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# An investigation into inequalities in adult lifespan

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## **Abstract**

People in the UK are living longer than ever but the gap between the oldest and shortest lived appears to be increasing. Based on data from the Human Mortality Database we measure the differences in age between the first 10% of adult deaths and the top 5% of survivors. We find that in the period from 1879 to 1939 this gap steadily closed. We cite evidence that the reduction in inequalities in age at death was due to significant improvements in the health and condition of the population through better housing, sanitation, mass vaccination, occupational health, clearer air and other public health improvements which disproportionately improved the lives of the poorest in society relative to the wealthiest. Although life expectancy continued to rise after 1950, the inequality gap remained roughly constant and in recent years has started to widen again – more so for men than for women. A key difference between pre-1939 and now is that deaths are much more likely to be from chronic rather than infectious diseases or environmental causes. Since chronic disease is often attributable to life choices such as smoking and diet, we maintain that the blame for the widening must be laid increasingly at the door of individual lifestyles rather than ambient risks and hazards.

**Key words:** Life expectancy\_ lifespan\_ inequalities\_ gender\_ historical trend

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# Inequalities in adult lifespan

## 1. Introduction

Although life expectancy has increased enormously in recent decades, the gap in life expectancy between the shortest and longest lived is widening for the first time since the late 1870s. After a sustained period when all parts of society benefited from advances in public health, including clean drinking water, antibiotics and mass vaccination, the trend towards greater equality paused in the 1950s and, in the case of men, went into reverse in the 1990s with a re-widening of the gap.

This paper finds that 5% of men in Britain that have attained the age of 30 are living on average to 96.0 years, 33.3 years longer than the lowest 10%. The longest surviving women reach on average 98.2 years by comparison, 30.9 years more than the lowest. In this paper, we argue that unhealthy lifestyles are the main reason for the very large inequalities in lifespan for both men and women.

Many of the big gains from public health improvements are now in the past and personal choices have become much more important. Most deaths today are from age related chronic diseases and so individual life choices are more significant. According to the ONS, deaths from potentially avoidable causes account for approximately 23% of all deaths in England and Wales, with the leading causes being ischaemic heart disease in males and lung cancer in females.<sup>2</sup>

Men in lower socio-economic groups are the most likely to make damaging life-style choices. They put themselves in harm's way on average more than women do ..... they smoke more, drink more and there are periods in their lives when they partake in riskier activities. The good news is that since 1975 the gap between male and female life expectancy has been reducing rapidly, and by more than in other countries. However, this does not apply to inequalities in lifespan between genders which are widening once again after being at parity for many decades.

Taking a longer view, figures for the past 150 years show a steadily rising life expectancy for both genders and, until 1939, a narrowing of the gap between the longest and shortest lived which we term the 'age inequality gap'. We believe the relatively abrupt switch after 1950 reflects the fact that previously achieved gains had more impact on early deaths e.g. work related accidents, contagious diseases, etc. Since this time, however, changes in mortality in old age has become the key driver in determining improvements in future life expectancy.

Although long run data connecting wealth and longevity is almost non-existent, the link between poverty and mortality is consistent with other research from the more recent period. Work by Smith et al using millions of UK personal medical records in the period 2005 to 2010 identifies a mortality gradient between the poorest and richest quintiles in middle

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<sup>2</sup>[http://webarchive.nationalarchives.gov.uk/20160105160709/http://www.ons.gov.uk/ons/dcp171778\\_362295.pdf](http://webarchive.nationalarchives.gov.uk/20160105160709/http://www.ons.gov.uk/ons/dcp171778_362295.pdf)

## Inequalities in adult lifespan

age in which mortality rates in the poorest poverty quintile are up to 2.5 times higher than in the richest quintile.<sup>3</sup> Mayhew et al (2018) analysing mortality rate differentials based on the Index of Multiple Deprivation found that male rates were up to 2.3 times the England average in the worst decile and 4.4 times those in the least deprived decile.

These findings do not mean that lack of wealth or income is directly responsible for the difference. According to Sasson (2016), who uses US data, the poorest groups are more likely to fall victim to the cumulative effects of decades of poor lifestyle and income inequality, reflecting the repercussions of a long succession of unhealthy behaviours. In other words, it would be wrong to blame inequalities simply on contemporary phenomena such as the rise in obesity or on a historical lack of clean water, etc.

The most likely explanation is that the wealthier used to be just as vulnerable as the poor to lifestyle-related diseases. Sasson argues that the wealthier are more likely to adopt healthy behaviours and hence are better placed to avoid or defer them to later in life. Sasson further notes that healthy behaviour spreads much faster through wealthier educated networks: for example, the educated better off were the first to quit smoking. In other words, more educated people can process information relevant to their health better than less educated people.

If people do not help themselves, it is tempting for governments to intervene which partly accounts for the continuing rise of the ‘nanny state’. Everybody was able to share in the benefits from water chlorination or reduced air pollution, but in today’s world, personal health behaviours are much more important determinants of lifespan. Tobacco consumption is a potent example of how personal choice effectively contributes to the deaths of over 100,000 people a year and shortens lives by up to ten years (e.g. see Doll et al 2010).

With tobacco consumption heavily regulated through higher taxes, advertising and smoking bans, smoking prevalence has fallen from a high point in the 1950s of 80% of the male adult population to under 16% today. The announcement of a sugar tax on soft drinks in the March 2016 budget is a different manifestation of this approach and is a strong sign that the government has woken up to the scale of what is a significant public health challenge, which reveals itself through higher prevalence of obesity, type 2 diabetes and consequent health challenges.

### 1.1 From convergence to divergence

We term the trend prior to 1940 the ‘convergent phase’ – a period in which the age inequality gap between rich and poor, as measured by the dispersion in lifespan, narrowed

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<sup>3</sup> Presentation to the Actuarial Research Conference (2014) held at the University of California, Santa Barbara, and entitled ‘The Impact of Relative Poverty on Mortality Rates in the United Kingdom’. Research based on general practice patient records supplied by THIN.

## Inequalities in adult lifespan

considerably. Indeed, if the pre-war trend had continued, inequalities would have eventually disappeared in the 2100s and life expectancy for everyone would have attained 106 years! Although life expectancy continued to rise throughout this period for both genders, the tendency towards convergence gave way to a different pattern. The gender gap i.e. the difference between male and female life expectancy, which had been relatively small up to 1940, started to widen post-1950 reaching a peak in 1970 when female life expectancy was 5.7 years greater.

The age inequality gap throughout this period remained relatively constant for both men and women and was similar in magnitude. It is reasonable to term the post-1950 period the ‘parallel phase’ which corresponded to rising life expectancy but relatively little change in the relative age of death i.e. the gap in survivorship signifying an end to convergence. We compared our findings against France and Italy, two other countries with similar populations and historical records, and also found a comparable convergent phase followed by a parallel phase.

Thus far, the impression gained is that these improvements are essentially a function of time. In fact, observed life expectancy is subject to annual fluctuations for a variety of reasons, the most obvious examples being wars and pandemics. This was more so in the past because society has learnt to control epidemics much better and deaths from military action or environmental disasters are rarer. In the absence of these interruptions the trends in age inequalities would have been much smoother, especially in the second decade of the 20<sup>th</sup> century.

A demographic implication of our analysis is that if life expectancy had continued to improve and that reductions in lifespan had continued to narrow at similar rates to pre-1940, inequalities would have eventually disappeared resulting in a ‘rectangularisation’ of the survival curve in which everyone lives to the same age (Fries 1980; Wilmoth and Horiuchi 1999; Mayhew and Smith 2011). In this process, survival curves would become more rectangular with mortality increasingly compressed in a narrowing age interval, with the slope of survival curve in that range becoming steeper as an age limit to human life is approached.

Research post-2000 finds that the picture is more nuanced with competing views about whether there is indeed a limit to human lifespan, as some people appear to live ever longer (Oeppen and Vaupel 2002; Harper 2005). We observe that rectangularisation is entirely consistent with what we term as ‘convergence’ above. Using data for England and Wales from 1870 to the present, our analysis identifies a parallel phase from 1950 in which inequalities in lifespan remain constant as oppose to narrowing. We also find tentative evidence of ‘divergence’ in lifespan post-1990 in the case of men i.e. widening inequalities.

Annex B sets out these three cases – convergence, parallel and divergence – in a deliberately simplified mathematical form to emphasize the differences. It shows how

## Inequalities in adult lifespan

survivorship and life expectancy are related in each of the cases to inequalities in lifespan and limits to life itself. Its purpose is to contextualise and position our results within the wider literature on this important topic and increase our understanding of the processes involved so that studies that follow can build on a wider investigative framework.

To deal with issues raised by this brief analysis, the rest of this paper is structured as follows; the next section describes the data and methodology to compare changes through time. Section 3 examines convergence and draws upon trends in France and Italy for comparison. Section 4 shows how convergence and the compression of mortality are linked in a more general way. A concluding section discusses possible changes to society that may account for the results obtained.

## **2. Method of analysis**

Inequalities in society conjure up all sorts of images whether it is to do with income or wealth, demographic inequalities including variations in life expectancy or more nebulous concepts such as well-being or personal behaviours. Research on inequalities is important because they signify the outcomes of complex processes operating in a society that are deemed to be positive or a cause for concern. A typical example would be the relationship between life expectancy and economic development or more specific correlates such as level of education, personal wealth or health behaviours.

There is a burgeoning literature on demographic inequalities thanks to the widespread availability of data covering long periods but the focus of attention varies enormously. Distinctions can be drawn between cross country or within country comparisons, cross sectional studies at a point or period in time, or changes through time. Similar countries, blocks or whole continents may be grouped and analysed accordingly (e.g. see Gillespie et al 2014; Edwards and Tuljapurkar 2005; or Clark 2011).

Most studies focus on the modern period since 1950 or later but some such as (Vallin and Mesle 2009) use data from the early twentieth century or much before to compare changes in life expectancy. The literature tends to be in universal agreement that the degree of convergence in the globalisation era is related to economic development but it is not guaranteed or uni-directional (Jorda and Sarabia 2015).

