The Healthy Cross-Sectional Average Length of Life (HCAL)

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Abstract

In this paper, we explore a new morbidity and mortality summary measure: The Healthy Cross-Sectional Average Length of Life (HCAL). It extends the Cross-Sectional Average Length of Life (CAL) to the health dimension by using Sullivan's method. We argue that applying CAL instead of conventional period life expectancy (LE) to Sullivan's method is more suitable from a conceptual point of view. In addition, HCAL features a population dynamics interpretation, which can be useful to assess dynamics in population health. We illustrate the method with data for France between 2004 and 2015 and the UK between 2005 and 2015. Moreover, we compare HCAL estimates with conventional healthy life expectancy (HLE) estimates by analyzing time trends in absolute, respective relative terms, and gender gap differences in healthy life years. We conclude that HCAL gives an alternative view on health and mortality, which adds useful insights to this field of research.

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1 Introduction

Demographers have studied mortality trends in all its facets using a various amount of longevity measures (Bongaarts 2005; Canudas-Romo 2010; Guillot and Kim 2011; Schoen and Canudas-Romo 2005). Undoubtedly, most developed countries have experienced remarkable mortality improvements over the last decades (Christensen et al. 2009; Oeppen and Vaupel 2002). These findings have led to the question if the gains in longevity are mostly healthy or unhealthy years (Christensen et al. 2009). Three different hypotheses have been proposed to tackle this question. Firstly, an expansion of morbidity occurs if medical technology improves survival and reduces disability from fatal diseases, but does not affect the nonfatal diseases of aging (Gruenberg 1983; Olshansky et al. 1991). In this scenario, the gained years in life expectancy are mostly years with disability. Secondly, in the paradigm of the compression of morbidity hypothesis, the onset of morbidity is postponed to later ages in a greater amount than life expectancy increases. Therefore, the gained life years will be mostly spend disability free (Fries 1983, 2000). Thirdly, Manton (1982) expresses the interplay of mortality and morbidity in a dynamic equilibrium. According to his hypothesis, an increase in life expectancy goes in hand with a constant number of disabled years (Manton 1982).

In order to evaluate these hypotheses conventional longevity measure are insufficient because they don't separate between gains in healthy and unhealthy life years. In this sense, the health expectancy indicator has become attractive for researchers. The measure combines mortality and morbidity into a single comprehensible indicator (Mathers 2002). The concept is closely related to life expectancy. While life expectancy at birth estimates the number of years an newborn can expect to live if he or she is subject to the age-specific mortality rates obtained in a particular period, health expectancy extends this information to the expected numbers of life years spend in good health.

Several approaches have been proposed to estimate the health expectancy indicator. Theoretically, the multi-state life table method is the preferred one (Barendregt, Bonneux, and Van der Maas 1994; Mathers and Robine 1992; Rogers, Rogers, and Belanger 1990). However, the method requires high quality panel data, which is usually not available (Mathers and Robine 1992). Therefore, the method proposed by Sullivan (1971) is the by far most widely used approach because it can be applied to many populations due to its low data requirements (Crimmins, Saito, and Hayward 1992).

However, the method has been criticized in the scientific literature because of its conceptual inconsistency (Barendregt, Bonneux, and Van der Maas 1994, 1997). Since Sullivan's method combines incidence death rates with cross-sectional health prevalence rates, it mixes a stock with a flow variable (Crimmins, Saito, and Hayward 1992). Consequently, Sullivan's health expectancy measure is not a pure period indicator (Mathers 2002). The accuracy has been tested in several simulation models comparing Sullivan's method estimates with multistate life table estimates (Barendregt, Bonneux, and Van der Maas 1994; Mathers and Robine 1997). The debate concluded that Sullivan's method "[...] is not capable of detecting a sudden change in disability transitions rates, but it provides a very good estimate of the multistate value if there are smooth and relatively regular changes over the longer term [...]" (Mathers and Robine 1997). Therefore, results based on Sullivan's method should be interpreted with caution if researchers would like to use them to assess the compression vs. expansion of morbidity debate (Nusselder 2003). To sum up the discussion about the appropriate estimation

approach, Sullivan's method seems to be rather popular due to its low data demand than because of its high reliability (Guillot and Yan 2009).
Against this background, researchers have recognized the need for a reliable method with realistic data requirements. Imai and Soneji (2017) as well as Davis, Heathcote, and O'Neill (2001) have proposed methods to calculate cohort health expectancies from subsequent cross-sectional surveys. Further, Lynch and Brown (2010) developed a Bayesian method to obtain multistate life tables from cross-sectional data. Finally, Guillot and Yan (2009) introduced the intercensal method, which relies on the multistate framework but uses two subsequent cross-sectional surveys instead of longitudinal data.

