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J. Epidemiol. Community Health 2002;56;128-131
doi:10.1136/jech.56.2.128

THEORY AND METHODS

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J Epidemiol Community Health 2002;**56**:128–131

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Accepted for publication 8 June 2001

Objectives: To explore various methods to quantify the burden of mortality, with a special interest for the more recent method at the core of calculations of disability adjusted life years (DALY).
Design: Various methods calculating the age schedule at death are applied to two historical life table populations. One method calculates the "years of life lost", by multiplying the numbers of deaths at age x by the residual life expectancy. This residual life expectancy may be discounted and age weighted. The other method calculates the "potential years of life lost" by multiplying the numbers of deaths at age x by the years missing to reach a defined threshold (65 years or 75 years).
Methods: The period life tables describing the mortality of Dutch male populations from 1900–10 (high mortality) and from 1990–1994 (low mortality).
Results: A standard life table with idealised long life expectancy increases the burden of death more if mortality is lower. People at old age, more prevalent if mortality is low, lose more life years in an idealised life table. The discounted life table decreases the burden of death strongly if mortality is high: the life lost by a person dying at a young age is discounted. Age weighting the discounted life table balances the effect of discounting.
Conclusions: For the purpose of description of the burden of mortality, the aggregate life table of the studied populations gives the better description of the age schedule at death. Discounting and the use of idealised lifetables as a standard increase the burden of mortality of degenerative disease at the end of life. The age weighted discounted life table violates the principle of parsimony.

One of the yardsticks used to evaluate health across populations, time or other characteristics is death rates. Mortality is easy to measure because of the unambiguous end point. But we all will die, but preferably at a later age. The burden of mortality is therefore defined by the age at death: how bad is it to die at a younger age instead of at an older age.

The classic epidemiological method to compare the mortality across populations with different age structures is to standardise mortality by age. Age specific rates are weighted by the age distribution of a standard population.[1] The demographers way to adjust for age is to calculate a life expectancy.[2] The (period) life expectancy is the mean age at death in a stationary population with fixed birth and age specific mortality rates of a given period, and is independent of the age distribution. The life table transforms occurrence (the age specific mortality rates) in time (the expected duration of life). The life expectancy summarises the age specific death rates of a certain period, and informs us about the average number of years a cohort may live if these rates remained constant.

Older public health measures of lost life were based on "potential years of life lost".[3] This measure values all deaths before a certain age with the number of years lost before a desirable age that everybody should reach (usually 65 years, but older thresholds are of course possible). A neonatal death loses 65 years, a death at age 1 64, and so on. Deaths at older ages are ignored. In occidental populations with low mortality, the majority of all deaths are therefore not counted as a burden.

Recently, the Global Burden of Disease Project introduced a new measure to summarise the age schedule of mortality in the DALY (disability adjusted life years).[4 5] In the description of this method, I only consider loss of life through death, not loss of quality of life through disease. The DALY adds four value judgements to the age at death.[4 5] Two judgements consider the desired age at death: the project chooses as a standard a life table of an idealised population with very high life expectancy, which is different for men (80 years) and women (82 years). Then a discount rate of 3% per year for any "future" loss of life is added. Then an age weighting formula is added.[4 5] A death at a certain age is multiplied by its residual life expectancy in this ideal gender specific life table, discounted by 3% per year of the life years foregone and weighted by the "value" of these life years at every future age a life year is lost.

In this paper, I explore empirically the different methods of summarising and valuing the age schedule of human mortality by comparing the burden of mortality of two historical populations: the Dutch male population in 1900–1910, with the high mortality comparable to present day Africa, and the Dutch male population in 1990–1994, with the low mortality common to all modern rich market economies.

METHODS

To assess the different methods of estimating the burden of mortality, I took the life tables of Dutch men of 1900–10 (henceforth called 1900) and 1990–94 (henceforth called 1990) and used these as examples of stationary populations with high (1900) and low (1990) mortality.[2] These life tables are in table 1. The male life expectancy in 1900 was 50.5 years, in 1990 74.1 years. The last column shows the age adjusted mortality ratios of these two periods.

