

The contribution of rectangularization to the secular increase of life expectancy: an empirical study

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Accepted 20 November 2012

Background In low-mortality countries, life expectancy is increasing steadily. This increase can be disentangled into two separate components: the delayed incidence of death (i.e. the rectangularization of the survival curve) and the shift of maximal age at death to the right (i.e. the extension of longevity).

Methods We studied the secular increase of life expectancy at age 50 in nine European countries between 1922 and 2006. The respective contributions of rectangularization and longevity to increasing life expectancy are quantified with a specific tool.

Results For men, an acceleration of rectangularization was observed in the 1980s in all nine countries, whereas a deceleration occurred among women in six countries in the 1960s. These diverging trends are likely to reflect the gender-specific trends in smoking. As for longevity, the extension was steady from 1922 in both genders in almost all countries. The gain of years due to longevity extension exceeded the gain due to rectangularization. This predominance over rectangularization was still observed during the most recent decades.

Conclusions Disentangling life expectancy into components offers new insights into the underlying mechanisms and possible determinants. Rectangularization mainly reflects the secular changes of the known determinants of early mortality, including smoking. Explaining the increase of maximal age at death is a more complex challenge. It might be related to slow and lifelong changes in the socio-economic environment and lifestyles as well as population composition. The still increasing longevity does not suggest that we are approaching any upper limit of human longevity.

Keywords Mortality, life expectancy, longevity

Introduction

In most countries, life expectancy at birth (LE_0) continues to rise steadily. In early stages of the demographic transition, the main underlying mechanism of this increase was the fall in infant and childhood

mortality.¹ In low-mortality countries, since the 1950s, trends in LE_0 have been driven by the mortality decline among the elderly. The underlying mechanism of the decrease in this oldest-old mortality remains however obscure, let alone its proximal and remote causes.^{2,3}

Thirty years ago, Fries explored the relationship between longer life expectancy and health.⁴ He introduced the rectangularization of the survival curve to link the decrease of premature mortality with the compression of morbidity and disability around the maximum life span. The underlying concept is that the improvement of the health status of the population resulted in the postponement of lethal diseases and thus to the rectangularization of both survival and healthy life curves.

Several indicators of mortality compression have been proposed to monitor these changes, measuring for example the rectangularity of the survival curve or the variability of age at death. Most studies in low mortality countries have shown concentration of deaths around increasing ages at death.^{5–13} There are however dissenting observations:^{14–16} some studies show a plateau, or even a slowdown, in the concentration of deaths despite a steady rise in life expectancy.^{5–8,10,11,17} In other words, the distribution of age at death is shifting towards higher values whereas its variability is remaining stable or is even increasing. Such an evolution has been termed the ‘shifting mortality scenario’.¹⁸

Based on prior work,⁵ Rousson and Paccaud developed two quantitative nonparametric indicators, rectangularity and longevity, to characterize the components of the secular increase in life expectancy.¹⁹ This paper aims to explore the contribution of longevity and rectangularization to the secular increase in life expectancy in selected low-mortality countries.

Methods

From the Human Mortality Database²⁰ we retrieved standard 1-year-period life tables between 1922 and 2006 for nine European countries, representing major geographical regions of Europe: four northern countries (Norway, Sweden, Denmark and Finland), three central (the United Kingdom, The Netherlands and Switzerland), and two southern (France and Italy). Both starting date and countries were selected according to the availability of data.

In what follows, we consider life expectancy at age 50 years (i.e. removing premature deaths) which is trimmed to the right by excluding the 10% highest ages at death (in order not to depend on mortality estimates based on small numbers at advanced ages), which might be noted as $tLE_{50,10\%}$ and which is abbreviated below as tLE . This concept is close to the ‘temporary life expectancy’ defined in Arriaga²¹ as ‘the average number of years that a group of persons alive at exact age x will live from age x to $x + i$ years’, with $x = 50$ years. Note however that the age $x + i$ that we use is not fixed as in Arriaga’s paper, but is determined by the distribution of the data (as the 90th quantile of the distribution of age at deaths in the group of persons alive at age 50), and is hence different from one life table to another. As described

in Rousson and Paccaud,¹⁹ tLE can be expressed as a function of two components, R and L , as follows:

$$tLE = 50 + R * (L - 50)$$

where R is the area under the survival curve divided by the area of the smallest rectangle containing that curve, and where L is the 90% quantile of the distribution above. R and L are interpreted as indicators of rectangularity and longevity, respectively (see Rousson and Paccaud for details¹⁹).