However, there is little commonality of approach among the many studies or one single measure that captures inequality and how to define it (e.g. whether based on demography, health, income or other measures). The starting point for measuring demographic inequalities are usually life table measures, such as life expectancy, survivorship or mortality, all of which in turn are underpinned by the registration systems in each country which record births and deaths.

The widespread availability of birth and deaths data, as compared with the relative lack of data on income and health, means that they are frequently used as a proxy for health or

## Inequalities in adult lifespan

income inequalities, especially in the search for trends over time (e.g. see Murray et al 1999). Since demographic inequalities are concerned with variations in life-span, researchers seek to devise indicators to capture this variation in a single summary measure.

Life expectancy itself is a composite measure since it is an average over all lifespans and is the most familiar of all the alternatives. It is widely used, for example, to compare countries, variations within countries, or between different socio-economic or ethnic groups or between genders. The empirical evidence that life expectancy and other demographic measures are related to socio-economic factors is relatively new and reliant on measures of relative deprivation rather than the much more difficult concept of absolute poverty.

This is the approach taken by Marmot (2010), for example, which found that people living in the poorest neighbourhoods in England had worse health and were likely to die sooner. Subsequent research by Mayhew et al (2018) finds a 10-year gap in life expectancy between neighbourhoods in England that are in the most relatively deprived percentile of neighbourhoods and those in the least. Gaps of this magnitude focus the minds of policymakers to understand the reasons for inequalities of this magnitude and to assist in the search for possible remedies.

In this paper we also use life expectancy to compare the difference in longevity between men and women over the longer term. However, as useful and as familiar as life expectancy is, it suffers from the problem that it only deals with aggregate inequalities in longevity and not inequalities in lifespan. This is because it conceals variations around the average that may be suppressing important information about lifespan inequalities (e.g. within a country or region with extremes of rich and poor).

Composite measures borrowed from economics and elsewhere are also common in the inequalities literature (e.g. see Allison 1978). The Gini-coefficient, normally used to measure economic inequalities, is also used in population studies - for example, see Becker et al (2005) or and Uddin et al (2012). Less common are measures such as Kullback-Lieber divergence which is found in d'Albis et al (2014), the Theil index in Smits and Monden (2009) or the Dispersion Measure of Mortality (Moser et al 2005).

For various reasons, aggregate measures such as these are less transparent than other available alternatives and can give false signals e.g. they may show a reduction in inequality simply because life expectancy is increasing and not because the spread in lifespan is reducing. This is obviously unhelpful if the aim is to understand the gaps in lifespan between individuals and whether they are changing for the better or worse.

Alternative methods for capturing dispersion in data include the standard deviation or variance in age at death, or the inter-quartile range (IQR) which measures the age gap between the bottom 25% and top 75% of deaths (e.g. see Wilmoth and Horiuchi 1999). Edwards (2011), for example, makes the important observation that within-country variance

## Inequalities in adult lifespan

in lifespan is higher than between country variance, a finding which would have been difficult to ascertain by any other method.

The IQR in age of death is arguably the most intuitive of all the measures considered. In this paper we extend this idea by defining the Inter-Percentile Range or IPR as the gap in years between any two specific survival percentiles. It differs from measures such as the standard deviation and variance because it can be used to investigate the central dispersion within different ranges and so is more flexible.

Our first illustration is based on the difference between the 5<sup>th</sup> and 90<sup>th</sup> survival percentiles, though we later broaden out to include other percentiles. However, we avoid the most extreme percentiles such as 1% and 99%, as these are more prone to fluctuation due to the smaller number of deaths involved in their calculation. How the IPR and life expectancy are related is formally explained in Annex B.

Note that an IPR is an absolute measure of dispersion expressed in years. It does not follow that changes to its value are directly correlated with changes in life expectancy for the reason that an average can increase even if dispersion is unchanged or even increasing. This leads us to a key finding of this paper, namely that the relationship between dispersion (i.e. inequalities) and life expectancy changed after 1950.

The start age from which to measure inequalities is also important with different results being obtained when comparing, for example, life expectancy at birth with some other age due to variations in infant mortality, childhood mortality, risk exposure and so on. Hence, it would be wholly inappropriate to include these younger age groups if the focus, say, is on inequalities in life at older ages.

On this point the literature does not provide any hard-and-fast advice although it recognises that there is a difference between trends in life expectancy and/or inequalities when looking at birth compared with other ages. Examples of different start ages in the inequalities literature include 10, 15, 50 etc (e.g. see Vallin and Mesle 2009; Edwards 2011; or Mayhew and Smith 2014). In this paper we start at age 30, as we wish to focus on inequalities that account for most of the normal adult lifespan.

In effect, we are treating inequalities in infant and early adult mortality in a different category to general survivorship, without relegating its importance in any way. This is to avoid the possible confounding effects of infant mortality, but also deaths in early adult age which tends to be higher for men than women (Kannisto 2000 and 2001; Mayhew and Smith 2014).

If we look at life expectancy at age 30, we find that for much of the previous century, life expectancy generally increased year on year. Two notable exceptions are the two world wars from 1914 to 1918 and 1939 to 1945, and the unusually deadly Spanish flu epidemic

## Inequalities in adult lifespan

between 1918 and 1920. These periods aside, we found that the IPR (using the 5<sup>th</sup> and 90<sup>th</sup> percentiles) was inversely correlated with life expectancy pre-1940 but not so post-1950.

Our data was obtained from the Human Mortality Database (HMD) which uses birth and deaths data for many countries to produce complete series of deaths by calendar year and single year of age for each gender in the form of life tables. The HMD is regarded as the most reliable source on complete life tables in existence and so its use ensures greater consistency, although clearly more historical data will be less accurate than recent data.

We focus chiefly on England and Wales but, as previously noted, we also draw comparisons with France and Italy as both of these countries have long historical records available from the HMD and also have comparable sample sizes based on the annual number of deaths. Although the HMD provides complete records for each year dating back to 1841 for England and Wales, we begin our analysis in 1870 in order to accommodate Italy such that each country had the same start year.

On this basis, life expectancy data at age 30 for each country was extracted for each year from 1870 to 2010. Using the  $l_x$  values in the life tables provides information on how many lives survived to exact age  $x$  based on a radix of 100,000 individuals. We applied linear interpolation to estimate the exact ages to which 99%, 98%.....1% of the population survived for both genders at annual intervals from 1870 onwards.

We used period data which means that life tables are based on current mortality rates at each age. An alternative would have been to use cohort tables to investigate changes in expected future life but two issues dissuaded us. Firstly, using cohort tables means that the last complete cohort would be for people aged 30 in 1940 (assuming a maximum age of 100), and so we would only have complete cohorts for those reaching aged 30 between 1870 to 1940. Secondly, as we later show, there are distinct historical phases which would become blurred if we had used cohort data.

### 3. Results

The data can be split in to different periods depending on historical focus and pattern change. In this paper, we focus our attention on the period from 1870 to 1939 and from 1950 onwards. We choose 1939 because it marks the start of the Second World War, and 1950 because it allows for a short respite after the war for the data to return to normality. We call the first period 'A' and the second period 'B'.

Tables 1 (a – d) show results for England and Wales based on life expectancy from age 30 for two 60 year periods, pre- and post-transition: these are 1879 to 1939 and from 1950 to 2010. It compares the magnitude and direction of change at six equi-spaced points in time terminating in 1939 and 2010: (a) and (b) compare age inequalities and life expectancy by gender; (c) gender differences in life expectancy; and (d) gender changes to the age inequality gap.

## Inequalities in adult lifespan

Table 1a shows that in the first period, male life expectancy rose from 31.8 years to 38.9 years and in the second period 40.5 years to 49.6 years, an improvement of 7.1 and 9.1 years respectively. Meanwhile, the age inequality gap between the top 5% and bottom 10% fell by 7.6 years in the first period; but in the second period it fell by only 1.0 years.

Table 1b shows that in the first period female life expectancy rose from 33.9 years to 42.4 years and in the second period from 44.6 years to 53.2 years, an improvement of 8.5 and 8.6 years. The age inequality gap between the top 5% and bottom 10% fell by 8.2 years in the first period and by 2.9 years in the second. Therefore, although the pace of reduction in inequalities slowed considerably, improvements for men were slightly greater than for women.

The results show that as life expectancy grew, the age inequality gap decreased in the period to 1939 which we label period A. After 1950 (period B) the age inequality gap showed very little further fall and in 2010 it was almost the same as it was in 1950 in the case of males. Since the tables are based only on snapshots at six points in time, the next step is to analyse the annual changes in greater detail.

Figure 1 uses annual data from 1870 onwards. There are four series plotted in the chart: one each for male and female life expectancy at age 30 which has an identifiable trend rising from left to right; secondly, age inequalities based on the difference in years between the ages of the 5<sup>th</sup> and 90<sup>th</sup> percentiles of male and female survivors which has an identifiable downward trend from left to right until 1950.

As can be seen, in period A life expectancy made steady progress for the whole period. In period B, the increase in life expectancy initially slowed in the case of males but then accelerated after 1970. It is particularly noticeable that the difference in life expectancy between males and females grew wider in the 1970s reaching a maximum of 5.6 years in 1972. Since then there has been a steady reversal, with the gender gap in life expectancy falling to 3.7 years in 2010.

We also note that the age inequality gap changes after 1950 for both sexes. Up to that point it had been falling almost continuously for the whole of period A with the obvious exception of the period 1914 to 1920. The transition after 1950 can be demonstrated in sharper relief using a 5-year moving average and measuring changes in the gradient at annual intervals which levels out from this point. Throughout most of period A it is noteworthy that, despite gender differences in life expectancy, gender differences in the size of the age inequality gap were actually very small.