The burden of mortality is defined by

$$BM = \sum_{x=0}^{x=\max} d_x w_x$$

Where BM is the burden of mortality, d_x are the numbers of death at age x and w_x is the weight. In a population d_x is the

Abbreviations: DALY, disability adjusted life years; PYLL, potential years of life lost

Table 1 Life tables of Dutch men of 1900–1910 and 1990–1994. The values are taken from the unabridged life table.[2] Values are in percentages

	1900			1990			
Age	qx	dx	ex	qx	dx	ex	Risk ratio
0	14.0	14.0	50.5	0.7	0.7	74.1	20.4
1–4	6.6	5.7	58.2	0.2	0.2	73.7	35.5
5–14	2.8	2.2	58.3	0.2	0.2	69.8	14.2
15–44	14.7	11.5	49.8	3.0	2.9	59.9	5.3
45–64	30.4	20.2	25.6	15.7	15.1	31.2	2.1
65–74	44.3	20.5	11.6	31.0	25.0	14.5	1.6
75+	100.0	25.8	6.7	100.0	55.8	8.6	1.4

"q_x" is the probability of dying in the age interval. "d_x" is the proportion of deaths in that age interval in the synthetic cohort. "e_x" is the residual life expectancy at the beginning of the age interval. The risk ratio compares the age adjusted risk of dying in 1990, compared with 1900.

absolute numbers of deaths at age *x*. In this life table exercise, "d_x" are the numbers of death in the age-interval *x* to *x+1* of the synthetic life table cohort.

In calculations of lost life years, the residual life expectancy (e_x) at the age of death is used as weight:

$$w_x = \frac{1}{l_x}\sum_{a=x}^{x_{\max}} L_a$$

l_x is the size of the surviving cohort at age x and ΣL_a is the number of person years yet to live at age x. This leaves the choice of the standard life table determining the life expectancy as weight. The Global Burden of Disease project chose an "ideal" standard, with a very old population (male life expectancy of 80 years). To explore the sensitivity of the chosen standard, I constructed two extreme standards, based on these historical life tables. I scaled the historical mortality ratios to a life expectancy of exact 50 years ("low standard") and exact 80 years ("ideal standard") (see table 2). The burden of mortality calculated by the standard life table with a life expectancy of 50 years is further called LL50, the burden calculated by the standard life table with a life expectancy of 80 years is called LL80.

In the DALY valuing system, the life expectancy is discounted by 3% per expected year yet to live. The discounted life expectancy is then

$$w_x^d = \frac{1}{l_x}\sum_{a=x}^{x_{\max}} L_a \frac{1}{(1+r)^{x-a}}$$

Where w^d_x is the weight from the discounted life table, l_x is the size of the life table cohort at starting age x, L_a are the person years lived at any future age *a* from starting age *x* onwards, and *r* is the discount rate, which in the Global Burden of Disease project is 3%. Note that in the period life table, "time" is equivalent to "age". I will use the notation DLL80 for the discounted life table (life years lost in the standard life table with a life expectancy of 80 years, discounted at 3% per future year of life lost).

These discounted life years are then age weighted:

$$w_x^{d,a} = \frac{1}{l_x}\sum_{a=x}^{x_{\max}} L_a \frac{0.1658\ a\ e^{-0.04a}}{(1+r)^{x-a}}$$

Where *a* is any age *a* from starting age *x* onwards. The implemented age weight formula is that of the DALY method.

The age weights are introduced to weight years lost at adult and productive life more than those lost at very young or very old ages.[4–6] I will use the notation ADLL80 for the age weighted discounted life table (life years lost in the standard life table with a life expectancy of 80 years, discounted at 3% per future year of life lost and age weighted according to the Global Burden of Disease project formula).

An older method of weighting the age at death are the potential years of life lost (PYLL). All deaths before a certain age (the youngest age threshold chosen is 65, the oldest 75) are weighted by the numbers of years lost before that age. Consequently, w_x = (T-x), where x is age at death and T is the desirable age everybody should reach. If that desirable age is 65, a death at age 0 loses 65 life years, a death at age 50 loses 15 life years, a death at age 66 loses nothing.