In this paper, we introduce and discuss another alternative health and mortality summary measure: The "Healthy Cross-Sectional Average Length of Life" (HCAL). It is innovative in the sense, that previous measures are based on the conventional life expectancy indicator with an extension to morbidity. In contrast, HCAL is build up from an alternative longevity measure, the "Cross-Sectional Average Length of Life" (CAL). Which is based on the whole mortality history experienced by various cohorts alive in a particular population in time t. CAL was originally introduced by Brouard (1986) and further elaborated more recently, by Guillot (2003) and Canudas-Romo and Guillot (2015). CAL has been used in emperical studies to compare the mortality history of cohorts, to study population dynamics, and to discuss tempo-effects in mortality (Bongaarts and Feeney 2006; Canudas-Romo and Guillot 2015; Guillot 2003; Luy 2010). In the previous health expectancy literature, the conceptual similarity between CAL and cross-sectional prevalence rates has been already mentioned (Brouard and Robine 1992; Guidici, Arezzo, and Brouard 2013). However, assessments of its empirical usability are still missing. The aim of this paper is to fill the gap of knowledge by firstly, exploring HCAL with respect to its underlying concept. Secondly, the measure will be illustrated by applying it to the French and UK population. Finally, HCAL estimates will be compared to HLE estimates in concrete empirical applications (differences between countries, genders, and calendar years) to investiage the difference between the two approaches.

2 HCAL Method

HCAL is based on CAL but uses Sullivan's method to apply the proportion of the unhealthy population to the person-years lived. In this way, it combines mortality and morbidity information in one single summary indicator.

$$CAL(t) = \sum_{x=0,n}^{\omega} {}_nL_x{}^c[t-x-n, t-x] \tag{1}$$

with ${}_nL_x{}^c$ is being the number of person-years lived between age x and $x+n$ in the life table for the cohort born between extact time $(t-x-n)$ and $(t-x)$. Thus, CAL reflects the sum of the cohort survivors (given the radix=1) in the particular period t.

$$HCAL(t) = \sum_{x=0,n}^{\omega} (1 - {}_n\hat{\pi}_x){}_nL_x{}^c[t-x-n, t-x] \tag{2}$$

where ${}_n\hat{\pi}_x$ is the sample fraction of the unhealthy population obtained from the health survey. While $CAL(t)$ sums up all person-years lived between age x and $x+n$ in the corresponding cohorts, HCAL sums up only the healthy proportion of these person-years lived. Therefore, HCAL corresponds to the healthy proportion of survivors in each cohort at time t.

Life expectancy at birth (LE) is estimated by using standard life table techniques (see e.g., Preston, Heuveline, and Guillot 2001). Applying the period life table person-years lived (Lx) to the sample fraction of the unhealthy population (${}_n\hat{\pi}_x$) gives the healthy life expectancy (HLE) indicator. Hence, the difference between HCAL and HLE depends only on the difference between the Lx function using the period life table or the CAL concept.

3 Population dynamics

CAL has been demonstrated to be very useful not only for the analysis of longevity, but also for the analysis of population dynamics (Guillot 2003, 2005). HCAL has a similar feature as it allows to measure the size of the healthy population. Imagine a fictive population with one birth per year exposed to actual morbidity and mortality conditions. CAL at time t is the total size of that population and HCAL is the total size of the healthy population at time t. Thus, analyzing HCAL trends can be seen as looking at population data of the healthy population over time but controlling for fluctuations in births[1]. The ratio of (H)CAL between two periods (time 0 and time T) is then the growth factor of the (healthy) population. The relationship between the growth factors for CAL, HCAL, and UHCAL (Unhealthy CAL) is illustrated in equation 3.

$$GF^{CAL}[0,T] = w_{healthy} \times GF^{HCAL}[0,T] + w_{unhealthy} \times GF^{UHCAL}[0,T] \tag{3}$$

The growth factor for CAL between time 0 and time T is the weighted average of the growth factors for HCAL and UHCAL between time 0 and time T. Where $w_{healthy} = \frac{HCAL[0]}{CAL[0]}$ is the weight for the HCAL growth factor and $w_{unhealthy} = \frac{UHCAL[0]}{CAL[0]}$ is the weight for the UHCAL growth factor.