Consider in a given country, two such trimmed life expectancies (tLE_0 and tLE_1) calculated at two different periods (1922 and 2006). Each period is characterized by rectangularity indices (R_0 and R_1) and longevity indices (L_0 and L_1). Let R_M be the average of R_0 and R_1 and let L_M be the average of L_0 and L_1 . Using the expression above, the gain in tLE between 1922 and 2006 can be decomposed as follows:

$$tLE_1 - tLE_0 = [(R_1 - R_0) * (L_M - 50)] + [(L_1 - L_0) * R_M]$$

The first term $[(R_1 - R_0) * (L_M - 50)]$ is the gain of (trimmed) life expectancy attributable to the rectangularization of the survival curve, whereas the second term $[(L_1 - L_0) * R_M]$ is the gain attributable to longevity extension, i.e. to the shift of the survival curve to the right.¹⁹ A similar decomposition has been applied by Kitagawa to a difference between two rates.²²

Results

Figure 1 shows the increase of tLE over the period 1922–2006, observable in all countries under study, and more marked in women than in men. The magnitude of tLE increase ranged from a minimum of 5.1 years for Danish men, to a maximum of 13.8 years for Swiss women. In general, the gain over the period was higher in countries with initial low tLE : Spearman correlation between tLE in 1922 and tLE gain between 1922 and 2006 was -0.80 in men and -0.93 in women.

Rectangularity and longevity both increased steadily over the period (Figures 2 and 3), however with two notable exceptions (Dutch and Danish men, whose rectangularity did not rise before the 1980s). Spearman correlations between the initial value of the indicators and its increase between 1922 and 2006 were negative (-0.90 and -0.53 for rectangularity; -0.88 and -0.98 for longevity for men and women, respectively). For longevity, the catching up was so pronounced that some countries with low initial levels in 1922 attained the highest longevity in 2006.

The calendar year corresponding to the most substantial change in the rhythm of increase has been identified by a two-segment regression model.²³ In Figures 2 and 3, the calendar year with the most important change of slope is indicated by a vertical line. In Figure 4a and b, the magnitude of the most