RESULTS

The resulting weights are in figure 1 and table 2. A (male) death at birth loses 80 years of life by applying the undiscounted high standard life table (LL80). The same baby loses 30 years by applying the discounted life table (DLL80), and 31 years by the discounted age weighted table (ADLL80). He will lose 50 years by applying the low standard life table (LL50). Altogether 65 potential life years are lost (PYLL65). At age 70, a death will lose 15 years (LL80), 12 discounted years (DLL80), 7 discounted and age weighted years (ADLL80), 9 life years in the low standard life table (LL50), and no potential life years before age 65 (PYLL65). Note that in any life table without a limiting threshold (such as the PYLL) at all ages people will lose life years. Even in the life table with a very low life expectancy of 50 years, a death at 90 year old will lose more than two years of life.

Table 2 Age weights, calculated by the various methods

Age at death	LL80	DLL80	ADLL80	LL50	PYLL65
0	80.0	29.9	31.2	50.0	65
10	71.0	29.1	36.4	54.0	55
20	61.2	27.7	34.2	45.4	45
30	51.4	25.8	28.9	37.5	35
40	41.7	23.3	22.7	29.3	25
50	32.3	20.2	16.6	21.6	15
60	23.4	16.3	11.3	14.6	5
70	15.3	11.9	6.8	8.8	0
80	8.5	7.3	3.4	4.8	0
90	4.1	3.8	1.4	2.2	0

LL80 are the weights from the ideal standard (life expectancy of 80 years). LL50 are the weights from the high mortality standard (life expectancy of 50 years). DLL80 are the weights from the discounted ideal standard life table. ADLL80 are the weights from the age weighted discounted ideal standard life table. PYLL65 describe the potential years of life lost before the age of 65.

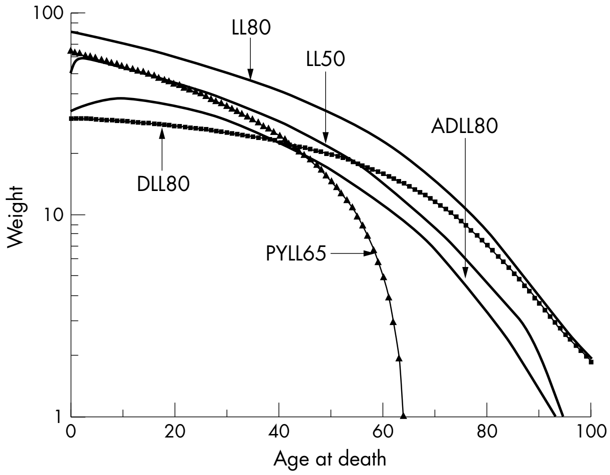

Figure 1 Age specific weights at age of death. The log scale shows the relative weights. LL80 are the weights from the ideal standard (life expectancy of 80 years). LL50 are the weights from the high mortality standard (life expectancy of 50 years). DLL80 are the weights from the discounted ideal standard life table. ADLL80 are the weights from the age weighted discounted ideal standard life table. PYLL65 describe the potential years of life lost before the age of 65.

Figure 1 shows how the weighting schedules of age at death for the pure life table standards of 80 years, 50 years and the age weighted discounted life table of 80 years (ADLL80) run in parallel. The absolute level of difference is high, but the relative difference by age is rather small. The discounted age weights, however, cut across all other life table schedules. Discounting devalues the value of life at younger ages more than at older ages, and decreases more sharply the burden of death if mortality is high and occurring at young ages.

The standardised mortality ratios of the population of 1900 compared with the population of 1990 were 2.48 (life table population 1900 as direct standard) or 2.03 (life table population of 1990 as direct standard). The mortality decrease differed substantially by age (see also table 1, last column), with very high decreases at younger ages and moderate decreases at older ages. The SMR calculated by a younger population standard yields a higher mortality ratio, because it weights more heavily death at younger ages.