4 Data

Our illustration and test of the method is based on data for France and the UK. The CAL estimation requires a long time series of mortality data which is provided by the HMD (2018). For the UK, HMD data is available from 1922 onwards. However, calculating CAL from 2005 onwards requires data beginning in 1915 (defining 90+ as the last open-age group). Therefore, we used mortality rates from England & Wales for the missing 8 years ($1915 - 1922$), assuming that they are not significantly different from the UK death rates.

The age-specific proportions of the (un)healthy population were obtained from the European Union Statistics on Income and Living Conditions (EU-SILC). Individuals were defined as healthy if they

[1] Note that this makes HCAL also less susceptible for tempo effects which can bias trends in HLE when conventional period life expectancy is as basis (see e.g., Bongaarts and Feeney 2010; Luy 2010; Luy and Wegner 2009)

did not report any activity limitations using the Global Activity Limitation Indicator (GALI) as the underlying health state question. The GALI question was essentially unchanged in the analyzed period (Jagger et al. 2013) which makes comparisons over time possible. The GALI question was not asked to individuals under the age of sixteen. To solve the issue of missing data in young age groups, we followed the Eurostat method (Eurostat 2018) [2]. Additionally, the SILC data does not provide single age prevalence rates between age 80 to 90+. Hence, we used the SILC estimate of the 85+ age group as estimate of the 90+ age group and interpolated the missing values between age 80 to 90+ assuming an exponential trend (see figure 1).

5 Preliminary results

As already mentioned above, differences between HCAL and HLE only depend on the differences between the CAL Lx function and the period life table Lx function. In the period life table, the Lx function refers to the person-years lived by a synthetic cohort, which is subject to the age-specific mortality rates observed in a particular period. In contrast, CAL reflects the actual mortality history of various cohorts alive in time t. More specific, CAL sums the proportions of survivors in each cohort at time t. For example, the French male cohort born in 1945 experienced higher mortality during their life course compared to the cohort born in 1944 (see figure 2). Consequently, the proportion of survivors for the 1945 cohort is lower compared to the 1944 cohort, indicated by the bump in the CAL curve in figure 2. The proportion of survivors decreases with time because older cohorts have been longer exposed to mortality and because some cohorts might have experienced high mortality during their life course[3]. The cross-sectional prevalence rates follow the same concept. They refer to the healthy proportion of a particular birth cohort. For example, the proportion healthy is higher for the 1944 birth cohort compared to the 1945 birth cohort (see figure 1). Therefore, using CAL instead of period LE as the underlying longevity measure overcomes, theoretically, the limitation of conventional Sullivan's method, i.e., combining real and synthetic cohort quantities. However, it does not fully address Sullivan's limitations if the goal is to examine a synthetic cohort reflecting the mortality and morbidity conditions in one particular period. Still, applying Sullivan's method to cohort survival gives a valid health expectancy estimate without stationarity assumption, i.e., in a cohort, the observed prevalence data reflects the result of the factual underlying multistate process (Imai and Soneji 2017).

[2] The method applies the prevalence for the first observed age group $16-19$ to the $15-19$ population age group. Further, the prevalence for the age group $0-15$ is assumed to be half of the prevalence of the age interval $16-19$ years (Eurostat 2018). This approach has been widely used in the previous healthy life years literature (e.g., Jagger et al. 2013). Since this analysis is based on singe age groups, the method needed some modification. Respondents aged 16 years were not observed in every SILC dataset. We assumed that persons aged 15 to 17 have equal health prevalence rates. Accordingly, the prevalence for the age group $0-14$ is half of the prevalence of the interval 15 to 17 years. Sensitivity analyses have shown that changes in the health prevalence rates for very young individuals have only little effect on the health measure estimate.

[3] A detailed explanation can be found in Guillot (2003).