In period B the age inequality gap noticeably levelled out and remained relatively flat thereafter for both genders. After 1990 this situation appeared to alter with the gap for women beginning to turn downward and for men upward suggesting age inequalities were

## Inequalities in adult lifespan

(a) Men	Period A			Period B		
Year	1879	1909	1939	1950	1980	2010
Age reached by top 5%	83.6	85.3	86.7	87.9	89.9	95.7
Age reached by bottom 10%	39.8	44.0	50.5	53.6	56.5	62.4
Inequality gap in years	43.8	41.3	36.2	34.3	33.4	33.3
Life expectancy at age 30	31.8	35.0	38.9	40.5	42.7	49.6

(b) Women	Period A			Period B		
Year	1879	1909	1939	1950	1980	2010
Age reached by top 5%	85.2	87.6	89.9	91.2	94.5	98.2
Age reached by bottom 10%	40.7	46.1	53.6	57.4	61.2	67.3
Inequality gap in years	44.5	41.5	36.3	33.8	33.3	30.9
Life expectancy at age 30	33.9	37.5	42.4	44.6	48.2	53.2

### (c) Difference in life expectancy

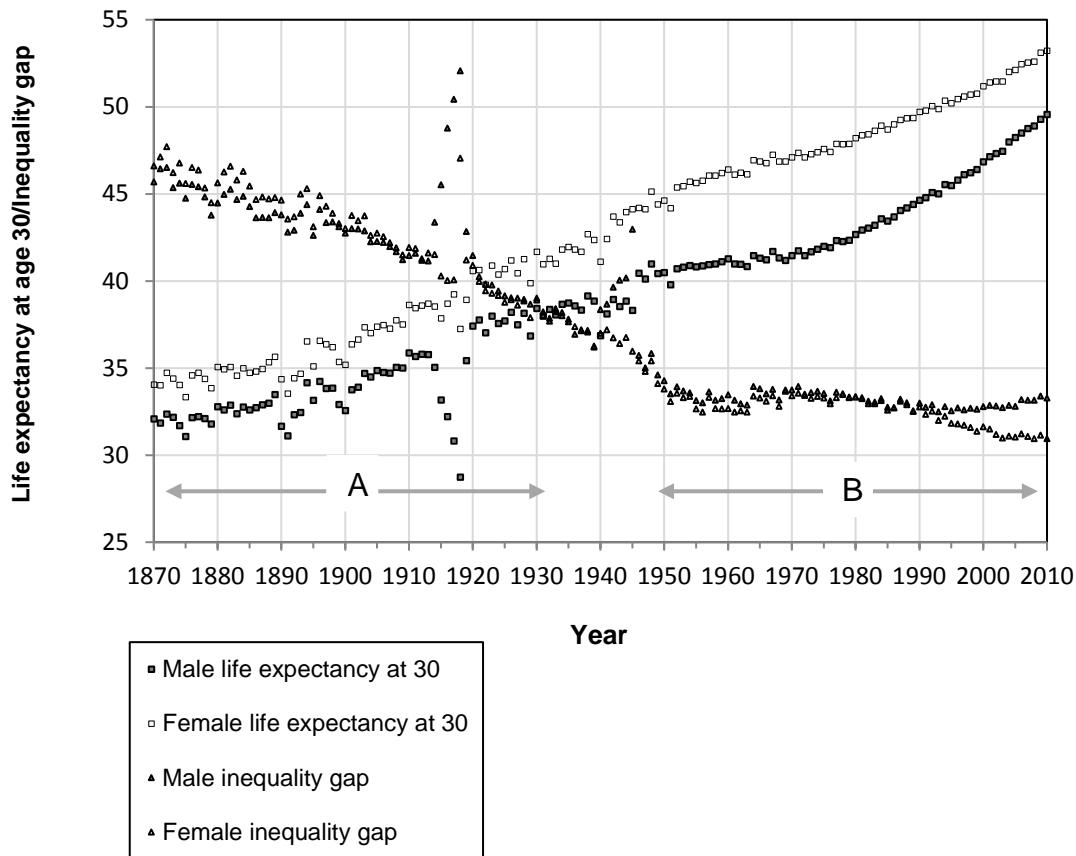
Difference in W-M life expectancy at age 30 (years)	2.1	2.5	3.5	4.1	5.5	3.6
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### (d) Change in gap

Gender	Change in gap 1879 to 1939	Change in gap 1950 to 2010
Men	-7.6	-1.0
Women	-8.2	-2.9

Tables 1 (a-d): Survival, age inequality gap and life expectancy at age 30 for the years 1879, 1909, 1939, 1950, 1980 and 2010 for England and Wales

## Inequalities in adult lifespan



*Figure 1: Chart showing the survival gap and life expectancy at age 30 for men and women in England and Wales from 1870 to 2010: (A) pre-1940; (B) post-1950*

re-widening. Between 1990 and 2010, for example, the inequality gap between men and women rose from being almost at parity to 2 years.

### 3.1 Comparisons with France and Italy

We compared the results from England and Wales with data from France and Italy. If similar trends were observed, it would be reasonable to infer that the same demographic drivers were operating. Italy and France are chosen because of their long demographic records and similarity in population size to England and Wales. For example, we could also have used Sweden, the country with the longest historical record of all, but since it has a much smaller population the data tend to be subject to random noise and hence harder to interpret.

Tables 2 and 3 (a - d) shows the results for France and Italy in the same form as Table 1 (a - d) for England and Wales. A close examination shows that both France and Italy experienced a similar transition as England and Wales in period A, i.e. a long period in which life expectancy increased and age inequalities reduced. As with England and Wales, there was also a shift in trend in period B, but with several important differences.

1. Male life expectancy in England and Wales at age 30 was higher in 2010 than in either France or Italy, although the margin of difference post 1950 is usually about one year or

## Inequalities in adult lifespan

- less. Female life expectancy in France and Italy in 2010 was higher than in England and Wales and has improved by greater amounts since 1950.
2. Greater differences occur when the gap between male and female life expectancies are compared. In England and Wales, the gender gap in life expectancy fell from 5.5 years to 3.6 years between 1980 and 2010 but in France it only fell from 7.3 to 6.3 years and in Italy it rose from 5.9 to 6.1 years.
  3. In absolute terms the male age inequality gap in 2010 was higher in France than in England or Wales which in turn is higher than in Italy. It was 37.0 years in France as compared with 33.3 years in England and Wales and only 31.7 years in Italy. The fact that male age inequalities in Italy continued to narrow in period B by more than in period A is especially worthy of note.
  4. In absolute terms, the female age inequality gap was lowest in Italy in 2010, standing at 28.2 years as compared with 30.6 years in France and 30.9 years in England and Wales. The level of improvement in Italy and France has been notably higher than in England and Wales. In Italy, for example, the gap closed by 5.8 years but in England and Wales by only 2.9 years.
  5. If gender differences in age related inequalities are compared, we find that the gap in 2010 was bigger in France than in either Italy or England and Wales and that it also continues to widen. In England and Wales the gender gap in age inequalities has been the lowest of all three countries and remarkably similar throughout periods A and B. However, this similarity ceased after 1990 when the gap started to re-widen.

Figures 2 and 3 provide us with an annual view of changes in demographic ageing for France and Italy which maybe compared with the earlier chart in Figure 1. All three charts show male and female life expectancy at age 30 from 1870 onwards and also male and female age inequalities between the 5<sup>th</sup> and 90<sup>th</sup> percentiles. It can be seen that the trends in each measure for men and women in England and Wales were strikingly similar whether measured in life expectancy or age inequalities especially in period A.

However, in period B, whilst life expectancy continued to rise the narrowing in the age inequality gap notably slowed, suggesting that the dynamics of inequalities were changing and moving into a new phase. It is also notable that the trend in age inequalities between men and women was noticeably different in France and Italy. In France, the male trend stagnated or worsened whereas females improved considerably. In Italy the age inequalities improved for both men and women but the disparity remained wider than for England and Wales.

Despite some similarities, the trends shown in these charts and the differences, especially between the genders, are hard to account for and hence explain. In the next section we seek to show that these trends are more systematic than at first appears and that all three

## Inequalities in adult lifespan

<b>(a) Men</b>		Period A		Period B			
Year		1879	1909	1939	1950	1980	2010
Age reached by top 5%		84.2	84.2	85.7	88.0	90.9	96.2
Age reached by bottom 10%		40.7	41.4	44.1	50.4	53.5	59.2
Inequality gap in years		43.5	42.8	41.6	37.6	37.4	37.0
Life expectancy at age 30		33.6	33.0	34.2	39.3	42.5	49.0

<b>(b) Women</b>		Period A		Period B			
Year		1879	1909	1939	1950	1980	2010
Age reached by top 5%		85.7	86.4	89.1	91.4	95.1	99.6
Age reached by bottom 10%		40.1	43.7	50.0	55.7	63.3	69.0
Inequality gap in years		45.6	42.7	39.1	35.7	31.8	30.6
Life expectancy at age 30		35.3	37.1	40.1	44.0	49.8	55.3

<b>(c) Difference in life expectancy</b>					
Difference in W-M life expectancy at age 30 (years)	1.7	4.1	5.9	4.7	7.3
	6.3				

<b>(d) Change in gap</b>		
Gender	Change in gap 1879 to 1939	Change in gap 1950 to 2010
Men	-1.9	-0.6
Women	-6.5	-5.2

Table 2 (a-d): Survival, age inequality gap and life expectancy at age 30 for years 1879, 1909, 1939, 1950, 1980 and 2010 for France

## Inequalities in adult lifespan

(a) Men		Period A			Period B		
Year		1879	1909	1939	1950	1980	2010
Age reached by top 5%		84.4	85.1	87.3	89.5	90.4	95.6
Age reached by bottom 10%		40.6	43.6	48.3	52.5	55.8	63.9
Inequality gap in years		43.8	41.5	39.0	37.0	34.6	31.7
Life expectancy at age 30		33.1	36.6	37.7	41.0	43.2	48.5

(b) Women		Period A			Period B		
Year		1879	1909	1939	1950	1980	2010
Age reached by top 5%		84.9	85.7	88.6	91.1	93.9	98.5
Age reached by bottom 10%		39.6	43.5	51.6	57.1	63.6	70.3
Inequality gap in years		45.3	42.2	37.0	34.0	30.3	28.2
Life expectancy at age 30		33.0	37.2	40.8	43.9	49.1	54.6