The burden of mortality results are in table 3. Weighted for the ideal standard without age weighting and discounting (LL80), the population of 1900 (with an observed life expectancy of 50.5 years) would lose 34 years per person and the population of 1990 (with an observed life expectancy of 74.2 years) would lose 14 years, a ratio of 2.4. Weighted by the low standard of 50 years of life expectancy (LL50), the population of 1900 would lose 23 years per person and the one of 1990 9 years, a ratio of 2.6. The low mortality standard is less sensitive, the high mortality standard more sensitive to the mortality occurring at younger ages. The policy maker would be indifferent to the choice between saving the life of one newborn and saving the lives of 23 (LL50) or 20 (LL80) persons at age 90 (LL50). Because of the high child mortality in the LL50 life table, the results are more at variance for young people: the policymaker would be indifferent to the choice between saving one teenager and 25 (LL50) or 17 (LL80) nonagenarians.

Discounting reduces the burden of mortality by 49% when mortality is high, but only by 28% when mortality is low (fig 1 and table 2). A nonagenarian has little to lose in the future: discounting will hardly affect his remaining life expectancy. A newborn has a lot to lose: discounting cuts deep in his remaining life expectancy. Discounting sharply increases the burden of death at older ages, at the detriment of those causes of death hitting at young and adult age. A policy maker would be indifferent to the choice between saving one live at age 0 and 20 (LL80) or eight (DLL80) lives at age 90.

Age weighting according to the burden of disease function does the opposite of discounting. Older people lose less (because of the discounting), but these losses are valued less (because of the age weights). A policy maker would be indifferent to saving one death at age 0 and 22 (ADLL80) deaths at age 90, or to one death at age 10 and 26 deaths at age 90. The value weights of the age weighted, discounted ideal life table (ADLL80) come very close to the unadulterated life table of the high mortality population (LL50).

The PYLL methods do the opposite of the life table methods. PYLL are weighting heavily death at younger ages, and ignore all deaths at older ages. A policy maker would never choose to invest in mortality at older ages than the age threshold, as long as the mortality at younger ages is non-zero.

Table 3 The burden of mortality in 1900 and 1990 in life years lost per person in the life table population

	1900	1990	1900/1990
LL80	33.9	14.0	2.4
LL80d	17.3	10.1	1.7
LL80ad	15.6	6.5	2.4
LL50	22.3	8.6	2.6
PYLL65	19.7	2.7	7.2

LL80 are the weights from the ideal standard (life expectancy of 80 years). LL50 are the weights from the high mortality standard (life expectancy of 50 years). DLL80 are the weights from the discounted ideal standard life table. ADLL80 are the weights from the age weighted discounted ideal standard life table. PYLL65 describe the potential years of life lost before the age of 65.

DISCUSSION

The absolute burden of mortality is unknown, as the ideal mortality schedule cannot be identified. The moral underpinning of any method assessing the burden of mortality is that it is better to live longer. The aim of any method is therefore relative: to compare populations and to assess the relative importance of causes of death. Any measure of the burden of mortality is determined by two dimensions, and only two: mortality and age. The humanitarian foundation of preventive medicine is defined by the late Geoffrey Rose: "It is better to be healthy than ill or dead."[7] In a life table, the corollary is: "It is better to stay alive until an older age, than to die at a younger age."

The most parsimonious way to compare the burden of mortality is to adjust the mortality by age, and calculate standardised mortality rates. The choice of standard leads to very different results because the mortality differences between high and low mortality populations are much higher in the younger age groups: taking the high mortality population as a standard will add more value to deaths occurring at younger ages and vice versa.

The life table transforms occurrences rates in residual life expectancies at any age. Each residual life expectancy is determined by the remaining age specific mortality rates of the surviving population. In the life table method of calculating the burden of death, numbers of deaths are multiplied by the residual life expectancy at age of death. As in a standardised rate, the standard matters. A life table standard with a very low mortality (as in the DALY method) increases relatively the burden of mortality at older ages. In a comparative evaluation of the burden of mortality of various causes of death, the choice of a very low mortality standard will inflate the burden of age related disorders compared with the burden of mortality at younger ages. The use of a very low mortality standard in a high mortality population is therefore inconsistent with the moral principle that it is better to die at an older age.

