser stability. In this work, we avoid such complications by imposing restrictions to the adjustment

coefficient ($0.001 \le k \le 2$) and not applying adjustments at certain ages. Hence, we neglect exposure distortions at the age groups 0 and x_m-30 (x_m is the age at minimal mortality, which is usually close to 10 years). This implies that in the exposure-adjusted life table and the mortality projections produced from it, independent adjustments are applied to mortality below age 10 (where the mortality schedule is usually compressed as compared to the conventional one) and above age 30 (where the mortality schedule is usually uncompressed as compared to the conventional schedule).

Forecasting mortality. The age transformation (3) may also be used to project mortality assuming constant mortality conditions as reflected by the exposure-adjusted life table. Formally, such a projection is indicated by Eq. (6):

$$\mu^*(x;t) = \mu^*{}_{x-(t-t0)}(x) = \mu^*\left(y\left(x-(t-t_0)\right)+t-t_0\right), \tag{8}$$

where t_0 is the base (observation) year when the projection starts. The logic of the method may be illustrated on a cohort basis by the following example. For UK females in 2006, $y(60) = 66$. That is, the mortality at age 60 in 2006 was the same as expected at age 66 in the exposure-adjusted life table. One year later, the cohort ages 61. If it experiences the exposures of the base year, its mortality rate will correspond to that of a 67 years old from the exposure-adjusted life table. By a similar logic, the mortality of the cohort in T years may be forecasted as the mortality at age 66+T in the exposure-adjusted life table.

5. We may live considerably longer than the conventional life expectancy indicates

Most recent conventional and exposure-adjusted life expectancies averaged over selected countries[24] are presented in Table 2 and Figure 8.

On average, the exposure-adjusted calculations produce period life expectancy at birth of about 90 years, which exceeds the conventional estimates by 12 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 correct account for exposures to the prevailing mortality levels reveal twice as higher variation in life expectancy as compared to the variation suggested by the conventional method.

Table 2. Conventional and exposure-adjusted life expectancy at birth and at age 65 estimated for most recent observation years [b]

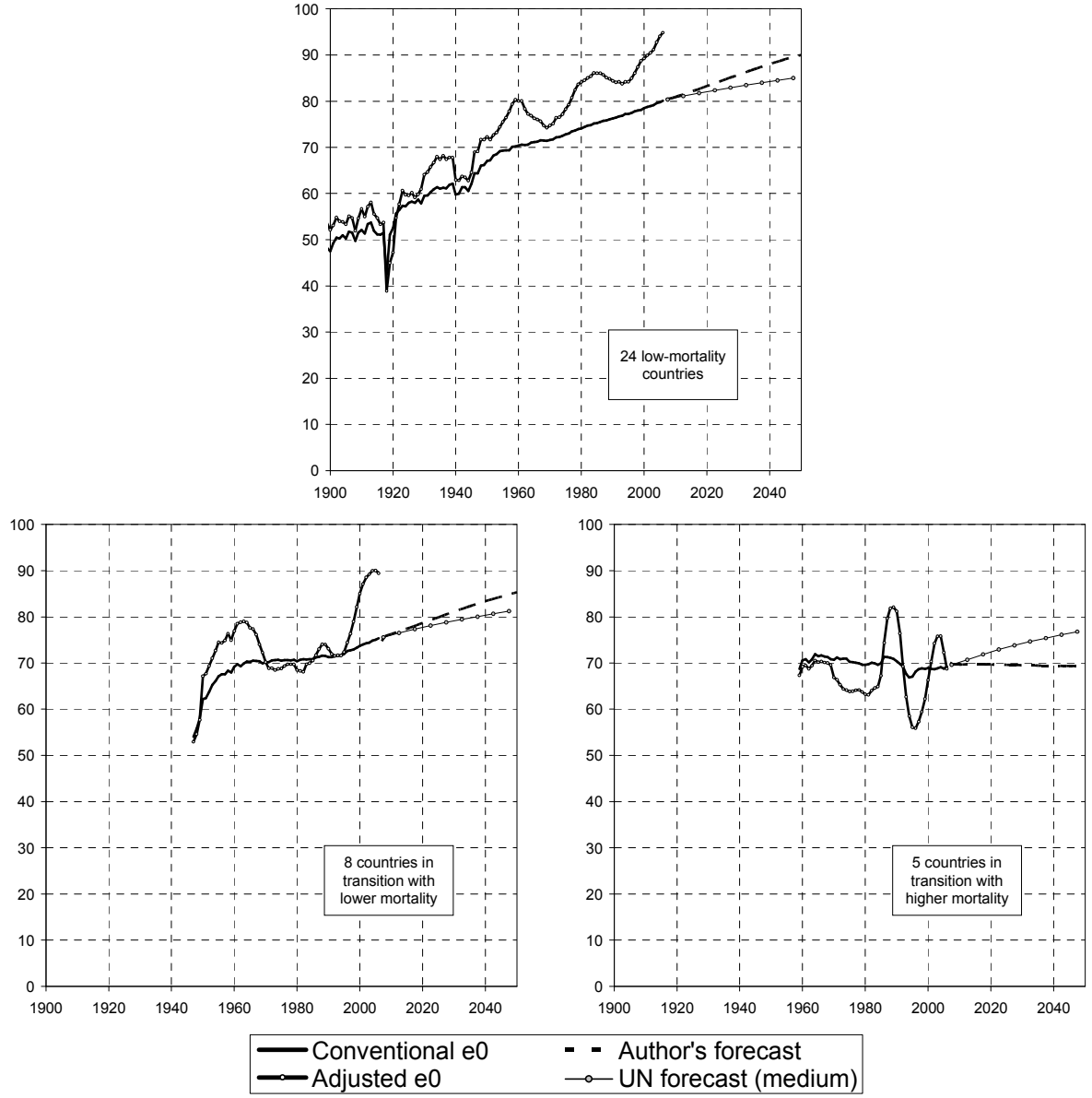
	Life expectancy at birth (years)		Life expectancy at age 65 (years)		
	conventional	adjusted	conventional	adjusted	adjusted - for those aged 65
Average over 37 countries	**77.8**	**90.2**	**18.2**	**30.3**	**21.4**
Standard deviation	*4.1*	*9.6*	*1.9*	*7.3*	*3.2*
Average – excluding CIT [a]	**80.3**	**94.8**	**19.3**	**33.5**	**23.3**
Standard deviation	*1.1*	*3.8*	*0.7*	*3.4*	*1.2*
Average over CIT [a]	**73.3**	**81.9**	**16.0**	**24.2**	**18.0**
Standard deviation	*3.7*	*11.5*	*1.4*	*8.7*	*2.8*