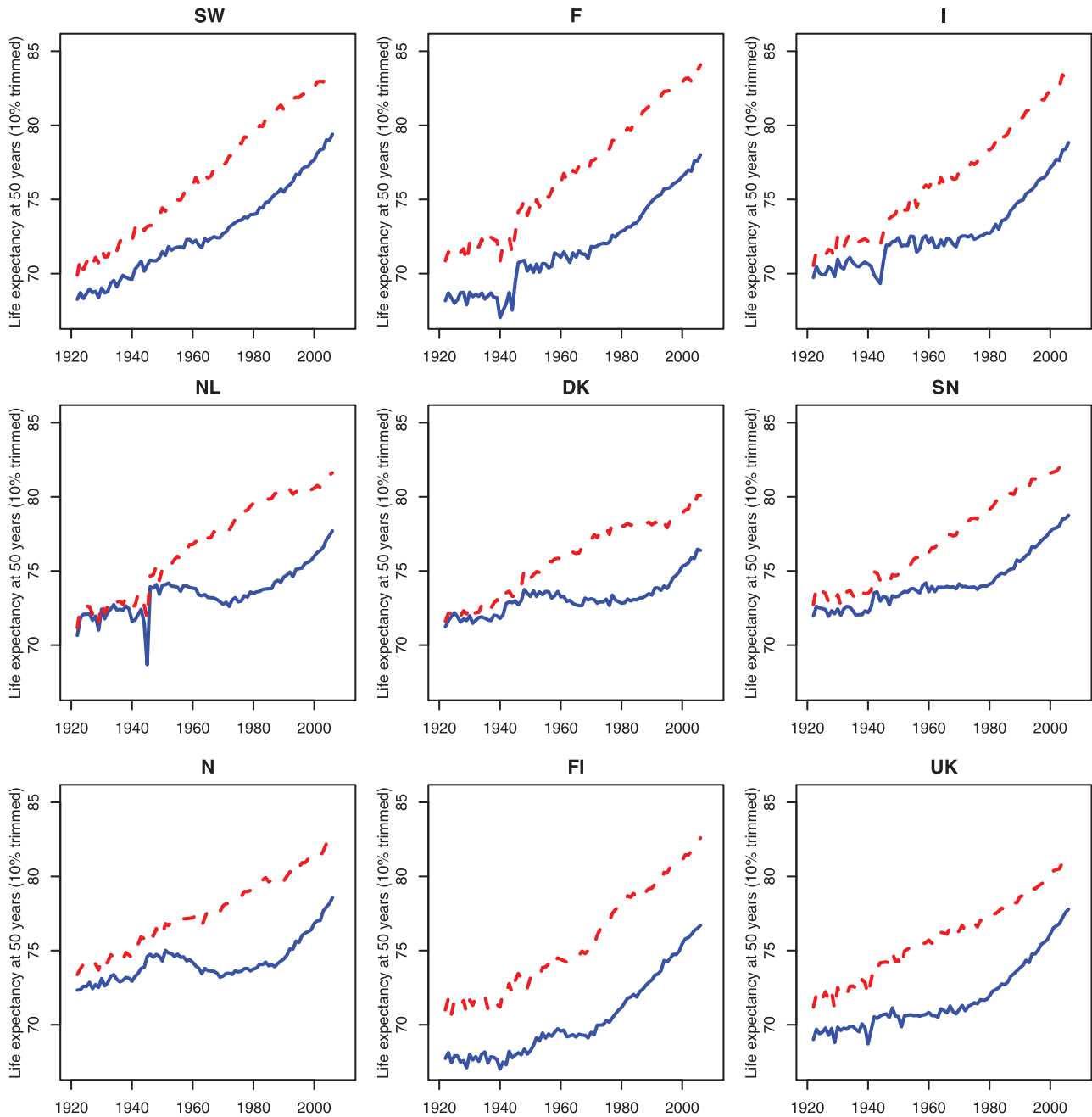


Figure 1 Life expectancy at 50 years (trimmed at 10% to the right): secular trends in nine European countries 1922–2006. SW, Switzerland; F, France; I, Italy; NL, Netherlands; DK, Denmark; SN, Sweden; N, Norway; FI, Finland; UK, United Kingdom. Men are represented by solid lines and women by dashed lines

important change of slope is plotted against the calendar year of change, for both rectangularity and longevity.

For men, rectangularization increased almost suddenly and simultaneously in all countries in the 1980s (Figure 4a). Since then, men have been making up women's rectangularity. In contrast, the slope in women changed towards lower values in most countries (Switzerland, Denmark, The Netherlands, Sweden, Norway and the UK), occurring

simultaneously in the 1960s. For women in France, Italy and Finland, there was no such deceleration, the most substantial change being an acceleration of rectangularization in the 1930s.

Regarding longevity extension, there was an acceleration everywhere for both men and women (i.e. a positive change of slope), with the exception of Dutch women. These changes tended to occur earlier in women than in men, i.e. between 1932 and 1964 versus 1969 and more in men. France was the only