Key points

- The burden of mortality is determined by the age at death. The life expectancy calculated in a life table is equal to the mean years yet to live by the life table population.
- The "years of life lost" method multiplies the numbers of deaths by the residual life expectancy at the age of death. The result depends on the choice of the standard life table used to calculate these expectancies.
- Discounting devalues the life years lost to death at a young age, and decreases the burden of death more if mortality is higher and occurs at younger ages.
- Age weighting as in the global burden of disease revalues the devalued life years in an age weighted discounted life table. The age distribution of the burden of mortality is comparable to that of the unweighted, undiscounted life table.
- The "potential years of life lost" method takes into account only death at younger ages. This method decreases the burden of death more if mortality is lower and occurs at older ages.

However, the effect of the choice of an idealised low mortality, instead of the actual mortality, is surprisingly small. Discounting the life table is a by far more important value judgement. Discounting devalues life years lived in the future, so it will devalue the residual life expectancy more if death occurs at younger ages. Discounting inflates very strongly the burden of mortality at older ages.[8 9] Discounting a life table violates the humanitarian principle that "it is better to stay alive until an older age" by devaluing strongly death at a younger age. Discounting has its place in comparative evaluations of interventions with different time dimensions of costs and benefits,[10] but nowhere else.

Age weighting a discounted life table, as in the ADLL method counteracts the effect of discounting. Mortality at younger age is devalued, but the effect is modest. This is because of the life table. A baby will lose the devalued life years of youth, but also the revalued life years lost at adult and middle age. Indeed: the main function of the age weights is to correct the discounting. Deaths at older age lose relatively less because of the discounting, but after age weighting these losses are valued less. Therefore, the burden of mortality calculated by the discounted, age weighted life table comes close again to that of unadulterated life table (see fig 1). From a philosophical point of view "one should not increase, beyond what is necessary, the number of entities required to explain anything (William of Ockham)".[11] Ockham's principle of parsimony warns us for the infinite number of possible models. The age weighted discounted life table violates this principle.

The PYLL method is both parsimonious and morally defensible. Everybody should reach a certain age, and (s)he loses more, the more that age is still far away. As long as that standard is not attained, investing in the prevention of death at older ages is unfair. There is an obvious problem in low mortality populations: more than 80% will die after the age of 65 and will not be counted (value weight 0). In high mortality populations, the PYLL methods weights heavily child mortality. In a population with a high fertility and a high mortality, deaths at very young ages are valued less by society.[12–14] In deprived populations, and without healthy adults to provide for them, babies have but poor prospects to enjoy their potentially long life expectancy.

Confusion about "health gaps"[15] could be avoided by the reminder that life expectancies are but transformations of age dependent death rates. These dwelling times have no implicit biological meaning: they only reflect the variance of mortality by age in a population. The 14 life years "lost" in the male population with life expectancy of 74 years (LL80) have no meaning whatsoever, except that it is less than the 34 years lost if life expectancy is 50.5 (which makes the "ideal state of health"[15] a lot less ideal in the high mortality population). Murray *et al* argue that such a health gap is needed to compare the loss of life in different populations.[5 16] That is identical to the statement that the crude mortality rate of Rwanda cannot be compared with that of Japan. That is why a standard is needed. Any life table standard will do: the lifetable of Rwanda, that of Japan, the aggregate life table of both populations or that of any other population. In fact, the fourth DALY assumption, different standards for men (80 years) and women (82 years), make these estimates incomparable.

The only dimensions in the burden of mortality are mortality and age. Strings of value judgements and assumptions, all pertaining to the one and only dimension of age, should be avoided. Rates can be transformed to dwelling times in a life table, but there transformations should stop. To make unbiased comparisons, the internal reference is the best standard: that is the aggregate life table of the studied populations.

ACKNOWLEDGEMENTS

The author wishes to acknowledge helpful comments and corrections of previous drafts of Dr Wim Van Damme (at Medecins Sans Frontieres, Cambodja), Anna Peeters, Michele Kruijshaar, Wilma Nusselder, Gerrit van Oortmarssen and Jan Barendregt (all at the Department of Public Health, Erasmus University Rotterdam).

Funding: the paper was financed by a grant of Zorgonderzoek Nederland (ZON), nr 99–0004 "Optimisation of cholesterol lowering therapies".

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