[a] Countries in transition include 13 populations of the former Eastern block
[b] Last observation years available from the Human Mortality Database[24] vary from 2006 to 2009 depending on country (those years are presented in table A1 of the Appendix)

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

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

Figure 8. Conventional and exposure-adjusted life expectancy at birth (years). Selected countries



Another optimistic outlook is indicated by the exposure-adjusted estimates of the probabilities to survive beyond a certain age. According to these estimates, in low-mortality

countries up to 40% of people may survive beyond age 100 in the future. A projection based on the assumption of constant mortality conditions (see the method above) implies that such probabilities of conventional period life tables could already exceed 20% by 2050. The probability to survive age 100 may well repeat the dynamics of the probability of surviving age 90, which has already increased from rather low levels to 20%. Meanwhile, according to our projections, the conventional life table proportion surviving beyond age 90 in low-mortality countries may exceed 50% in the coming half-century.

6. 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 above). The efficiency of the forecasting method is illustrated by forecasts assuming constant mortality conditions since 1980 (Table 3, Figure 9).

Table 3. Extrapolations of the conventional life expectancy at birth and at age 65 assuming time-invariant mortality conditions since 1980 as compared to observations (only those countries with data available since 1980 are included in calculations)

Population	Conventional life expectancy at birth (years)					Conventional life expectancy at age 65 (years)		
	1980	1990		last year [b]		1980	last year [b]	
	observed	observed	forecast	observed	forecast	observed	observed	forecast
Average over 34 countries	**72.8**	**74.4**	**73.5**	**77.7**	**74.7**	**15.1**	**18.1**	**16.8**
Standard deviation	*2.4*	*3.0*	*3.8*	*4.3*	*6.5*	*1.1*	*2.0*	*4.0*
Average – excluding CIT [a]	**74.2**	**76.3**	**76.0**	**80.4**	**78.9**	**15.7**	**19.4**	**19.4**
Standard deviation	*1.3*	*1.2*	*1.7*	*1.1*	*2.7*	*0.8*	*0.8*	*2.3*
Average over CIT [a]	**70.1**	**70.7**	**69.0**	**72.9**	**67.0**	**14.1**	**15.8**	**12.1**
Standard deviation	*1.2*	*1.1*	*1.8*	*3.5*	*3.2*	*0.8*	*1.3*	*1.2*

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

[b] Last observation years available from the Human Mortality Database[24] vary from 2006 to 2009 depending on country (those years are presented in table A1of the Appendix)

An examination of results country by country reveals that these were 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, including the decline at old age (Table 4, Figures 8, 10).