Figure 1: Proportion with activity limitations (GALI), France, Males, 2008

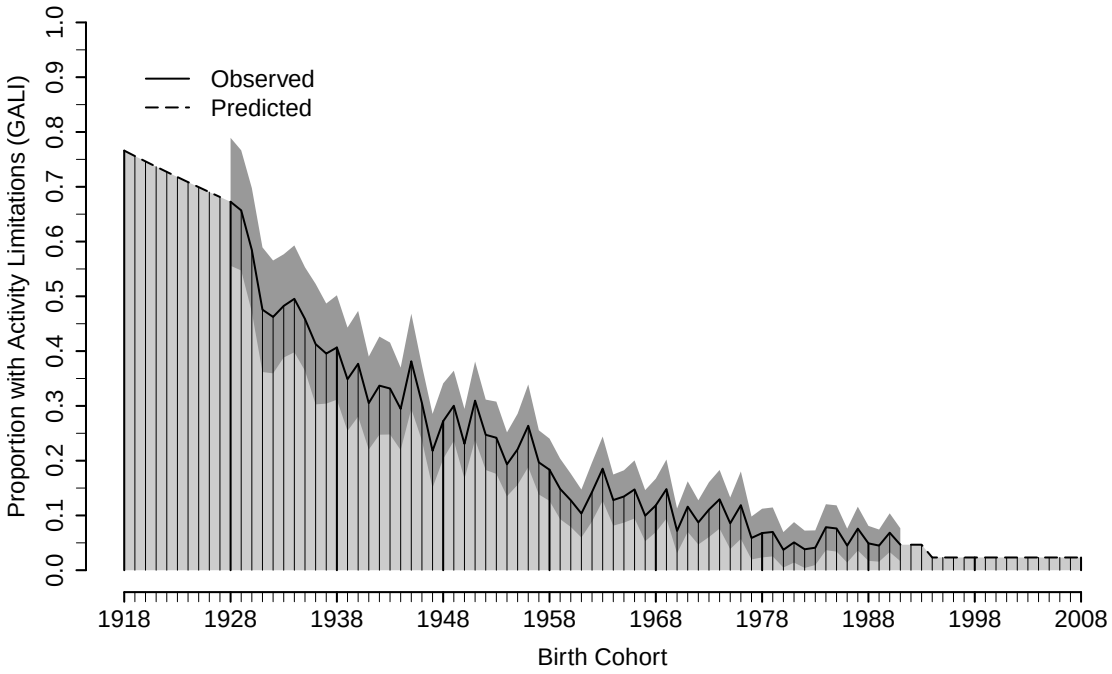
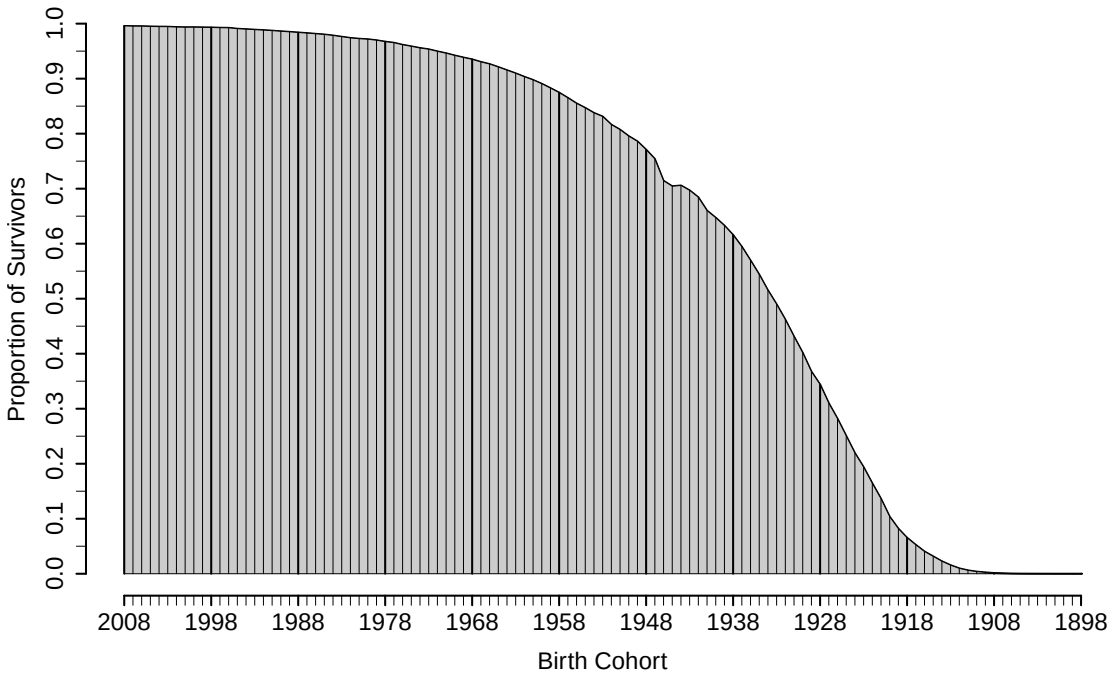