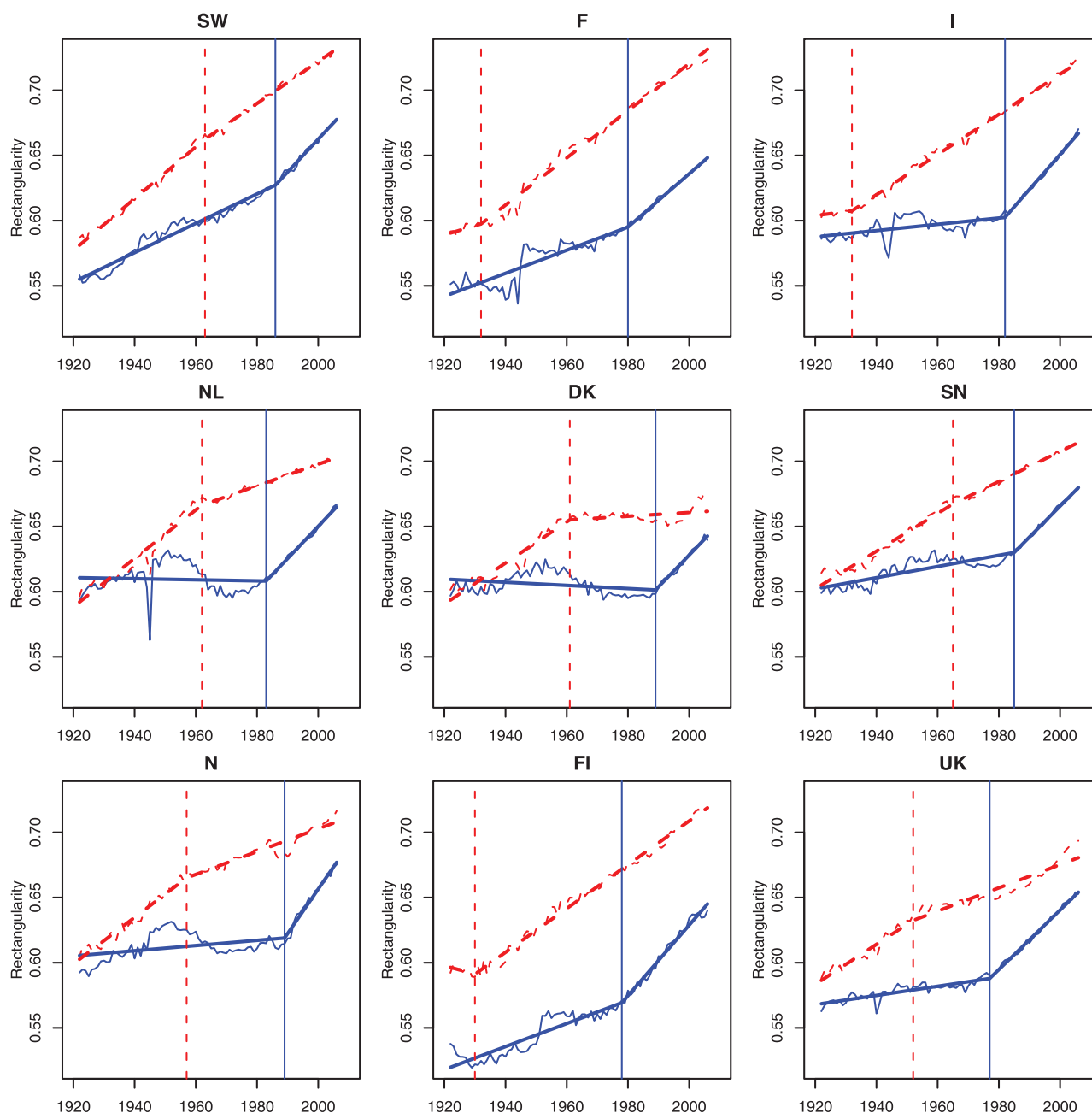


Figure 2 Rectangularity index: secular trends in nine European countries 1922–2006. SW, Switzerland; F, France; I, Italy; NL, Netherlands; DK, Denmark; SN, Sweden; N, Norway; FI, Finland; UK, United Kingdom. Men are represented by solid lines and women by dashed lines. A two-segment regression model has been fitted and added to the plots to improve readability. The vertical line corresponds to the calendar year with the most important change of slope

exception, where the change occurred simultaneously for men and women in 1940.