A comparison of our forecasts based on recent data to the medium-variant UN projections[25] (Table 4, Figure 8) reveals that our method, even 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. Comparison to other traditional forecasts also shows that they may significantly underestimate the future mortality decline.[10,26,27] (Yet, unconventional forecasts based on extrapolating life expectancy at birth provide results that are similar to ours.[28])

Table 4. Extrapolations of the conventional life expectancy at birth and at age 65 assuming time-invariant mortality conditions after the last observation year [b]

Population	Conventional life expectancy at birth (years)				Conventional life expectancy at age 65 (years)		
	2015	2025	2050	UN 2045-50	2015	2025	2050
Average over 37 countries	**79.4**	**81.5**	**86.2**	**83.0**	**20.0**	**22.3**	**28.3**
Standard deviation	*4.6*	*5.4*	*7.6*	*3.3*	*14.9*	*15.6*	*15.4*
Average – excluding CIT [a]	**82.1**	**84.5**	**90.0**	**85.0**	**16.9**	**18.4**	**22.1**
Standard deviation	*1.2*	*1.3*	*2.2*	*1.0*	*20.0*	*22.4*	*29.1*
Average over CIT [a]	**73.9**	**75.3**	**78.2**	**79.2**	**21.1**	**22.9**	**27.4**
Standard deviation	*4.3*	*5.6*	*8.6*	*2.8*	*20.4*	*22.0*	*27.3*

[a] Countries in transition include 13 populations of the former Eastern block
[b] Last observation years available from the Human Mortality Database[24] vary from 2006 to 2009 depending on country (those years are presented in table A1of the Appendix)

Conventional extrapolations of mortality tended to underestimate the nearly linear growth of life expectancy in the past.[11,29,30] Our model, on the contrary, 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. This way, it is impossible to foresee the onsets of the mortality decline which, as was usually the case at advanced ages, are precluded 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[31] and also applied to project mortality in Japan.[32] This resulted in the forecast life expectancy at birth, which is still below our estimates by about four years.

Figure 9. Age profiles of mortality rate (logarithmic scale) averaged over 23 low mortality countries with data available since 1980: observed in 1980, exposure-adjusted in 1980, extrapolated under constant mortality conditions since 1980 and observed in 2006

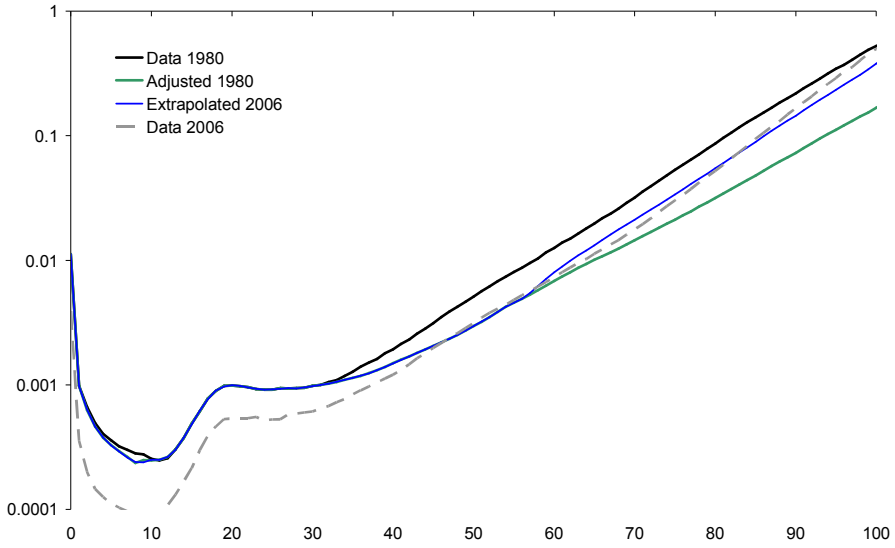
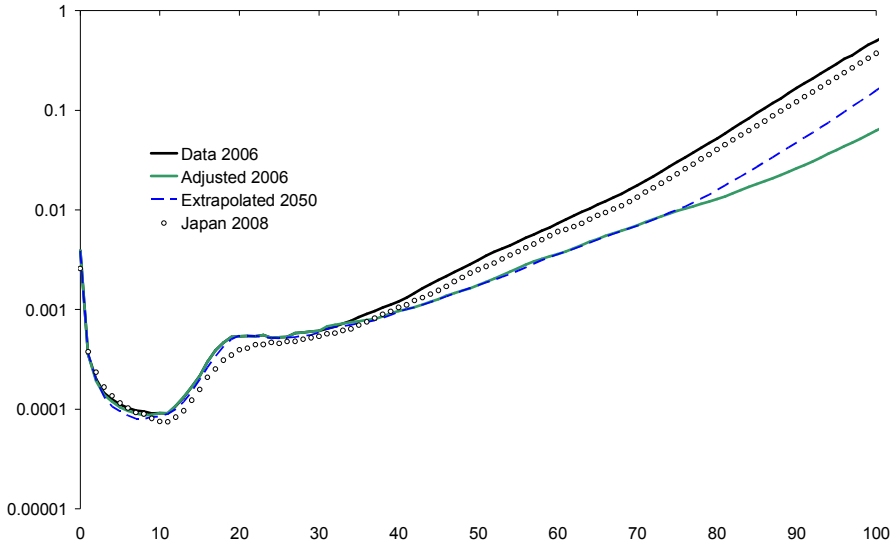