Figure 2: Proportion of survivors, France, Males, 2008



The figures 3 and 4 show that conventional LE is higher than CAL. This is a consequence of the fact

that CAL reflects the whole mortality history of the currently living cohorts, whereas the conventional LE reflects the mortality of only one single year. Further, the difference between 2004 resp. 2005 and 2015 is higher in CAL because CAL is steadily increasing during the period, while LE is more fluctuating with a relatively low value in 2015 (see table 1 and 2). Accordingly, the increase in HCAL is higher than the increase in HLE between 2004 and 2015 in France. In the UK, HLE for males remained the same in 2005 and 2015 but HCAL slightly increased. For UK females, both, HLE and HCAL decreased in absolute numbers. However, the decrease is stronger using HLE. Comparing HLE and HCAL trends shows the impact of the selected Lx function. The contrast becomes clearer when we compare HLE for UK males between 2014 and 2015. LE was decreasing from 2014 to 2015 but CAL increased. Both, HLE and HCAL increased during that period. The absolute increase for HLE was significantly smaller compared to the increase of HCAL (0.29 vs. 0.94). If the health conditions remained constant between 2014 and 2015 (constant prevalence rates), HLE would have even decreased while HCAL would have increased.

In relative terms, the proportion of the unhealthy life years increased during the analyzed period for both HLE and HCAL. Yet, it is smaller in CAL compared to the unhealthy share in LE.

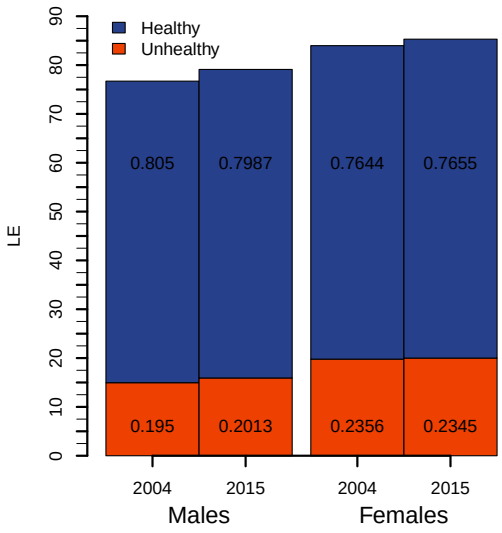
Another application for the conventional HLE and HCAL concepts is the analysis of gender differences in healthy life years. Figure 5 shows that the gender gap is wider using HCAL for France in 2004 and 2015. This holds also for the UK in 2005. In 2015, however, both measures give higher estimates for males. Especially the HLE estimate for males exceeds the one of females. This results in a wider gender gap using HLE compared to HCAL.

Finally, we use the population dynamics interpretation of (H)CAL explained in section 3, to analyze the population change with respect to the health state. For example, HCAL for French males increased from 58.08 in 2004 to 60.29 in 2015 by a growth factor of 1.04. The estimate of 58.08 can be interpreted as the total size of a fictive population with constant births (1 birth per year) exposed to the actual underlying morbidity and mortality process of the French male population in 2004. The increase from 58.08 to 60.29 is, therefore, a clear sign of improvement. In this perspective, figures 3b and 4b show the total population size of France and the UK in 2004 resp. 2005 and 2015 after controlling for fluctuations in births. The blue shaded proportion indicates the healthy population and the orange shaded share corresponds to the unhealthy population. In all 4 populations, the proportion unhealthy has increased between the two points in time.

Figure 6 illustrates the growth of these fictive populations. CAL for French males increased from 70.21 in 2004 to 73.96 in 2015 by a factor of 1.05, which is slightly higher than the corresponding growth factor of HCAL of 1.04 during the same period. Assuming again a constant birth population, the change in population size is only attributed to morbidity and mortality improvements. Thus, comparing the HCAL growth factor with the CAL growth factor indicates that the healthy population does not grow as fast as the total population. Applying equation 3 shows how much of the total population growth was attributed to the growth of the healthy (indicated by the blue color) respective unhealthy population (indicated by the orange color). In general, the population growth is higher for males compared to females in the UK and in France, i.e., the bars for males are higher. In addition, the healthy share of the population growth is also higher for males compared to females.