Since rectangularity and longevity are not measured on the same scale, it is difficult to compare directly their increase during the same period (see Methods). Thus, Figure 4c plots the number of gained years of tLE attributable to rectangularization against the number of years attributable to longevity extension over the period 1922–2006. For example, the gain of

13.8 years observed in Swiss women is decomposed into 8.2 years (59%) attributable to longevity extension, and 5.6 years (41%) attributable to rectangularization. In both genders and in most countries, the contribution of longevity extension was higher than the contribution of rectangularization (Norway being the only exception). In general, the predominance of longevity over rectangularity in the trends was still observed during the most recent period (1970–2006)

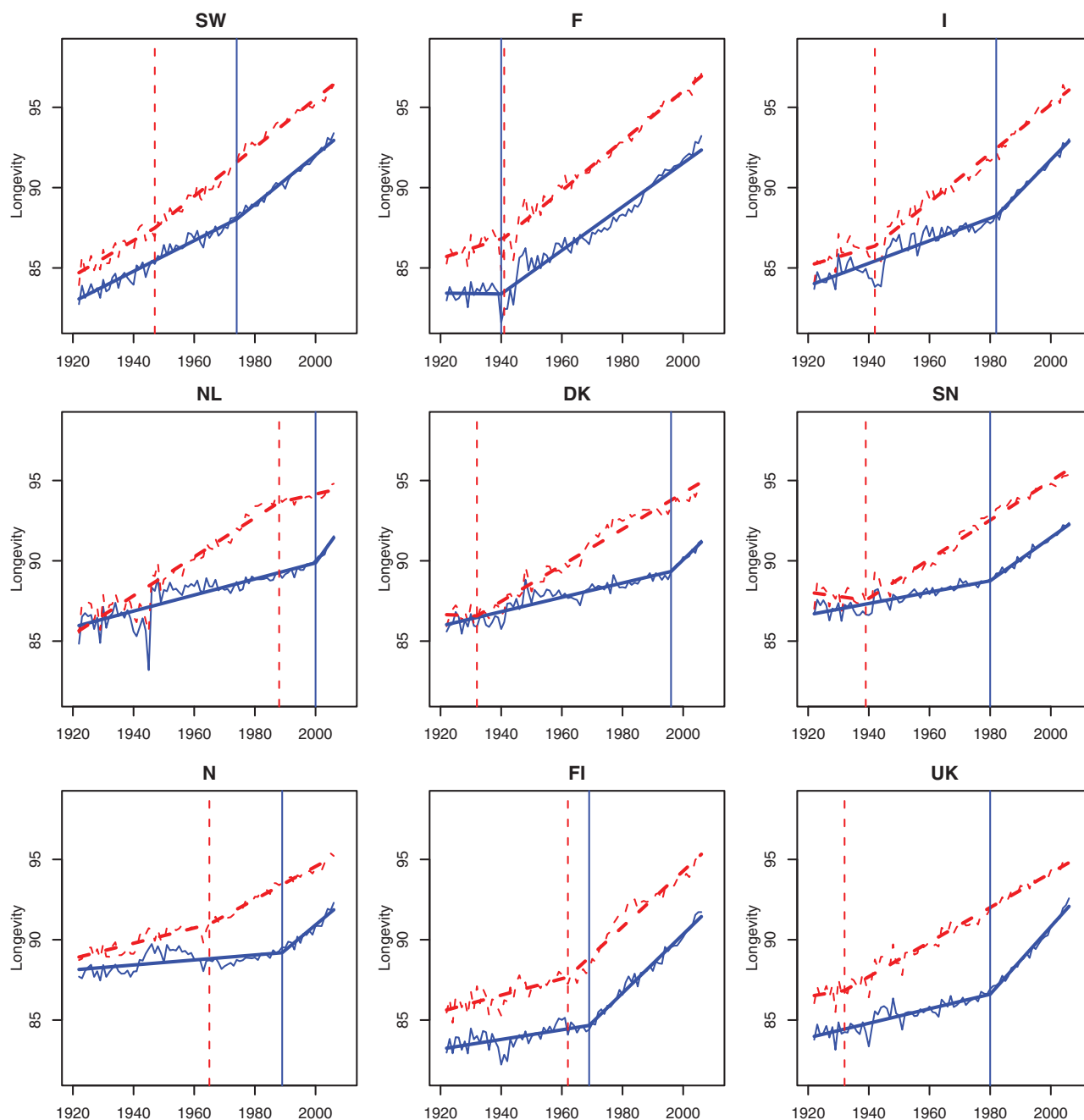


Figure 3 Longevity index: secular increase in nine European countries 1922–2006. SW, Switzerland; F, France; I, Italy; NL, Netherlands; DK, Denmark; SN, Sweden; N, Norway; FI, Finland; UK, United Kingdom. Men are represented by solid lines and women by dashed lines. A two-segment regression model has been fitted and added to the plots to improve readability. The vertical line corresponds to the calendar year with the most important change of slope