Figure 10. Age profiles of mortality rate (logarithmic scale) averaged over 23 low mortality countries with data available since 1980: observed in 2006, exposure-adjusted in 2006 and extrapolated under constant mortality conditions since the last observation [b]



[b] Last observation years available from the Human Mortality Database[24] vary from 2006 to 2009 depending on country (those years are presented in table A1of the Appendix)

7. Discussion

The approach presented was inspired by the previous work on tempo theory[17] and clearly fits into the discussion on mortality tempo. Several 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.

The decompression coefficient $k(x)$ in the outer integral in Eq. (7) of the exposure-adjusted life expectancy at birth makes this formula different from the usual tempo-adjusted life expectancy[33,Eq.11] which, instead of adjusting the timing of mortality for the compression induced by the period cross-section, inflates the mortality rate in the inner integral by a similar coefficient. While the age profile of the mortality rate of the conventional life table is a compression of the one produced by the exposure-adjusted life table, the usual tempo-adjusted deaths' and survival profiles are compressions of the exposure-adjusted ones.

Our indicators of human lifespan are more volatile as compared to conventional life expectancies. On the one hand, this happens because we applied only a moderate graduation when estimating exposure durations. On the other hand, the lower volatility of conventional life expectancy is due to ignoring the variation of mortality conditions caused by changing exposure durations. The higher volatility of our results may be interpreted as providing more information about dynamics of mortality conditions than the conventional indicators provide. A causal explanation of those dynamics by age and cohort effects, socio-economic conditions might be a promising line of mortality research. Longevity in

the eastern European countries is a good example. The sudden change of socio-economic conditions in the former Eastern Block countries that joined the European Union slowed down health deterioration in those countries and extended exposure durations to lower mortality levels. This was promptly reflected by the exposure-adjusted life expectancy, which already indicates convergence of those countries to the western European trends. (It does not indicate cross-over, however, as the usual extrapolation would do.)

One may also note that the conventional life expectancy showed a remarkably smooth pattern only in the recent period, when the exposure-adjusted life expectancy was consistently and considerably higher. In fact, one may need to explain this extraordinary smoothness and linearity of the conventional life expectancy, which was widely reported and utilised in mortality forecasts, but never actually explained. Our interpretation is that in those periods when the exposure-adjusted period life expectancy is consistently higher (lower) than the conventional one, the latter must tend to shift monotonically towards the former. This shift should be about linear because, by the logic of mortality inertia, by every year one young cohort living under new mortality conditions will replace one older cohort used to live under the past mortality conditions, thereby shifting the period cross-section of mortality rates one step closer to the eventual pattern predicted by the exposure-adjusted life table. In about 100 steps, when all old cohorts will be replaced by newer ones, the convergence will be completed. (More accurate assessment is in a good agreement with actual dynamics of the conventional life expectancy: given that exposure adjustments to adult mortality start at age 30, the adjusted life expectancy 95 years in low-mortality countries, and the conventional life expectancy 80 years, the latter should increase by 15

years in about 95-30=65 years time, i.e., by 2.3 years per decade, which is rather close to the reported temps of 2.1[34] to 2.5[35] years per decade)

