THE CONSTRUCTION OF THE DALY: IMPLICATIONS AND ANOMALIES*

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ABSTRACT

The disability-adjusted life year (DALY) is a measure of aggregate ill-health whose construction depends on a counterfactual – the number of life-years a person could have expected to live had she or he not died. There are two ways of specifying the DALY counterfactual to estimate years of life lost (YLL) – by employing an 'exogenous' or an 'endogenous' life table. An exogenous life table is independent of the mortality risks experienced by the population whose health (longevity) is being assessed, whereas an endogenous life table is composed of precisely these risks.

Exogenous life tables have been used to construct the DALY in the Global Burden of Disease (GBD) studies – with different exogenous life tables used in the GBD 1990 and GBD 2010 (and later) exercises. However, an endogenous life table is more appropriate for predicting life-years lost from premature mortality in any given country, and allocating resources through health interventions there on the basis of DALYs averted.

Whether an exogenous or an endogenous life table is used, anomalies can arise. Furthermore, the approach adopted in GBD 2010 onwards adds special difficulties of its own. GBD 2010 and later GBDs use an exogenous reference life table which is the *same* for men and women. This leads to an underestimation of the disease burden of women relative to that of men.

1. INTRODUCTION

Health assessment is usually undertaken by means of a measure that compares populations according to the extent of their health. A measure of aggregate health should be sensitive to the number of healthy life-years that a population has experienced or expects to experience. Thus, relevant information concerning health experience must be identified and aggregated for any measure of population health.

Many metrics of population health rely implicitly or explicitly upon *conditional* statements. For example, the most commonly-used concept in assessing the health of a population – life expectancy at birth – is based on a conditional assumption. Life expectancy at birth (LE) is defined as the number of years that a newborn *would* expect to live *if* she were to face the currently prevailing age-specific mortality risks (as identified in a life table).[1] Measures such as health-adjusted life expectancy (HALE), which take account of both mortality and morbidity in a population, are conditional constructs of a similar kind. The objects of value in LE (or HALE) are the lengths-of-life (or lengths-of-healthy-life) *expected* to be lived by the members of the population.

By contrast, the disability-adjusted life year (DALY) is a measure of population *ill-health* based on 'years of life lost' due to premature mortality. Life-years lost as a result of premature death is a measure that is necessarily dependent on a *counterfactual* assumption – which is a special type of conditional assumption. Counterfactual statements refer to what would be the case if a particular feature of the world were different from what it is. In the case of DALYs, a counterfactual assumption is invoked to answer questions such as: If a person had not died from AIDS in Mozambique, how many years could he have expected to live? In this way the health loss from AIDS and other diseases can be estimated.

[1] Life expectancy at birth is not the average number of years lived by those who die in a given period, which involves a straightforward summation and is not defined through a conditional. The metric of LE (defined using a conditional) is independent of the age structure of the population, and can be seen as one way of summarizing the population's current age-specific mortality rates. The average number of years lived by those who die in a given period does depend on the age structure of the population, and may be an appropriate metric for some purposes.

In addition to years of life lost (YLL) through premature mortality, DALYs also take account of morbidity (or 'disability') in determining the health loss. Thus years lived with disability (YLD) – calculated using 'disability weights' for different morbidity or ill-health conditions – are added to YLL to arrive at an aggregate measure of 'equivalent years' of healthy life lost, viz. DALYs. [2, 3] In an earlier incarnation (GBD 1990), DALYs also valued life-years lived at different ages and at different times differently. However, the DALY of GBD 2010 and subsequent GBDs has dropped these embellishments – in response, it seems, to criticisms of age-weighting and discounting by Anand and Hanson (1997, 1998).

For the main points to be made in this paper it is not necessary even to consider morbidity through YLD. YLD is based on an empirical calculation of time loss from prevailing diseases and injuries (with their corresponding disability weights), so YLD does not depend on a counterfactual, and we abstract from it here. Essentially, it is the counterfactual of premature death in terms of life-years lost, i.e. YLL, that is our central concern.