Figure 3: LE and CAL for France in 2004 and 2015

(a) LE



(b) CAL

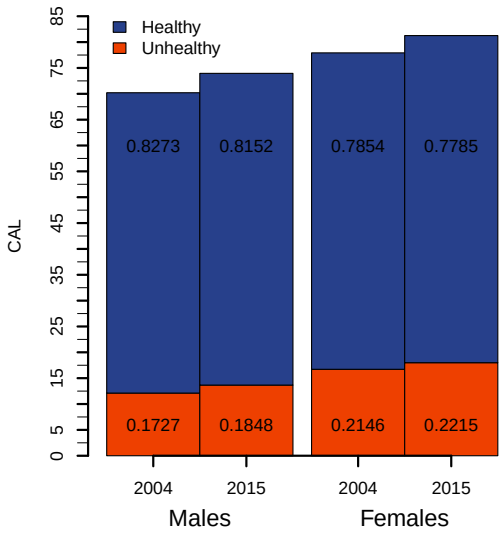
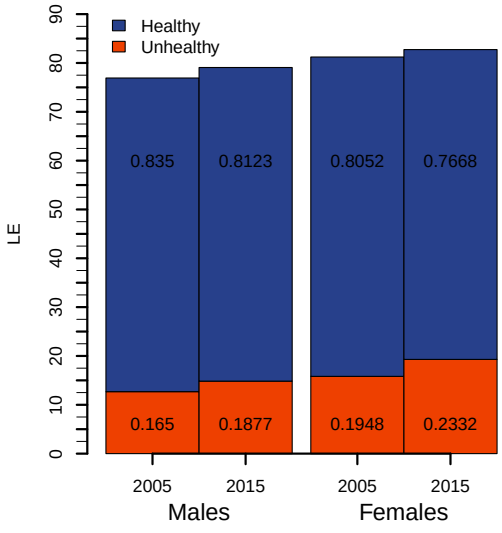


Figure 4: LE and CAL for UK in 2005 and 2015

(a) LE



(b) CAL

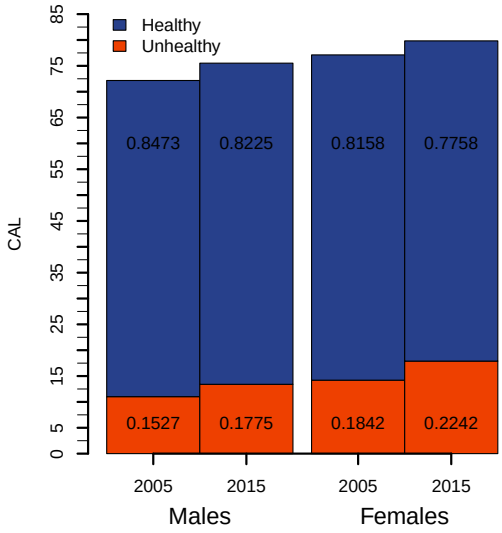
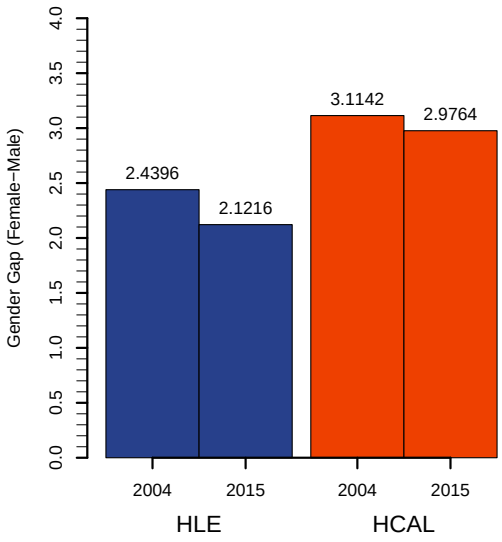