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. Under certain conditions, CAL (*Cross-sectional Average Length of Life* [4, 36-38], the sum over all cohorts of proportions survived to the observation period), for instance, may be interpreted as the mean age at death in a standardised population [6]. It is a useful indicator of the effect of past mortality conditions on the contemporary age distribution of population and, hence, of deaths. CAL is also helpful in assessing the role of past mortality on current population size and population momentum [38] and on actual longevity of cohorts observed at the moment [6,7,39]. 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 [3,6]. 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. 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 better current mortality conditions would have aged more slowly and had a lower mortality at each age as compared to older cohorts. 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.

Differences between the theories become evident when composing the 'constant mortality conditions' scenario. Usually tempo adjustments imply mortality rates to jump in the direction opposite to the observed tendency; conventional theory suggests time-constant rates; and the exposure-adjusted life table suggests a transition period when mortality rates continue changing in the same direction as observed. Researchers have suggested that "death can be delayed not because the rate of increase of mortality with age is being slowed but because people are reaching very old age in better health."[35] Our theory is supported by,

and provides theoretical interpretation to, those observations. At the same time, our theory dos not necessarily endorse a limitless expansion of the human lifespan. The exposure-adjusted life table may, in a sense, be taken as a proxy to moving "intrinsic mortality signatures of human populations".[40] A stagnation of the exposure-adjusted life expectancy in the future could indicate that a biological limit to the lifespan is being approached. (It would, of course, be combined by further near-linear growth of the conventional period life expectancy during a transitory period determined by mortality inertia.) So far, however, such a prospect of stagnation in EAL is not in view.

The new approach to mortality forecasting was presented here only to illustrate mortality inertia. In practice, it may need some improvements. First, the considerable deviations of the adjusted life expectancy from the general upward trend even for low-mortality countries may require smoothing and extrapolating the trend and using the extrapolated adjusted life tables for mortality forecasts. Also, the higher variance of conventional life expectancies suggested by the mortality inertia as compared to the observed variance indicates the necessity of assuming an inter-country convergence of adjusted mortality schedules in the projection.

Appendix. Additional derivations and detailed tabulations

Derivation of the formula for exposure-adjusted life expectancy at age x

Given the adjusted mortality schedule $\mu^*(\cdot)$, one may compute the life expectancy at age *w* in the exposure-adjusted life table in a usual way:

$$e^*(w) = \int_w^\infty e^{-\int_w^s \mu^*(v)dv} ds \,. \qquad \text{(A1)}$$

After applying the transformation (3) to change variables in both integrals ($s = y(z), v = y(u)$, i.e., $ds = k(z)dz$, $dv = k(u)du$) and using Eq. (4), this yields:

$$e^*(w) = \int_{y^{-1}(w)}^\infty e^{-\int_{y^{-1}(w)}^{y^{-1}(y(z))} \mu^*(y(u))k(u)du} k(z)dz = \int_{y^{-1}(w)}^\infty e^{-\int_{y^{-1}(w)}^{z} \mu(u)k(u)du} k(z)dz \,. \qquad \text{(A2)}$$

This implies for the life expectancy at age x for those currently observed at that same age:

$$e^*{}_x(x) = e^*(y(x)) = \int_x^\infty e^{-\int_x^z \mu(u)k(u)du} k(z)dz \,, \qquad \text{(A3)}$$

which is a general form of the relation (7) presented in the main text.

Additional tables

Table A1. Selected conventional and exposure-adjusted estimates of life expectancy at birth (e_0) and at age 65 (e_{65}).

		Life expectancy at birth (years)		Life expectancy at age 65 (years)		
Population	**Year**	**conventional**	**adjusted**	**conventional**	**adjusted**	**adjusted - for those aged 65**
Australia	**2007**	81.5	100.0	20.2	38.7	25.2
Austria	**2008**	80.4	99.6	19.3	37.9	24.1
Belgium	**2007**	79.7	95.2	19.1	33.9	22.8
Canada	**2007**	80.7	94.5	19.8	33.2	23.4
Denmark	**2008**	78.7	94.5	18.1	33.0	21.5
West Germany	**2008**	80.0	99.1	19.0	37.0	22.8
Finland	**2008**	79.7	94.1	19.4	33.2	24.4
France	**2007**	81.0	98.1	20.5	37.0	25.1
Iceland	**2008**	81.8	90.4	19.5	28.1	21.7
Ireland	**2006**	79.6	100.9	18.4	39.7	25.2
Israel	**2007**	80.4	97.1	19.0	35.2	22.8