(Figure 4d). However, for men in The Netherlands, Norway and Sweden, the contribution of rectangularization became higher than the contribution of longevity extension.

Discussion

This empirical study provides further insight into the secular changes of survival in low-mortality countries.

During the period 1922–2006, the increase in mean duration of life after age 50 years was associated with the increase of both rectangularity and longevity. These patterns were observed in both genders. However, rectangularization accelerated in men in the 1980s in all countries, but decelerated in women in the 1960s in most countries. On the other hand, there was no slowing down in longevity extension (except for Dutch women), which contributed to

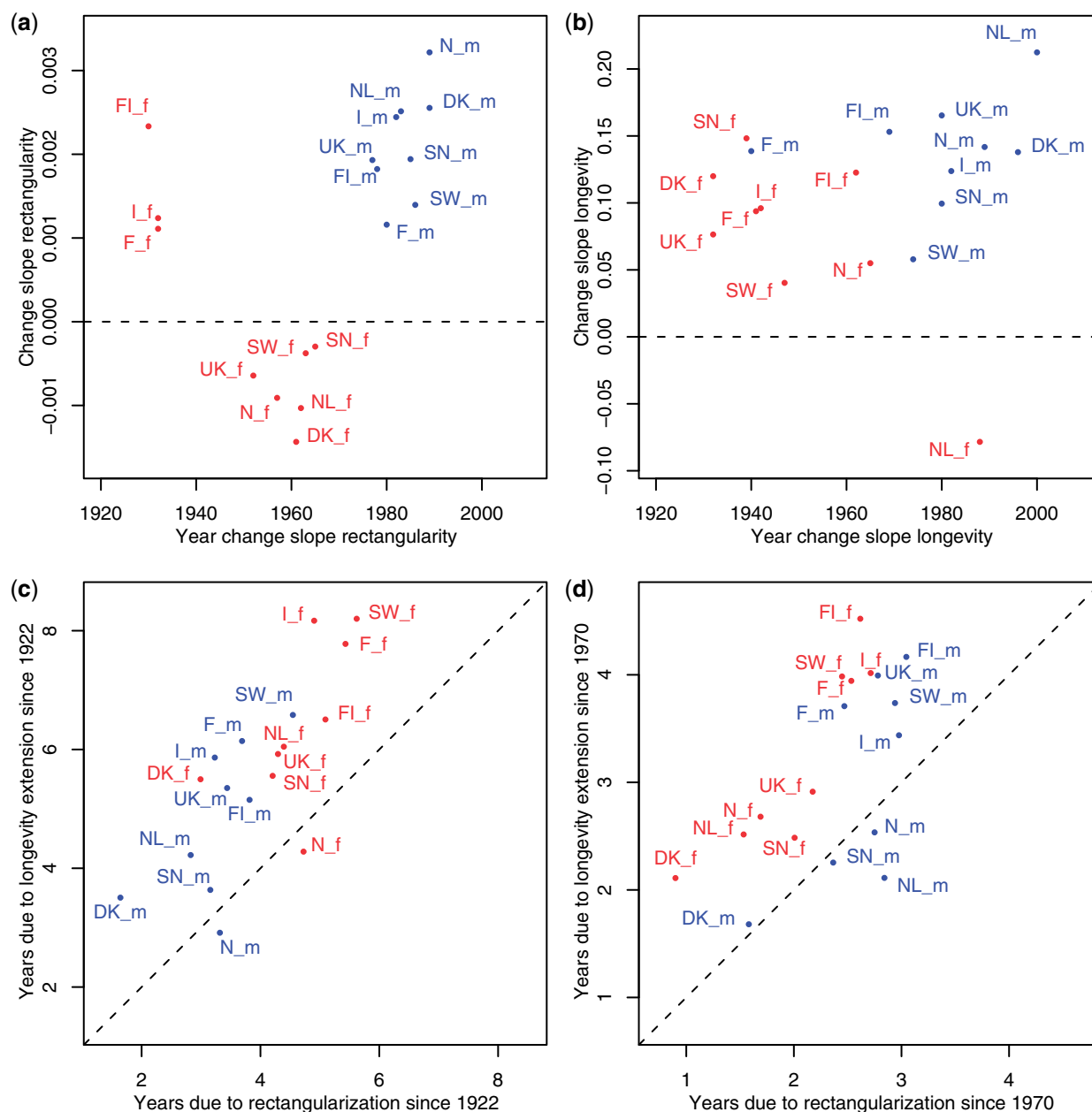


Figure 4 Summary of evolution of rectangularity and longevity indices in nine European countries. Abbreviations: SW, Switzerland; F, France; I, Italy; NL, Netherlands; DK, Denmark; SN, Sweden; N, Norway; FI, Finland; UK, United Kingdom; m, men; w, women. Panels a and b show the relationship between most important change of slope value and calendar year of change, as obtained by a two segment regression model, for the rectangularity index (panel a) and the longevity index (panel b). Panels c and d show the years of life gained after 50 years attributable to rectangularization versus longevity extension between 1922 and 2006 (panel c) and between 1970 and 2006 (panel d). An identity line is plotted as reference line

more years than rectangularization (except in Norway). This predominance was still observed after 1970 in most countries, suggesting that we are still far from any upper limit of age at death.^{3,24} Thus, rectangularization is by far not the single source of life expectancy increase as originally suggested by Fries.⁴ In fact, our observations are compatible with a model of survival including a complete rectangularization

(i.e. with no premature mortality) plus a continuing increase of the upper limit of longevity. Such coexistence has been found in other studies in low-mortality countries and suggested new models of mortality.^{25,26}