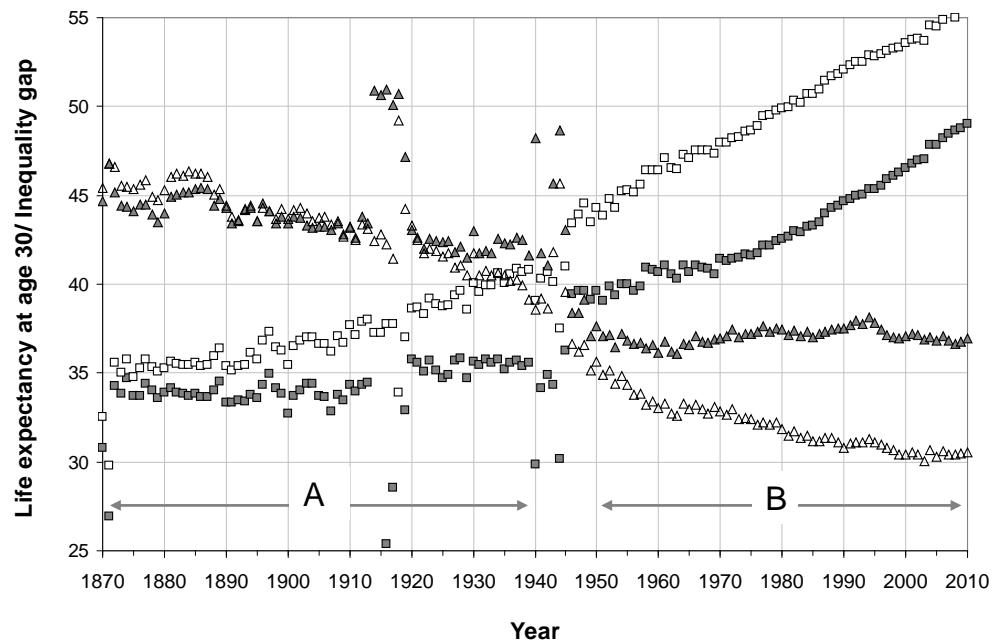
(c) Difference in life expectancy							
Difference in W-M life expectancy at age 30 (years)		-0.1	0.6	3.1	2.9	5.9	6.1

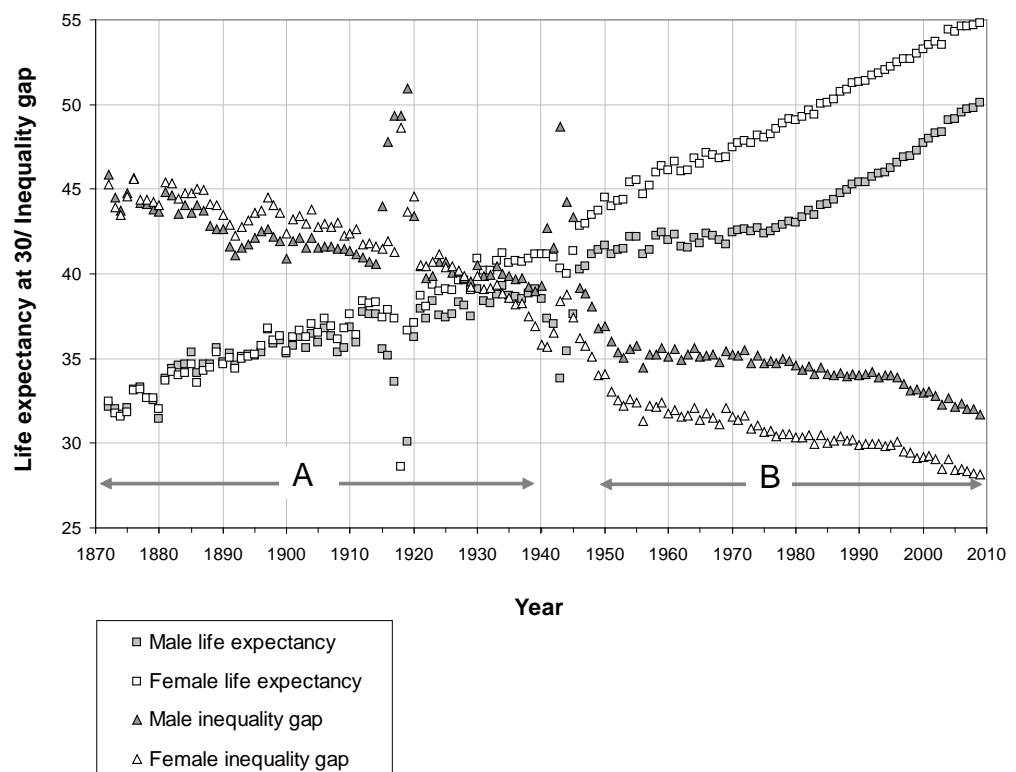
(d) Change in inequality gap		Change in gap 1879 to 1939	Change in gap 1950 to 2010
Gender			
Men		-4.8	-5.3
Women		-8.3	-5.8

Table 3 (a-c): Survival, age inequality gap and life expectancy at age 30 for years 1879, 1909, 1939, 1950, 1980 and 2010 for Italy

## Inequalities in adult lifespan



*Figure 2: Chart showing the life expectancy at age 30 and the age inequality gap for men and women in France from 1870 to 2010: (A) pre-1940; (B) post-1950*



*Figure 3: Chart showing the life expectancy at age 30 and the age inequality gap for men and women in Italy from 1870 to 2010: (A) pre-1940; (B) post-1950*

## Inequalities in adult lifespan

countries share a common pathway despite being at different points along that pathway. These points are likely to be caused by differences, not in the ambient risk factors to which both genders are exposed, but in the adoption of healthy lifestyles which, as we have argued, impact on each gender separately.

### 4. Relationship between lifespan inequality and life expectancy

Previously we saw that in period A as life expectancy increased the age inequality gap reduced, i.e. as people lived longer differences in lifespan became smaller. However, in period B the relationship changed such that improvements to life expectancy did not necessarily correspond to a narrowing of the gap and in addition the pace of improvement in life expectancy appeared to slow, especially in the case of men.

We also observed that improvements in life expectancy are not a monotonic process in which improvement in one year is followed by further improvement in the next. Reasons for major fluctuations in period A included major wars, pandemics, and insufficiently developed health care systems able to cope with infectious diseases or harmful bacteria. The data show that their effects were random both in their timing and shock value.

For the most part, improvements in lifespan and reduction in risks were incremental. In period A especially there were many improvements which imparted health benefits to all. These included better housing, clean water supply, improved sanitation, the discovery of antibiotics, and reductions in air pollution and poverty. In period B the data show fewer fluctuations demonstrating how society has learned to protect itself through better living conditions combined with scientific progress.

However, there will always some fluctuations in observed mortality, especially at older ages. For example, particularly cold winters can increase the death rate for pensioners. The statistical noise created by such fluctuations, especially in period A, can conceal any relationship between age inequalities and life expectancy. The questions arising therefore are: if there is a systematic relationship between life expectancy and inequalities can one be used to predict the other; secondly, has the nature of that relationship changed given the findings of the previous section?

#### 4.1 The convergent case (period A)

Using the same data as before, to show whether the inequality gap is increasing or decreasing we plotted the ages of death to which different percentiles of men in England and Wales survived against life expectancy at age 30. The percentiles proceed in 10% steps starting with the age attained by 90% of survivors until the top 10% followed by a separate category for the top 5% (i.e. the 5% surviving to the highest age).

## Inequalities in adult lifespan

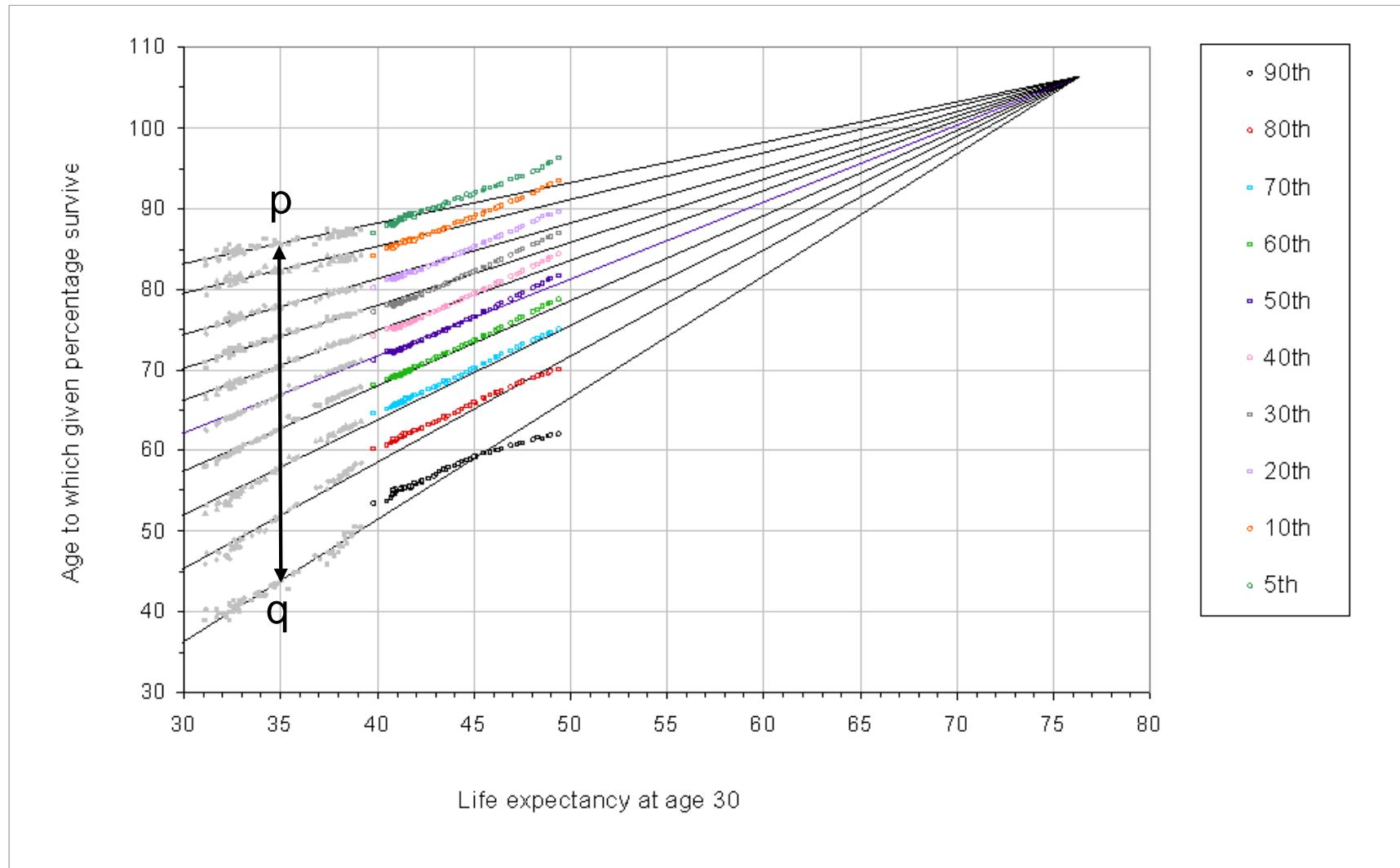


Figure 4: The compression (1870 to 1939 – shown as lightly shaded filled markers) and slow expansion of mortality (1950 to 2010 – shown as open markers) showing the age inequality gap pq: Males in England and Wales

## Inequalities in adult lifespan

The chart shows that the highest point attained for future male life expectancy at age 30 in period A is almost 40 years and in period B almost 50 years. The age inequality gap is denoted by the vertical line  $pq$  and is the difference in age between the 90<sup>th</sup> and 5<sup>th</sup> percentiles, but it is also seen to be the case that different IPRs would lead us to the same conclusion, namely that the age inequality gap for males in England and Wales is converging.