		Life expectancy at birth (years)		Life expectancy at age 65 (years)		
Population	**Year**	**conventional**	**adjusted**	**conventional**	**adjusted**	**adjusted - for those aged 65**
Italy	**2006**	81.4	94.9	19.9	33.6	24.5
Japan	**2008**	82.7	93.2	21.3	31.8	25.0
Luxembourg	**2006**	79.5	91.3	18.7	30.6	22.8
Netherlands	**2006**	79.8	92.9	18.6	31.1	21.6
New Zealand	**2008**	80.4	96.7	19.5	35.7	23.6
Norway	**2008**	80.7	95.2	19.3	33.6	23.0
Portugal	**2009**	79.5	95.2	18.9	34.5	23.1
Spain	**2006**	80.8	91.4	19.8	30.3	22.8
Sweden	**2007**	81.0	97.7	19.3	35.3	21.8
Switzerland	**2007**	81.8	97.7	20.3	35.9	24.4
Taiwan	**2008**	78.4	89.6	18.7	30.2	22.5
United Kingdom	**2006**	79.4	89.7	18.7	29.2	23.0
United States	**2006**	78.1	85.7	19.0	26.4	21.3
Lower mortality countries in transition:						
Bulgaria	**2007**	73.0	81.8	14.9	22.7	16.3
Czech Republic	**2008**	77.2	91.1	17.1	30.1	20.5
East Germany	**2008**	79.5	99.1	18.8	37.4	23.1
Estonia	**2007**	73.2	89.3	16.3	31.9	19.0
Hungary	**2006**	73.5	88.5	15.9	29.0	18.2
Poland	**2006**	75.2	88.0	16.9	29.0	20.4
Slovakia	**2008**	74.9	84.4	16.0	24.9	17.9
Slovenia	**2006**	78.2	95.7	18.1	35.1	21.9
Higher mortality countries in transition:						
Belarus	**2007**	70.3	72.0	14.6	16.4	15.2
Latvia	**2007**	71.2	75.6	15.4	19.4	16.3
Lithuania	**2007**	70.9	67.5	15.8	12.5	15.8
Russia	**2008**	67.9	67.0	14.4	14.6	15.5
Ukraine	**2006**	67.9	64.5	13.9	11.3	14.1
Average		**77.8**	**90.2**	**18.2**	**30.3**	**21.4**
Standard deviation		*4.1*	*9.6*	*1.9*	*7.3*	*3.2*
Average - excl. CIT [a]		**80.3**	**94.8**	**19.3**	**33.5**	**23.3**
Standard deviation		*1.1*	*3.8*	*0.7*	*3.4*	*1.2*
Average - CIT [a]		**73.3**	**81.9**	**16.0**	**24.2**	**18.0**
Standard deviation		*3.7*	*11.5*	*1.4*	*8.7*	*2.8*

[a] CIT stands for 'countries in transition' and includes populations of the former Eastern block