The gender-specific pattern of rectangularization (see Figures 2 and 4a), i.e. a simultaneous acceleration in men and deceleration in women, occurring at different periods, is likely to be related to secular

trends in cigarette smoking, i.e. the single most important determinant of premature mortality in the 20th century in Europe. Men adopted smoking earlier than women, thus suffered from more premature deaths and showed a slower rectangularization. In the 1980s, smoking started to decline among men while it was increasing among women from the 1960s. Because smoking has such a strong impact on population health and mortality,²⁷ it is likely to explain the gender-specific history of rectangularization.

This is corroborated by the descriptive epidemiology of tobacco consumption in Europe,²⁸ which showed a decrease in lung cancer mortality (the closest marker of cigarette consumption) in the 1980s among the UK men aged 55–74, whereas an increase among women of same age was observed in the 1960s. In both Finland and the UK, tobacco attributable mortality decreased among men between 1975 and 1985, whereas an increase was observed among UK women from 1955, especially at ages 70–79 years.²⁹

Another convergent observation was provided by Pampel *et al.*³⁰ who analysed the gender-related differential in mortality between 1975 and 1995 in 21 countries. Three patterns of secular trends in sex differentials (stable, widening and narrowing) were identified. Most mortality differences between patterns were attributable to tobacco. Countries which experienced a widening of the differential, and an increase in the female advantage (e.g. France) showed a small decline in the female tobacco-attributable mortality. On the contrary, countries with an increasing female disadvantage showed a convergence in male and female tobacco-attributable mortality (e.g. The Netherlands, Denmark, Sweden, Norway and the UK). Finally, in countries with a stable pattern (e.g. Italy), there was a worsening of the female tobacco-attributable mortality. This is consistent with the country-specific patterns of rectangularization in women in our study. Our findings may also partly reflect the impact of smoking history by cohort as shown with US data.³¹