We can also see that there is a change of pattern between the grey and coloured symbols. The age inequality gap remains broadly constant from the point at which life expectancy turned 40 (which occurred around 1950). This remained so for many years but then we observe a further change as life expectancy reaches 45 where the gap noticeably widens again suggesting that age inequalities are now starting to diverge i.e. lifespan inequalities are increasing.

As a further aid to the interpretation of Figure 4, solid lines are fitted to percentiles spanning period A and the trends then extrapolated until they meet. The results show that the age of survival was on a convergent path such that each improvement in life expectancy was accompanied by a reduction in age inequalities in lifespan. To find this point we pooled all the data for both genders in England and Wales, France and Italy so as to combine the survival experiences across all data sets from 1870 to 1939.

The method of fitting is by the method shown in Annex A. Briefly it is an iterative method in which the convergent point is varied to maximise goodness of fit. Of particular interest is the finding that there was no appreciable difference in the quality of fit in terms of the solid lines between countries and genders when all the data are pooled. We inferred that this was most probably indicative of a common evolutionary process in a survival sense, though we are not claiming it is proof.

In other words, although life expectancy in each country differs at any given point in time, in survival terms it can be argued that they are travelling along a common evolutionary path. Since this path is common to both genders and each country, it suggests that that there is no fundamental reason why male life expectancy should not eventually catch up with women as appears to be happening in England and Wales. This is assuming that there are no fundamental biological reasons to prevent this.

Our fitted percentiles also mean that had improvements in life expectancy continued on this path there would have eventually come a point, admittedly theoretical, when all inequalities would have disappeared. Diagrammatically, this would occur as  $pq$  approached zero which would be projected to occur when life expectancy at 30 had reached 76 years (i.e. everyone dies exactly at age 106). Based on statistical trends up to this point, this would not have occurred before well into the 22<sup>nd</sup> century.

## Inequalities in adult lifespan

**(a) Men**

Survival percentiles	England and Wales	France	Italy	Average slope value $\beta'_p$
5%	0.5013	0.5057	0.5072	0.5047
10%	0.5784	0.5792	0.5857	0.5811
20%	0.6890	0.6818	0.6878	0.6862
30%	0.7794	0.7670	0.7721	0.7728
40%	0.8645	0.8504	0.8530	0.8560
50%	0.9543	0.9414	0.9374	0.9444
60%	1.0543	1.0450	1.0353	1.0449
70%	1.1710	1.1717	1.1561	1.1663
80%	1.3165	1.3329	1.3182	1.3225
90%	1.5116	1.5410	1.5435	1.5320

Amended $R^2$	9.9204	9.1896	8.9836	9.3645
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**(b) Women**

Survival percentiles	England and Wales	France	Italy	Average slope value $\beta'_p$
5%	0.4760	0.4884	0.5120	0.4921
10%	0.5586	0.5649	0.5921	0.5719
20%	0.6697	0.6691	0.6911	0.6766
30%	0.7620	0.7550	0.7720	0.7630
40%	0.8489	0.8368	0.8484	0.8447
50%	0.9385	0.9243	0.9269	0.9299
60%	1.0407	1.0263	1.0184	1.0285
70%	1.1661	1.1536	1.1350	1.1516
80%	1.3313	1.3358	1.3119	1.3263
90%	1.5657	1.5970	1.5748	1.5792

Amended $R^2$	9.8516	9.8126	9.6340	9.7661
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*Table 4: Regression slope  $\beta'_p$  values for different survival percentiles 1870-1939: (a) Males; (b) Females: England and Wales, France and Italy*

The statistical parameters of the fitted solid lines are shown in Table 4 (a and b). The detailed regression results for both genders and all three countries show that:

- Percentile slope values are inversely related to survival percentiles as predicted by the stylised model described in Annex A and also show remarkable similarity, again, regardless of country and gender. This lends further support to the idea of a single convergent point.
- The slope value for the 50<sup>th</sup> percentile (i.e. median survival age) is close to a value of 1.0 showing that median survival and life expectancy track one another very closely. The proof of why they should be closely related is explained in Annex B.

## Inequalities in adult lifespan

- Our measure of the goodness of fit which we call *Amended R<sup>2</sup>* is explained further in Annex A and is based on the summation of the individual percentile values for  $r^2$ . It can be seen that the values are very similar for men and women, regardless of country.

### 4.2 The parallel case (period B)

We repeated this procedure for period B. A key difference is that this time we used ordinary least square (OLS) regressions to fit equations to each data point for every percentile in each population. That is to say, we ran the regressions separately for each gender and country without the constraint that the fitted percentile should pass through a convergent point. The aim now is to test the hypothesis that the inequality gap remains parallel and hence independent of changes in life expectancy.

Table 5 (a and b) shows the slope values for the set of percentile regressions as for period B. A value of 1.00 would indicate that a given percentile of survivors is increasing at the same rate as life expectancy i.e. the trends are perfectly in step regardless of which percentile is compared. A value of less than one means that the increase in survival for that percentile rising more slowly than overall life expectancy, and a value greater than one more quickly.

As can be seen, the results show that slope values are very similar regardless of either gender or country, as is to be expected from a visual inspection of Figure 4. Goodness of fit is now based on  $R^2$  i.e. the standard measure for the proportion of explained variance using OLS regression. We also introduce a summary measure of fit which we call amended  $R^2$  which is simply the sum of the individual  $R^2$ 's for each percentile which has a maximum possible value of 10 using our specified ten percentiles but 100 if all percentiles are used.

For both genders and each country, the table shows 99%+ of the possible maximum is achieved in all cases, indicating a very good fit to the data assuming that a linear relationship holds. Additionally, most of the slope parameter values shown in the middle columns of the tables are very close to one, as is required by the parallelism hypothesis, but there are two noteworthy points of difference:

- The post-1950 phase is not perfectly parallel. Each country in our group shows that the age to which 90% survive has a parameter of less than one for men but greater than one for women. It shows that men in the 90<sup>th</sup> percentile have not kept pace with the overall pace of change in life expectancy, unlike women.
- Between roughly the 30<sup>th</sup> and 80<sup>th</sup> percentiles, survival is running slightly ahead of the overall trend in life expectancy for both men and women (i.e. slope values are greater than one). Among other percentiles the slopes at slightly less than one meaning that survival is not quite keeping pace relative to life expectancy.

## Inequalities in adult lifespan

**(a) Men**

Survival percentiles	England and Wales	France	Italy	Average slope value $\beta$
5%	0.892	0.871	0.791	0.851
10%	0.932	0.926	0.830	0.896
20%	0.986	1.002	0.882	0.957
30%	1.034	1.059	0.924	1.006
40%	1.072	1.103	0.969	1.048
50%	1.098	1.132	1.019	1.083
60%	1.123	1.140	1.074	1.112
70%	1.126	1.118	1.137	1.127
80%	1.075	1.031	1.193	1.100
90%	0.929	0.828	1.188	0.982

Amended $R^2$	9.963	9.956	9.937	9.952
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**(b) Women**

Survival percentiles	England and Wales	France	Italy	Average slope value $\beta$
5%	0.852	0.777	0.796	0.808
10%	0.900	0.824	0.840	0.855
20%	0.951	0.884	0.897	0.911
30%	0.975	0.934	0.939	0.949
40%	1.001	0.982	0.974	0.986
50%	1.017	1.030	1.008	1.018
60%	1.029	1.082	1.041	1.051
70%	1.040	1.139	1.079	1.086
80%	1.076	1.194	1.127	1.132
90%	1.130	1.183	1.191	1.168

Amended $R^2$	9.943	9.983	9.981	9.969
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*Table 5: Regression slope  $\beta'_p$  values for different survival percentiles 1950-2010: (a) men; (b) women*

If the size of the gap between the 5th and 90<sup>th</sup> percentiles is evaluated using the fitted regression lines we find that it has fallen as a percentage of life expectancy in all three countries. This is obviously better than if it had stayed the same because it would mean that relative rather than absolute inequality was rising. Also, with no sign of a convergent point as before, we can only conclude that an upper value of life expectancy has become effectively indeterminate at this point in time.

The trends in period B are measured over a 60 year period and do not take account of further indications of possible change occurring from 1990 onwards. If we concentrate our analysis on this period, we observe a further but less established change of pattern which is denoted by a widening gap in age related inequalities for males. This is obviously

## Inequalities in adult lifespan

concerning, especially if it persists and becomes the new normality, because it shows that policies to reduce inequalities are not working as they should.