Table A2. 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

Population	Conventional life expectancy at birth (years)					Conventional lie expectancy at age 65 (years)		
	1980	1990		last year [b]		1980	last year [b]	
	observed	observed	forecast	observed	forecast	observed	observed	forecast
Australia	**74.5**	76.9	77.3	**81.5**	**82.0**	16.0	20.2	22.1
Austria	**72.7**	75.8	74.2	**80.4**	**76.7**	14.9	19.3	18.3
Belgium	**73.3**	76.1	74.8	**79.7**	**77.0**	15.0	19.1	18.5
Canada	**75.1**	77.4	76.8	**80.7**	**79.8**	16.7	19.8	20.1
Denmark	**74.1**	74.9	74.5	**78.7**	**74.9**	15.7	18.1	16.4
West Germany	**73.4**	76.0	75.3	**80.0**	**78.2**	15.1	19.0	19.2
Finland	**73.6**	75.0	76.4	**79.7**	**81.2**	15.1	19.4	21.0
France	**74.2**	76.8	76.0	**81.0**	**78.9**	16.3	20.5	20.1
Iceland	**76.6**	78.4	79.3	**81.8**	**83.7**	17.3	19.5	23.3
Ireland	**72.6**	74.9	73.5	**79.6**	**75.3**	14.2	18.4	15.6
Israel	**(n.a.)**							
Italy	**74.1**	77.0	75.2	**81.4**	**77.5**	15.4	19.9	17.5
Japan	**76.1**	79.0	79.3	**82.7**	**85.5**	16.2	21.3	24.5
Luxembourg	**72.8**	75.6	74.9	**79.5**	**78.3**	14.5	18.7	18.7
Netherlands	**75.8**	77.0	77.4	**79.8**	**79.9**	16.3	18.6	19.4
New Zealand	**72.9**	75.4	74.2	**80.4**	**77.1**	14.9	19.5	17.4
Norway	**75.6**	76.3	76.7	**80.7**	**78.9**	16.2	19.3	18.1
Portugal	**71.7**	74.2	73.3	**79.5**	**76.2**	15.0	18.9	18.6
Spain	**75.5**	76.9	77.6	**80.8**	**81.0**	16.4	19.8	20.7
Sweden	**75.7**	77.6	76.3	**81.0**	**76.9**	16.2	19.3	17.2
Switzerland	**75.6**	77.4	77.5	**81.8**	**80.5**	16.4	20.3	20.6
Taiwan	**(n.a.)**							
United Kingdom	**73.6**	75.7	74.6	**79.4**	**76.3**	15.0	18.7	16.9
United States	**73.7**	75.4	76.3	**78.1**	**80.5**	16.4	19.0	21.5
Lower mortality countries in transition:								
Bulgaria	**71.1**	71.3	70.5	**73.0**	**69.4**	13.7	14.9	12.5
Czech Republic	**70.3**	71.4	70.8	**77.2**	**71.9**	12.9	17.1	13.5
East Germany	**71.9**	72.9	72.3	**79.5**	**72.3**	13.8	18.8	14.3
Estonia	**69.5**	69.9	67.9	**73.2**	**64.7**	14.2	16.3	11.1
Hungary	**69.1**	69.4	67.6	**73.5**	**64.9**	13.2	15.9	10.7
Poland	**70.2**	70.7	69.5	**75.2**	**67.5**	14.1	16.9	12.9
Slovakia	**70.4**	70.8	70.3	**74.9**	**69.9**	13.7	16.0	13.0

Population	Conventional life expectancy at birth (years)					Conventional lie expectancy at age 65 (years)		
	1980	1990		last year [b]		1980	last year [b]	
	observed	observed	forecast	observed	forecast	observed	observed	forecast
Slovenia	**(n.a.)**							
Higher mortality countries in transition:								
Belarus	**71.1**	71.2	68.9	**70.3**	**65.0**	15.4	14.6	11.1
Latvia	**69.2**	69.6	67.4	**71.2**	**64.1**	14.5	15.4	10.9
Lithuania	**70.7**	71.4	69.3	**70.9**	**66.3**	15.5	15.8	12.9
Russia	**67.5**	69.2	65.8	**67.9**	**62.7**	14.2	14.4	10.8
Ukraine	**69.7**	70.5	68.0	**67.9**	**65.0**	14.4	13.9	11.3
Average	**72.8**	**74.4**	**73.5**	**77.7**	**74.7**	**15.1**	**18.1**	**16.8**
Standard deviation	***2.4***	*3.0*	*3.8*	***4.3***	***6.5***	*1.1*	*2.0*	*4.0*
Average - excl. CIT [a]	**74.2**	**76.3**	**76.0**	**80.4**	**78.9**	**15.7**	**19.4**	**19.4**
Standard deviation	*1.3*	*1.2*	*1.7*	*1.1*	*2.7*	*0.8*	*0.8*	*2.3*
Average - CIT [a]	**70.1**	**70.7**	**69.0**	**72.9**	**67.0**	**14.1**	**15.8**	**12.1**
Standard deviation	*1.2*	*1.1*	*1.8*	*3.5*	*3.2*	*0.8*	*1.3*	*1.2*

[a] CIT stands for 'countries in transition' and includes populations of the former Eastern block
[b] Last observation years available from the Human Mortality Database[24] vary from 2006 to 2009 depending on country (those years are presented in table A1)