Our data do not offer any direct argument on the determinants of the steady increase of longevity after the age of 50 (see Figure 3). Obvious candidates are related to the lifelong improvement of the environment. An earlier paper showed that the increase of the oldest-old in Switzerland started in the 1950s.³² This might correspond to some contemporary improvement of the sanitary and socio-economic environment directly benefiting the old and the oldest-old (i.e. antibiotics, pensioning scheme, etc.). However, the increase of late longevity may also be related to improvements in the early life of the birth cohorts, especially those related to foetal, perinatal and childhood periods. Steady trends have been observed for the decrease of the age at menarche (becoming earlier by two or three months per decade in Europe and in the US^{33,34}) and the increase of adult height and

weight.^{35,36} These markers are thought to reflect the improvement of the overall nutritional status³⁷ and, more generally, the socio-economic environment. Other papers have also discussed in depth and detail the background of the improved old-age survival.^{38,39} Further studies should explore the association between these sorts of indicators and longevity.

This study has some limitations. We considered nine European countries sharing a similar demographic, socio-economic and health-related history. Further work should explore other countries and during other periods to understand how far the use of the indicators developed by Rousson and Paccaud¹⁹ may improve our understanding of trends in life expectancies, especially in countries at earlier stages of epidemiological transition.

We cannot exclude technical problems explaining the evolution of rectangularization. One of them is that rectangularity index is bounded by a maximum value (one). Thus, the deceleration may occur earlier in women because the index is higher, i.e. closer to the upper boundary. However, the same analysis conducted with the logit scale (i.e. with $\text{Log}[R/(1-R)]$ for which there is no upper limit) produces similar results (data not shown).

Another limitation is that rectangularization and longevity extension are intrinsically linked with each other, the shift of age at death being partly a direct consequence of rectangularization, and any complete separation of both phenomena is difficult to achieve. However, the pace of longevity extension is not completely related to rectangularization: as summarized by Figure 4a and b, there are substantial differences in the pace of change of rectangularization and longevity extension.

Finally, it should be noted that the indicators of rectangularity and longevity, as well as the decomposition of the increase of (trimmed) life expectancy, can also be applied using quantiles different from 90%.¹⁹ To explore the robustness of the procedure, we have applied the method using the quantile 95% instead of 90% (hence excluding only the 5% highest ages at death). The overall picture was not affected. Only two noticeable changes were observed for Sweden and Switzerland. The most substantial secular change of slope in rectangularity for the Swedish women occurred in the 1930s (with an upward trend) rather than in the 1960s (with a downward trend): Sweden is hence similar to France, Italy and Finland. Also, the major deceleration of rectangularization for the Swiss women occurred in 1987 rather than in the 1960s. However, our three main conclusions of this study (namely, (i) the simultaneous acceleration of rectangularization in men, (ii) the absence of slowing down in longevity extension except for the Dutch women and (iii) the higher gain of years due to longevity extension except in Norway) remain valid, and are thus independent from the use of the quantiles 95% or 90%.

In conclusion, the present study illustrates the merits of a decomposition of the secular increase in life expectancy. The two components, rectangularization and longevity extension, both contribute to the increase in life expectancy, but each relates to specific conditions. The gender-related change in cigarette smoking is likely to explain both the agenda and the direction of the trends in rectangularization in men and women, as tobacco is one of the major drivers of mortality differences. This is particularly relevant when considering premature mortality,⁴⁰ whereas the steady and unabated increase in longevity, if confirmed in other settings, might reflect a

more fundamental change in the population and its environment. In any case, an important message here is that the increase in longevity is a long-standing factor of the increase in the overall life expectancy.

Funding

This work was supported by the Institute for Social and Preventive Medicine, Lausanne University Hospital, Lausanne, Switzerland.

Conflict of interest: None declared.

KEY MESSAGES

- Rectangularization and longevity extension both contribute to the increase in life expectancy in low-mortality countries, but longevity extension contributes to more years than rectangularization.
- There is a gender-specific pattern of rectangularization, i.e. a simultaneous acceleration in men in the 1980s and a simultaneous deceleration in women in the 1960s occurring in most countries.
- The gender-related change in cigarette smoking is likely to explain both the agenda and the direction of the trends in rectangularization in men and women.

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