### 4.3 The divergent case (period C)

Since 1990, annual data for England and Wales show that the inequality gap has widened for men and fallen for women whereas previously they had been more or less on the same track as each other. If the male gap is regressed on life expectancy from 1990 to 2010 instead of from 1950 to 2010 as before, recent improvements in life expectancy are associated with an accompanying widening of the age inequality gap. For the purposes of this paper we designate the post-1990 period as period C.

Although period C is short compared with periods A and B and overlaps with B, the widening gap apparent in Figure 5 is indicative of male age related inequalities increasing. This is in contrast to women for whom the age inequality gap is slightly narrowing. Regressions fitted to male post-1990 percentiles versus life expectancy data yield slope values that are consistent with a widening gap which we call the ‘divergent phase’.

What are the reasons for this change? The mathematical reason is clear which is that men at the bottom end of the survival distribution (i.e. those with the shortest lifespan) are not keeping pace with those at the top (i.e. those with the longest lifespan). Among the highest 5% of survivors, the slope coefficient is 0.95 as compared with the 90<sup>th</sup> percentile which has a slope coefficient of only 0.69. In other words, life expectancy at the top of the distribution is increasing faster than at the bottom thereby demonstrating that inequalities in lifespan are increasing.

Therefore, whilst the longest lived are still showing very slight convergence with the rest of the population as their slope coefficient is less than one (and so they are not quite benefitting in full as the overall population’s expected life increases), the main problem is that the shortest lived are being left behind. Although some of these early deaths cannot be prevented as yet e.g. accidents, genetic diseases, etc. we can be relatively certain that most of these early deaths are preventable and are lifestyle-related.

These findings are consistent with Mayhew and Smith (2014), using a different methodology, which found that the standard deviation in age at deaths was increasing for men and slightly decreasing for women. According to that research this trend looks set to continue into the next decade during by which time life expectancy between men and women at age 30 would converge (but not in terms of age related inequalities).

## Inequalities in adult lifespan

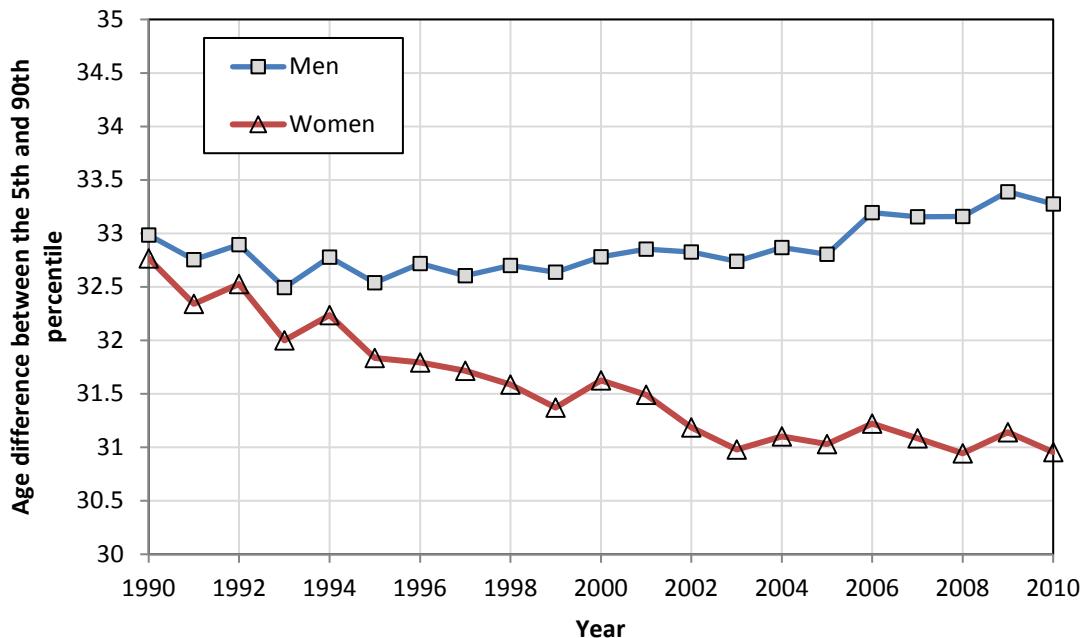


Figure 5: Change in age inequality gap between 1990 and 2010 in England and Wales during period (C)

## 5. Concluding remarks

The evidence of this paper is that economic development and general improvements in life expectancy come with a narrowing of the inequalities of age at death. However, the narrowing does not continue indefinitely and there comes a point at which it slows or stops. It has been suggested that the inequality gap plateaus roughly at the point a country has completed its demographic transition from high mortality and low fertility to low mortality and low fertility (Wilmoth and Horiuchi 1999; Edwards and Tuljapurkar 2005; Wilson 2011).

We find that this pattern appears to have been replicated in England and Wales, France and Italy. In the period from 1870 to 1939, life expectancy increased and the gap in age related inequalities closed. These improvements affected men and women roughly equally, but with women having an approximate 2 to 3 year advantage in life expectancy throughout much of this period. We termed this period the convergence phase as society became more equal and the gap in lifespan between rich and poor reduced.

After 1950, the increase in life expectancy slowed at first but then picked up again in the mid-1970s. This period was marked by a widening gap in the life expectancy of men and women in England and Wales, reaching a peak of 5.6 years in 1972. From this point, male life expectancy started to catch up with women, thereby reversing a 20-year trend. We also found that male age related inequalities ceased to narrow after 1950 and for women the improvements slowed noticeably. We termed this period the 'parallel phase' because there was little improvement in age related inequalities in spite of improvements in life expectancy.

## Inequalities in adult lifespan

This phase takes us to 2010 but around 1990 we observed that inequalities started to diverge with the gap among men widening relative to women. Between 1993 and 2009, for example, the difference in the gender inequality gap increased by about two years. As the data still cover only a relatively short period this finding may only be temporary. Nevertheless, it suggests that age related inequalities among men are currently diverging. The main reason for this is that men in the top 5% of the survival distribution are increasingly living longer and roughly equalling women in terms of longevity, but at the bottom end, age of death has levelled out.

These trends are shared by France and Italy but with some notable exceptions. As in England and Wales, life expectancy for men and women has risen but the gender gap in France and Italy is much larger. Women do better both in France and Italy in terms of life expectancy but males generally fare worse, especially French men where age related inequalities in lifespan are also much higher. In Italy, the gap in life expectancy between men and women is also higher than in England and Wales but in marked contrast to England and Wales, age related inequalities are reducing for both genders.

Various questions arise from this analysis such as what causes are driving these patterns and whether they are set to continue. In addition, if they are set to continue, is it possible to influence them in some way? In addressing this issue, it is important to separate gains in life expectancy prior to 1940 from those after 1950. Pre-1940 improvements derived from societal changes from which everybody benefited but in different measure i.e. the poorest in society closed the gap on the richest that benefitted less.

Taking Britain as an example, improvements in water quality, sanitation, living conditions and nutrition began in the mid-19<sup>th</sup> Century. These did not bring about a decline in mortality rates in adults until the 1870s, as gastrointestinal infections such as cholera and dysentery were slowly brought under control. For decades, about one death in every three was attributable to infectious disease with one third due to tuberculosis, a bacterial infection linked to poor living conditions (see the Health of Adult Britain – 1841 to 1994 Vols. I and II: Charlton and Murphy eds., 1997). Although more persistent, tuberculosis declined in importance as housing and general living conditions improved. However, it was not fully brought under control until new therapies were developed in the 1950s.

The adult pattern of mortality may be contrasted with childhood mortality from infectious diseases which had also been in decline long before the introduction of mass immunisation in the 1950s. Reductions in childhood mortality can likewise be attributable to improvements in living standards especially housing and diet (Charlton and Murphy, 1997, op. cit.). It is particularly noteworthy that the health benefits of all these improvements generally pre-dated the most important advances in health care generally occurring in the second half of the 20<sup>th</sup> century.

## Inequalities in adult lifespan

In the modern period, deaths from neoplasms and diseases of the circulatory system completely supersede deaths from infectious disease and are now the major causes of mortality. In parallel, there have been significant reductions in occupational related mortality and vehicle accidents, associated with a decline in heavy industry such as coal mining, and safer cars and stricter laws on drink driving. Apart from a few exceptions, this suggests that further improvements of the kind that led to the eradication of infectious diseases cannot be relied upon to produce large reductions in inequalities in future, the implication being that the very big gains are now in the past.

What has changed? Clearly, there has been a transformation in the way people die. Most deaths today are from chronic rather than infectious disease or other causes including accidents. We know that nearly all chronic disease is associated with middle to old age and affects strands of society differently. The introduction referred to a study using general practice patient records which found that mortality rates in middle age to be over twice as high in the poorest quintile of households than in the richest quintile suggesting that a lack of income may be a root cause.

To address what it believed to be the root cause of the problem, the UK government introduced a target in 2003 such that by 2010 health outcomes between the best and worst areas of the country would differ by not more than 10 per cent at most, as measured by life expectancy. It had been anticipated that if more health care resources could be directed to economically deprived areas, the gap would narrow (House of Commons 2009). However, we now know that the opposite occurred and that the gap in life expectancy between areas actually increased.

A difference today compared with the earlier period pre-1940 is that exposure to harm is mainly under the control of individuals rather than ambient risks which affected everyone. A key point is that the causes of ill health are increasingly life-style related and rooted in the cultures of different socio-economic groups – these include smoking, excessive drinking, drug abuse, mental illness and obesity (Marmot 2010). Tobacco smoking which causes about one in six deaths is the best example of this because it shortens lifespan by as much as ten years (see Doll et al 2004).

Much of the gain in male life expectancy in men and the closure of the gap with women who smoke less is attributable to smoking reduction which causes cancer, heart and respiratory disease (Preston and Wang 2006; Pampel 2006; Murphy and Di Cesare 2012; Mayhew and Smith 2014; Peters et al 2016)<sup>4</sup>. Smoking habits developed from the 1920s onwards, reaching a peak in 1948 when 82% of adult males in Great Britain smoked. This compares with only 16% who are cigarette smokers today.