Table A3. 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

Population	Base year	Conventional life expectancy at birth (years)				Conventional life expectancy at age 65 (years)		
		2015	2025	2050	UN 2045-50	2015	2025	2050
Australia	**2007**	83.5	86.4	93.2	86.2	22.0	24.6	31.4
Austria	**2008**	82.1	84.9	91.8	85.0	20.7	22.9	29.7
Belgium	**2007**	81.3	83.7	89.1	85.0	20.4	22.3	27.4
Canada	**2007**	82.4	84.6	89.7	85.2	21.3	23.3	28.0
Denmark	**2008**	80.3	82.7	88.7	83.0	19.3	21.3	26.8
West Germany	**2008**	81.5	84.1	90.6	84.4	20.1	22.1	28.1
Finland	**2008**	81.4	83.9	89.0	84.5	20.9	23.0	27.6
France	**2007**	82.8	85.4	91.2	86.0	22.0	24.2	29.6
Iceland	**2008**	83.1	85.0	89.6	86.0	20.5	22.3	27.2
Israel	**2007**	82.2	84.7	90.8	85.4	20.5	22.8	28.6
Ireland	**2006**	82.8	86.5	94.5	84.5	21.2	24.6	32.9
Italy	**2006**	83.7	86.3	92.4	85.4	21.8	24.3	30.9

Population	Base year	Conventional life expectancy at birth (years) 2015	2025	2050	UN 2045-50	Conventional life expectancy at age 65 (years) 2015	2025	2050
Japan	**2008**	84.1	86.1	90.5	87.2	22.5	24.4	28.9
Luxembourg	**2006**	81.6	84.1	88.8	84.6	20.5	22.7	27.8
Netherlands	**2006**	81.6	83.8	88.8	84.2	20.0	21.9	26.7
New Zealand	**2008**	82.0	84.6	91.2	85.2	20.8	23.2	29.8
Norway	**2008**	82.3	84.8	90.9	85.2	20.5	22.7	29.0
Portugal	**2009**	80.9	83.5	89.5	83.2	20.0	22.3	28.3
Spain	**2006**	82.4	84.4	88.7	85.5	21.1	22.9	27.4
Sweden	**2007**	82.4	84.4	90.1	85.2	20.4	22.0	27.3
Switzerland	**2007**	83.7	86.2	92.3	86.6	21.8	24.0	30.2
Taiwan	**2008**	80.2	82.5	87.2		20.2	22.6	27.5
United Kingdom	**2006**	81.5	83.8	88.0	84.1	20.6	22.9	27.4
USA	**2006**	79.5	81.0	83.8	83.3	20.3	21.6	24.3
Lower mortality countries in transition:								
Bulgaria	**2007**	74.2	75.8	79.5	79.5	15.8	16.7	20.0
Czech Republic	**2008**	78.9	81.4	86.9	81.9	18.4	20.4	25.5
East Germany	**2008**	81.2	84.0	90.8	84.4	20.2	22.5	28.6
Estonia	**2007**	75.3	78.1	84.3	80.0	17.6	19.5	26.0
Hungary	**2006**	75.6	78.2	83.8	79.6	17.3	18.8	23.7
Poland	**2006**	77.5	80.0	84.7	80.9	18.7	20.6	25.3
Slovakia	**2008**	76.2	78.0	82.0	80.3	16.9	18.4	22.1
Slovenia	**2006**	80.7	83.6	90.3	83.3	20.0	22.4	29.1
Higher mortality countries in transition:								
Belarus	**2007**	70.8	71.3	72.0	76.2	15.0	15.4	16.4
Latvia	**2007**	71.9	72.8	74.8	79.1	15.9	16.3	18.2
Lithuania	**2007**	70.3	69.3	67.7	78.7	15.7	14.9	12.8
Russia	**2008**	68.1	68.2	67.5	74.9	14.9	15.6	15.4
Ukraine	**2006**	67.4	66.5	64.6	75.1	14.0	13.9	11.6
Average		**79.4**	**81.5**	**86.2**	**83.0**	**19.5**	**21.2**	**25.9**
St. Deviation		*4.6*	*5.4*	*7.6*	*3.3*	*2.3*	*3.0*	*5.1*
Average		**82.1**	**84.5**	**90.0**	**85.0**	**20.8**	**22.9**	**28.4**
St. Deviation		*1.2*	*1.3*	*2.2*	*1.0*	*0.8*	*1.0*	*1.8*
Average - CIT		**73.9**	**75.3**	**78.2**	**79.2**	**16.7**	**17.8**	**20.5**
St. Deviation - CIT		*4.3*	*5.6*	*8.6*	*2.8*	*1.8*	*2.7*	*5.6*

[a] CIT stands for 'countries in transition' and includes populations of the former Eastern block

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