Figure 5: Gender gap in France and the UK

(a) France



(b) United Kingdom

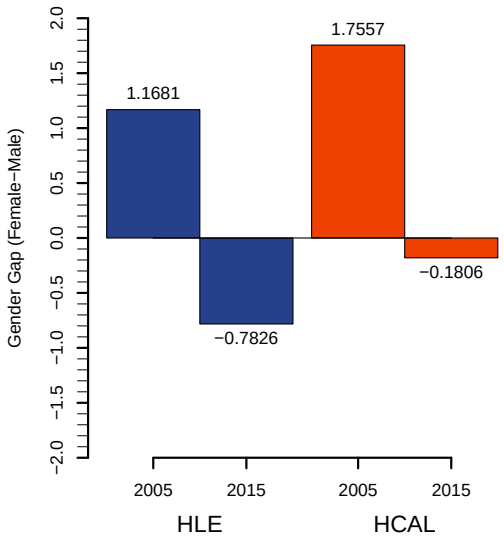
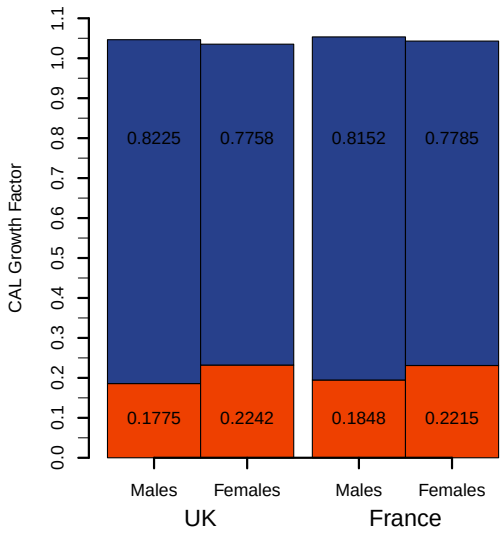


Figure 6: Growth factor



6 Conclusion

Previous research has brought up different health summary measures to study morbidity and mortality in populations. Most of them are based on the conventional period life expectancy concept, i.e., being based on a synthetic cohort. This approach is attractive for mortality research because period death rates are widely available. Multistate transitions rates (between the states 'healthy', 'unhealthy' and

'dead') in a given period, however, are usually not available. Therefore, the health expectancy research struggels with this concept. We propose a health summary measure with the different underlying concept. Following a cohort approach, HCAL gives a useful alternative view on population health and mortality.

We argue that cross-sectional prevalence rates fit better to the CAL concept than the conventional period life table concept. Our results suggest that HCAL and HLE estimates differ in absolute and relative terms. In general, HCAL shows smaller absolute values and the relative healthy share is higher. Further, HCAL is less affected by period mortality fluctuations. Moreover, HCAL gives a new perspective on the gender gap in morbidity and mortality. By taking into account the full mortality history, the gap is wider for France in 2004 and 2015. In the UK, the gap is wider in 2005 but smaller in 2015. Last but not least, HCAL has the additional advantage that it features a population dynamics interpretation. In this perspective, the measure assess population change with respect to changes in health and mortality what can be very handy in the analysis of the trends and changes in population health, i.e., in the context of the expansion vs. compression of morbidity debate.

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A Appendix

Table 1: France, 2004 – 2015

Year	LE		HLE		UHLE		CAL		HCAL		UHCAL	
	F	M	F	M	F	M	F	M	F	M	F	M
2004	83.98	76.71	64.19	61.75	19.79	14.96	77.92	70.21	61.20	58.08	16.72	12.12
2005	83.88	76.74	65.08	62.36	18.80	14.38	78.16	70.53	62.21	58.86	15.96	11.66
2006	84.21	77.17	64.57	63.23	19.64	13.94	78.50	70.88	61.91	59.66	16.58	11.23
2007	84.37	77.39	64.82	63.34	19.55	14.05	78.81	71.22	62.12	59.74	16.69	11.48
2008	84.28	77.59	64.79	63.07	19.49	14.52	79.08	71.56	62.24	59.73	16.84	11.83
2009	84.38	77.75	64.14	63.49	20.24	14.26	79.40	71.91	61.84	60.19	17.56	11.72
2010	84.70	78.05	63.75	61.95	20.95	16.10	79.82	72.30	61.42	58.83	18.40	13.47
2011	85.14	78.51	64.36	63.18	20.78	15.32	80.22	72.67	62.03	59.81	18.19	12.86
2012	84.99	78.57	64.15	62.96	20.83	15.61	80.46	72.99	61.94	59.83	18.53	13.16
2013	85.24	78.85	64.93	63.27	20.31	15.59	80.79	73.32	62.71	60.11	18.08	13.21
2014	85.68	79.39	64.90	63.95	20.79	15.44	81.15	73.69	62.66	60.64	18.49	13.05
2015	85.30	79.11	65.30	63.18	20.00	15.93	81.26	73.96	63.27	60.29	18.00	13.67