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<sup>4</sup> See WHO report on the global tobacco epidemic, warning about the dangers of tobacco, [http://www.who.int/tobacco/global\\_report/2011/en/](http://www.who.int/tobacco/global_report/2011/en/)

## Inequalities in adult lifespan

The increasing trend towards obesity is another manifestation of self-harm. Obesity is linked to poor diet and a lack of exercise, including the consumption of high levels of sugar in processed food products. In most cases, negative health outcomes of these habits are disproportionately associated with the poorest in society who live in economically more deprived areas. All of the above suggests that extra healthcare or other financial support given to poorer areas is not as important as encouraging healthier lifestyles i.e. skewing resources towards prevention rather than treatment.

In addition to poor diet and a lack of exercise, there are many other examples of life choices that have negative effects on health e.g. excessive alcohol consumption and drug addiction. All of these lifestyle choices are associated with the early onset of chronic disease and also mental ill-health which is especially expensive to treat. US research (Islami et al 2017), for example, found that 47.9% of deaths from cancer were attributable to avoidable risk factors including cigarettes (33.1%), excess body weight (5.7%) alcohol (4.3%) and other factors such as low physical exercise, diet etc (4.8%).

In conclusion, it is important to stress that personal choice does not exist in a vacuum and pressures are placed on individuals through exposure to advertising, their communities and peer groups. If the poorest in society could be made healthier through greater redistribution of available health care resources, the obesity crisis would have been solved already or even nipped in the bud but this is plainly not the case. Income becomes a critical determinant only in circumstances where access to a healthy lifestyle is denied due to lack of access or income. This suggests that other policy tools aimed at changing behaviour are needed to steer people towards healthy lifestyles, including the greater use of taxation, because if they benefit all of society benefits.

## Inequalities in adult lifespan

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## Inequalities in adult lifespan

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## Annex A: Estimating the point of convergence

The purpose of the annex is show how life expectancy at the convergent point can be estimated. Note that this method is appropriate for period (A) to 1939 for which convergence is applicable but not for (B) post 1950. Initially, we regressed the percentile age on life expectancy using ordinary least squares (OLS). For each survival percentile we fitted the regression:

$$y_p = \alpha_p + \beta_p e_{30} + \varepsilon_p$$

Where:

- $y_p$  is the expected age where  $p$  per cent of the population are still alive
- $e_{30}$  is the expected future life expectancy at age 30
- $\alpha_p$  is the constant term for the percentile  $p$
- $\beta_p$  is the slope for the percentile  $p$
- $\varepsilon_p$  is the normally distributed random error for the percentile  $p$

Although we found that OLS provides good fits to the data, the inclusion of a non-constrained constant term in the estimating equation means that the projected lines did not all cross at exactly the same value for future life expectancy due to random error.

Since the requirement for convergence is that all percentiles should pass through a single point, we imposed the condition that all regression lines should meet this requirement. An algorithm is therefore needed to ascertain what the co-ordinates of this point should be.

The easiest way to prevent this happening is to remove the constant term from the regression equation i.e. in effect, make the constant term equal to zero. This achieved by transforming the data to a temporary convergent point based at the origin (i.e. 0,0).

Let us assume that everyone will live to their 100<sup>th</sup> birthday and then die; it implies that at age 30, future life expectancy would be calculated as 70 years and the value of age of death for each percentile would be 100.

We can thus transform the data by deducting 70 from 100 the maximum age at death and then fit regression lines that to each percentile such that they all pass through the origin.

## Inequalities in adult lifespan

In other words, if we transform our data as suggested and then for each percentile we can then fit the following regression:

$$y'_p = \beta'_p e'_{30} + \varepsilon'_p$$

Where:

$y'_p$  is the transformed expected age where  $p$  per cent of the population are still alive

$e'_{30}$  is the transformed expected future life expectancy at age 30

$\beta'_p$  is the slope for the percentile  $p$  using the transformed data

$\varepsilon'_p$  is the normally distributed random error for the percentile  $p$  using the transformed data

Figure 4 is based on fitting data to the following survival percentiles; 5<sup>th</sup>, 10<sup>th</sup>, 20<sup>th</sup>, 30<sup>th</sup>,..., 80<sup>th</sup> and 90<sup>th</sup>. Starting with a value of life expectancy of 40 years at age 30, we increased life expectancy 0.1 year steps refitting the regressions at each step.

With OLS, we can use  $R^2$  as an indication of whether one model is better than another. In this case  $R^2$  has a maximum value of one and cannot be improved upon, so it is easy to see if it is a good fit or not. However,  $R^2$  cannot be used when it is forced to go through the origin, since  $R^2$  is no longer constrained to a maximum value.

Instead, we can use something similar by considering the sum of the squared deviations based on each of our observations. In this way we are able to fit the best convergence point for all countries and genders separately. Since convergence implies that everyone dies at the same age, we pooled all data regardless of gender or country in order to produce a ‘single fit’.

Our convergence point is defined as that giving the lowest squared deviations across all data sets. Mathematically we aimed to minimise:

$$SS_E = \sum_{pop} \sum_p \sum_{i=1}^n \varepsilon_{i,p,pop}^2 = \sum_{pop} \sum_p \sum_{i=1}^n (y_{i,p,pop} - \hat{y}_{i,p,pop})^2$$

Where:

$SS_E$  is the total sum of the squared deviations

$\varepsilon_{i,p,pop}^2$  is the squared error term for the observation in the  $i^{\text{th}}$  calendar year for the age of the  $p^{\text{th}}$  survival percentile, for the given population

$y_{i,p,pop}$  is the observation in the  $i^{\text{th}}$  calendar year for the age of the  $p^{\text{th}}$  survival percentile for the given population

## Inequalities in adult lifespan

$\hat{y}_{i,p,pop}$  is the predicted age of the  $p^{\text{th}}$  survival percentile in the  $i^{\text{th}}$  year given the expected life observed in the  $i^{\text{th}}$  calendar year for the given population

We can approximate a value similar in construction and value to  $R^2$  as an alternative. Since it is convex i.e. has a unique optimum it can be considered an alternative to  $R^2$  for this purpose which we define as:

$$\text{Approx } R_{p,pop}^2 = \frac{\sum_{i=1}^n (\hat{y}_{i,p,pop} - \bar{y}_{p,pop})^2}{\sum_{i=1}^n (y_{i,p,pop} - \bar{y}_{p,pop})^2}$$

Where

$\bar{y}_{p,pop}$  is the mean value of the  $p^{\text{th}}$  percentile survival age for a given population

As we are interested in the overall fit of all the percentiles we are investigating we can aggregate these into a total amount which we will call *Amended  $R^2$* :

$$\text{Amended } R_{pop}^2 = \sum_p \text{Approx } R_{p,pop}^2$$

## Annex B: Life expectancy, convergence and the distribution of age of death

### B.1 The survival curve

Mathematically the survival curve,  $S(x)$ , denotes the probability of surviving to age  $x$ , whereas  $e(x)$  defines life expectancy at age  $x$ . With no loss of generality, we describe a simple, stylised model from which we derive the relationship between survival, life expectancy and the distribution of ages at death.

Imagine a stationary population in which there are a constant number of births and deaths, no migration and which are subjected to the same mortality regime each year. Consider Figures B.1 (a) – (c), which show the mortality curves ABC for three such hypothetical populations *at a given point in time*. The vertical axis shows the number of survivors  $I_x$  and the horizontal axis age  $x$ .

We define the point  $x_1$  in each case, as the onset of mortality, the age at which death begins, which can range from zero upwards. For simplicity, we assume there are no deaths before this age. We call the point where BC cuts the age axis as  $x_2$  or the maximum age to which anyone lives.

Both  $x_1$  and  $x_2$  are somewhat fuzzy quantities in the real world. In developed countries, we could assume the onset of mortality ( $x_1$ ) occurs from around 60 years onwards.

However, our purpose is to use  $x_1$  and  $x_2$  as conceptually useful devices to anchor and compare distributions and mortality processes, rather than to determine them empirically.

Now imagine the age distribution of the population at another point in time. In model (a), we see that  $x_1$  is unchanged, whilst  $x_2$ , the oldest age, has advanced to  $x'_2$  (point D). In other words, the onset of mortality is unchanged, but now some people live to older ages. The consequence of this is a decline in the mortality gradient BD compared with BC. In model (b), we see that both  $x_1$  and  $x_2$  have advanced by the same amount, such that the mortality gradient is the same before and after.

In model (c),  $x_2$  has remained constant but  $x_1$  has advanced to  $x'_1$  (point E), with the effect that the mortality gradient is steeper. For reasons that will become apparent shortly, we call (a) the divergent mortality model, (b) the parallel mortality model and (c) the convergent mortality model.

Clearly, the convergent model most closely reflects the compression hypothesis in the literature on ageing in which the shape of the survival curve becomes increasingly

## Inequalities in adult lifespan

rectangular over time, but the other two variants do not have any comparators as far as we know.

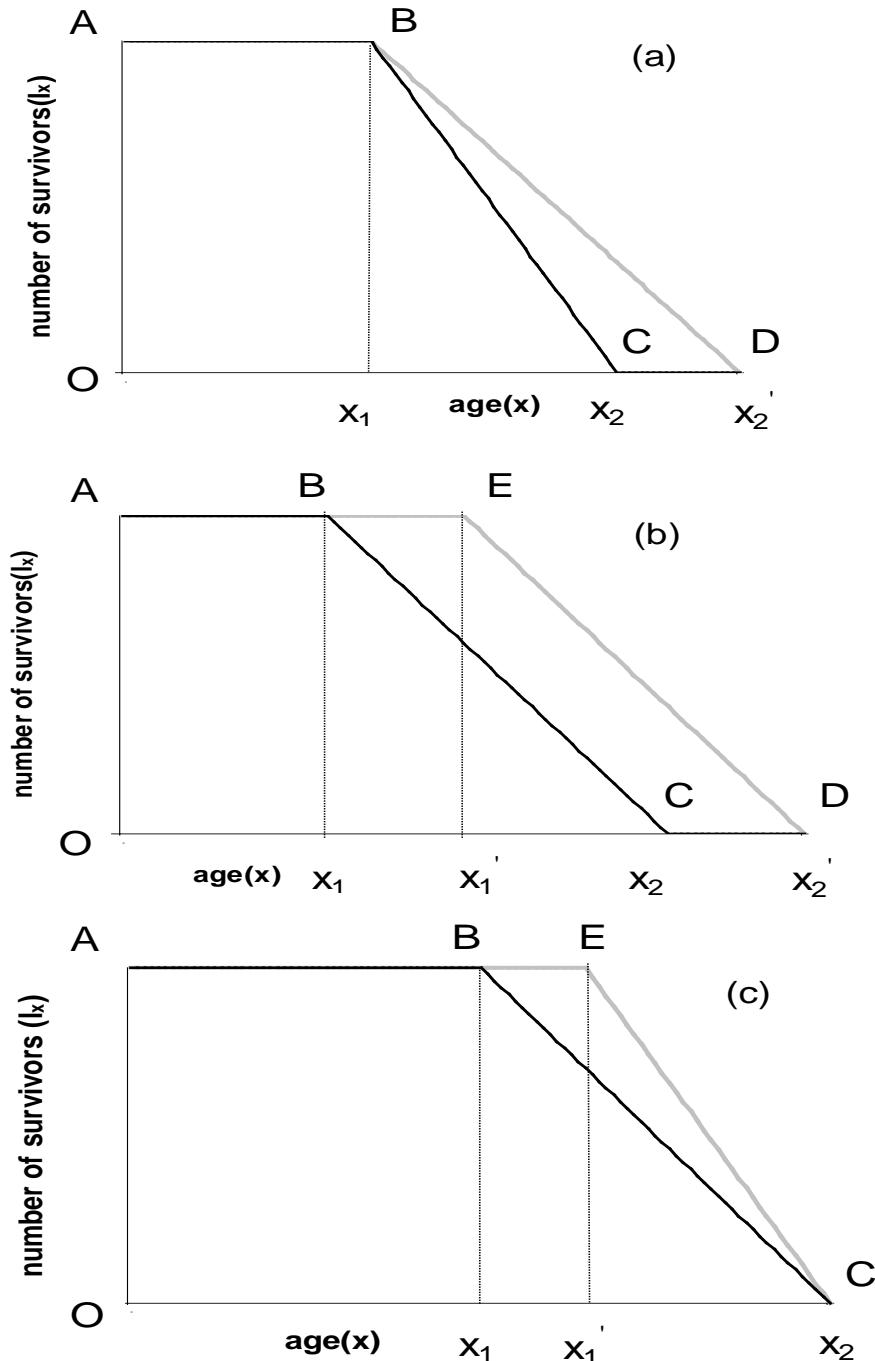


Figure B.1: Three hypothetical mortality models (a), (b) and (c)

## B.2 Properties of the Simple Model

## Inequalities in adult lifespan

### Future expectation of life

To derive the future expectation of life we need to calculate the area under the population curve divided by the starting population. In the models above we can see that all the models are formed from two basic geometric shapes – a rectangle and a right-angled triangle. If we assume the starting age is  $x_0$  and the lives in the population at this point is  $l_0$  then the area under the curve is:

$$l_0 \times (x_1 - x_0) + \frac{l_0}{2} (x_2 - x_1) = l_0 \left( \frac{x_2 + x_1}{2} - x_0 \right)$$

and hence:

$$e_{x_0} = \frac{l_0}{l_0} \left( \frac{x_2 + x_1}{2} - x_0 \right) = \left( \frac{x_2 + x_1}{2} - x_0 \right)$$

Which means that the expected age at death for someone currently aged  $x_0$  is:

$$x_0 + \left( \frac{x_2 + x_1}{2} - x_0 \right) = \frac{x_2 + x_1}{2}$$

### Median Age of Death

The median age of death will occur when half the population has died. As we know that the survival curve in the parts where lives are observed to die is a right-angled triangle then to find the point half way down the hypotenuse we need to go half way along the base. The median age of death is therefore

$$\frac{x_2 + x_1}{2}$$

### Relationship between expectation of future life and median age of death

The values derived above show that initially the expected age at death and the median age of death are the same value. As all changes in the values of  $x_1$  and  $x_2$  will always leave us with the same basic geometric shapes then the value of the expected age at death must always be the same as the median age of death.

### Relationship of percentiles to the future expectation of life

## Inequalities in adult lifespan

We can calculate the theoretical relationship between cumulative mortality  $p(x)$ , life expectancy at  $x_1$  and a specified age,  $x$ , that is greater than  $x_1$ . For the initial population this would be:

$$p(x) = \frac{x - x_1}{x_2 - x_1}$$

However, as the population changes we will see the values of  $x_1$  and/or  $x_2$  change i.e. to  $x'_1$  and/or  $x'_2$ . This will affect both the expectation of life and the ages at which a certain proportion of the population will die.

If we consider the value of  $p(x)$  separately from the expectation and allowing for the possibility that  $x'_1 = x_1$  or  $x'_2 = x_2$  we can generalise to:

$$p(x) = \frac{x - x'_1}{x'_2 - x'_1}$$

However, we can also calculate

$$e_{x_1} = \left( \frac{x'_2 + x'_1}{2} - x_1 \right)$$

And hence we can link the percentiles with expectation of life as:

$$p(x) = \frac{x - x'_1}{2[e_{x_1} - (x'_1 - x_1)]}$$

This equation is most easily understood in the context of Figure B.2 (a-c). Figure B.2a depicts the dispersion case which equates with rising inequalities or divergence. Here  $x_1$  is assumed fixed while  $x_2$  increases. On the vertical axis is life expectancy, which is assumed for illustrative purposes to equate with  $x_1$ . Each line represents the subsequent age to survival of 90%, 80%, 70%..... 30%, 20%, 10% and 5% of the population. In this case all percentiles converge at the origin.

In Figure B.2b, we have the same axes as before but percentiles are now parallel; that is to say, each advance in life expectancy has exactly the same proportional effect on the chances of survival at all ages above the given age and hence all age groups benefit equally. Since for

## Inequalities in adult lifespan

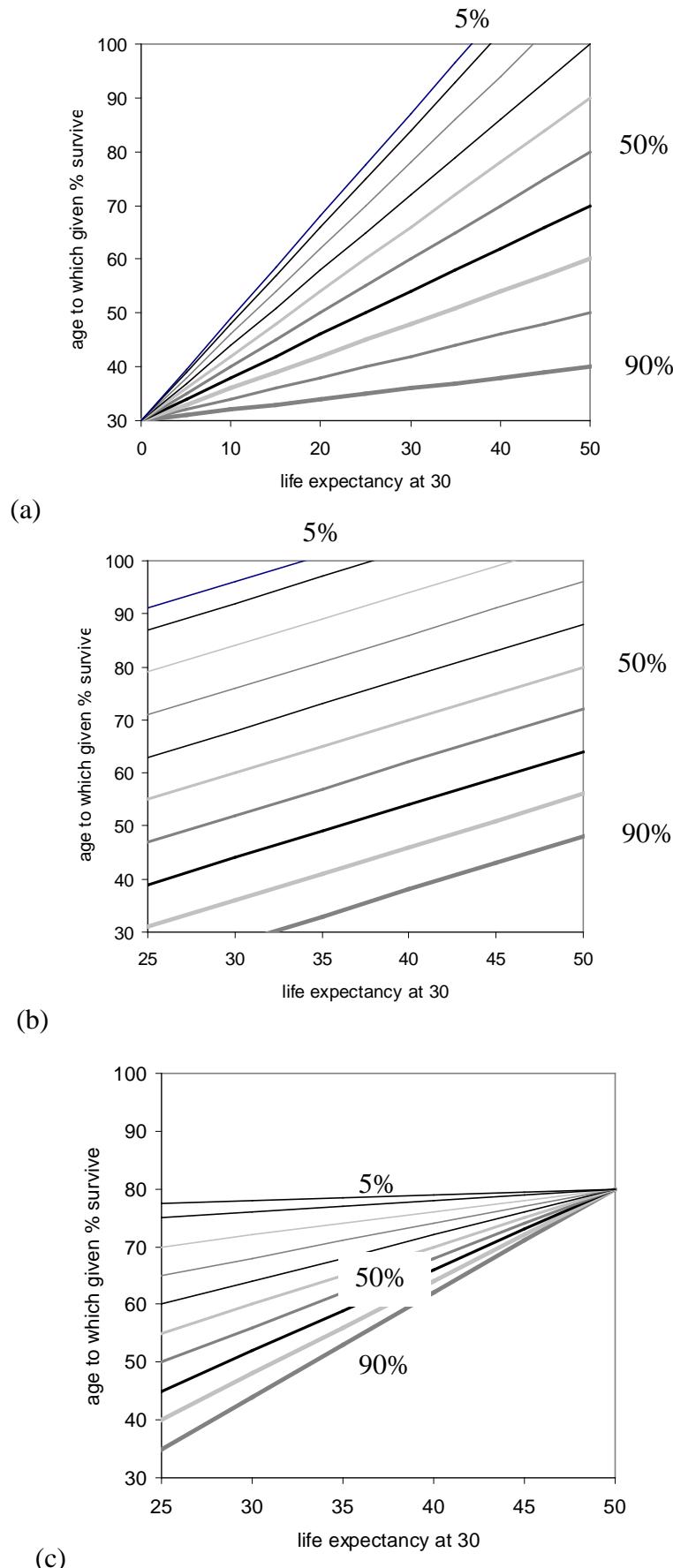


Figure B.2: Cumulative survival models: (a), (b) and (c)

## Inequalities in adult lifespan

this model, the increase in values for  $x_1$  and  $x_2$  must be the same value, each one-year increase in life expectancy advances both  $x_1$  and  $x_2$  by one year.

In Figure B.2c, the convergent case, all percentiles converge to a point as  $x_1$  advances, while  $x_2$  is held constant. Since  $x_2$  is fixed, each one-year advance in life expectancy equates to a 1-year delay in the onset of mortality,  $x_1$ , up to a maximum of  $x_2$ , and so the rate at which the lines converge depends on advances in life expectancy. This is case which describes best the changes from 1870 to 1939 described in the paper.

Of the three models, it is readily apparent that (c) comes closest to the model originally proposed by Fries (1980), which became known as the compression hypothesis (Period A). The parallel model is observed in our data from 1950 onwards (Period B); signs of divergence (a) do not appear until 1990 (Period C)