Table 2: UK, 2005 – 2015

Year	LE		HLE		UHLE		CAL		HCAL		UHCAL	
	F	M	F	M	F	M	F	M	F	M	F	M
2005	81.22	76.92	65.40	64.23	15.82	12.69	77.11	72.17	62.91	61.15	14.21	11.02
2006	81.51	77.14	65.02	65.06	16.49	12.08	77.41	72.51	62.59	62.11	14.82	10.40
2007	81.63	77.36	66.20	64.92	15.43	12.44	77.69	72.86	63.85	62.09	13.85	10.78
2008	81.67	77.56	66.95	65.18	14.72	12.37	77.92	73.19	64.64	62.41	13.29	10.78
2009	82.21	78.04	66.09	65.06	16.13	12.98	78.32	73.58	63.89	62.17	14.43	11.41
2010	82.37	78.39	66.30	64.85	16.07	13.53	78.53	73.89	63.99	62.00	14.54	11.89
2011	82.79	78.83	65.66	65.57	17.13	13.26	78.92	74.28	63.33	62.66	15.59	11.62
2012	82.72	79.00	64.69	64.22	18.03	14.79	79.14	74.61	62.80	61.72	16.34	12.89
2013	82.82	79.04	64.76	64.79	18.06	14.25	79.39	74.92	62.98	62.24	16.42	12.69
2014	83.06	79.30	63.72	63.94	19.34	15.36	79.69	75.25	62.03	61.71	17.66	13.54
2015	82.74	79.07	63.45	64.23	19.30	14.84	79.83	75.52	61.93	62.11	17.90	13.40

Figure 7: Mortality rates from 1905 – 2015, France

(a) Females

(b) Males

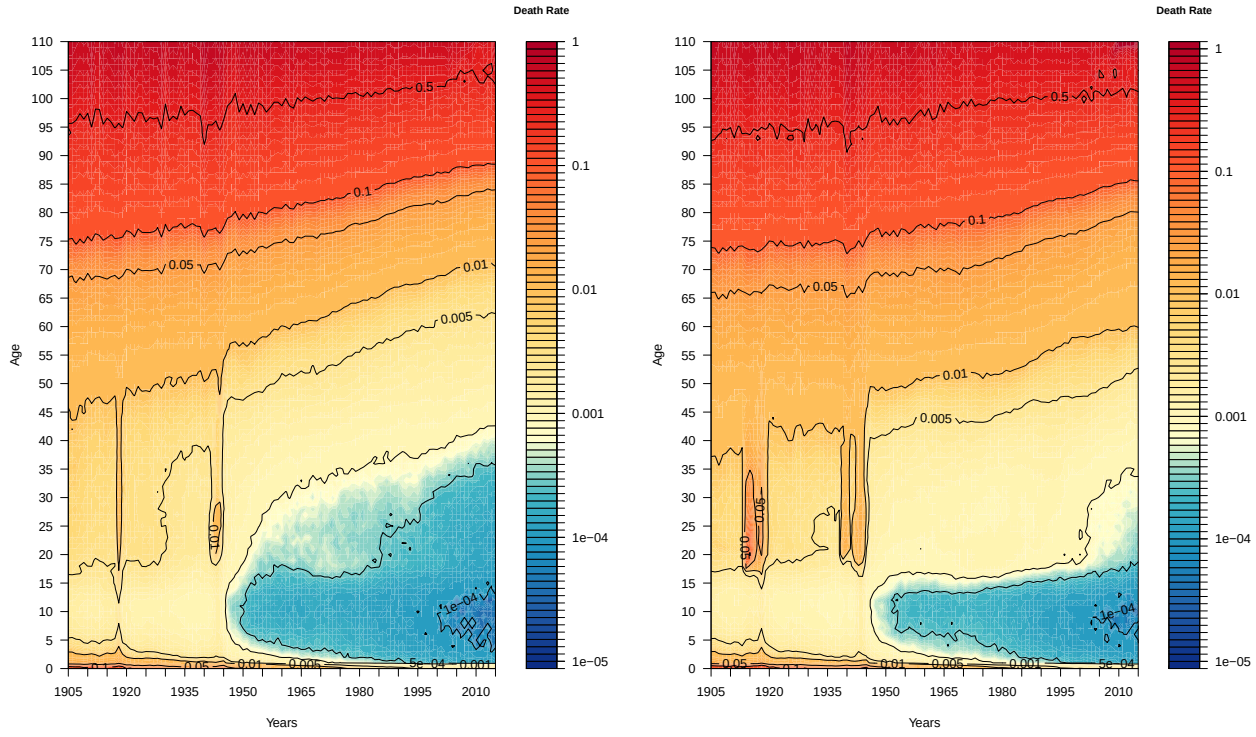

Figure 8: Mortality rates from 1905 – 2015, UK

(a) Females

(b) Males