The 'yardstick' used to assess premature death – i.e. the disvaluation placed on death at any age – depends on the counterfactual that is invoked. Typically, a life table is identified for the purpose of calculating life-years lost. This is in keeping with other measures of health status such as LE, which also requires a life table for its definition as a conditional. But while LE

[2] Note that YLD and YLL are different types of variable that are being added up. YLD is an empirical estimate of actual conditions of living with a disease or disability, whereas YLL is a hypothetical estimate of years of life lost due to 'premature mortality'. The implications of the separability and independence assumptions in adding YLD and YLL to arrive at total DALYs are not examined in the GBD literature. In particular, if a person dies of some grave disease with a serious disability, is it reasonable to assume that had he not died he would have lived in perfect health for his remaining years (i.e. his life expectancy at that age)? For example, does a permanently-disabled person in a wheelchair (with a disability weight of ½) who dies of TB at age 40 lose his perfectly healthy life expectancy at age 40, or does he lose only *half* those years because he is permanently disabled and would still have remained in the wheelchair if he had not died of TB? The definition of YLL assumes that every year of life lost from premature mortality would have been in perfect health. The counterfactual of experiencing *morbidity* – rather than perfect health – in estimating YLL seems to be overlooked in the GBD literature. DALYs are supposed to measure years of *healthy* life lost, which comprise both years lived with disability (YLD) and years of *healthy* life lost from premature mortality. The latter depend on *both* the mortality risks *and* the morbidity risks that a person would face if he had not died, – not just the mortality risks as is the case in the current construction of YLL.

[3] Another issue to consider is the life table to be used in estimating YLL in a country. Whereas YLD in the GBDs is calculated from empirical data on disease and disability in the country itself, YLL is calculated from data on mortality risks in *other* countries. A consistent approach to assessing morbidity and mortality in a given country would seem to require using the data of the country itself (including its own life table) to estimate both YLD and YLL (i.e. the disease burden) in *it*.

shares with DALYs a dependence on conditional judgements, it does not require counterfactual assumptions to define it.

We will argue below that the assessment of health states and priorities resulting from use of the DALY can be critically sensitive to the way in which the counterfactual (*loss* of life-years) is identified. It seems, moreover, that whichever approach is used to identify the counterfactual leads to its own difficulties. These problems distinguish the DALY from other measures of aggregate health status such as LE, HALE, or quality-adjusted life years (QALYs).

We shall attempt to show that each way of specifying the counterfactual in constructing the DALY has implications that can conflict with basic evaluative intuitions – in regard to both the quantification of the disease burden and the choice of interventions. These are not problems encountered by other measures of aggregate health, and stem from the distinctive feature of the DALY, viz. its focus on life-years *lost*. We shall also argue that employing *different* counterfactuals for different purposes does not offer a solution. Our paper attempts to expose these dilemmas in the use of the DALY.

2. CHOICE OF COUNTERFACTUAL

DALYs combine "time lived with a disability and the time lost due to premature mortality" (Murray 1994, p. 441). There are alternative approaches to identifying the time lost due to premature mortality. For example, premature mortality may be defined in relation to a fixed counterfactual length-of-life, T, for all persons – corresponding, for instance, to the maximum length-of-life observed in the modern world.[4] In this case, the years of potential life deemed to be lost by the death of a 40-year old adult, say, is the same ($T - 40$) irrespective of the country in which the death occurs.

[4] This currently corresponds to a value of T equal to 122 years (see *Guinness World Records*). We omit Biblical accounts of longevity, such as to Methuselah who is supposed to have lived for 969 years.

Life-years lost may also be determined with respect to a life table, which enumerates the age-specific risks of mortality. In this approach, the years of life lost due to death at any age are identified with the life expectancy at that age. The life table chosen may be the same irrespective of a person's sex, country of residence, socio-economic class, and other factors – and depend only on age – as in the Global Burden of Disease (GBD) 2010 and subsequent GBD studies (on which more in Section 2.1). In this case, too, the years of potential life deemed to be lost by the death of a 40-year old adult is the same irrespective of the person's sex or the country in which the death occurs.

More generally, the years of potential life deemed to be lost may depend on a wider range of a person's characteristics, including sex and country of residence, in addition to age. In this case, the years of potential life deemed to be lost by the death of a 40-year old adult will depend on the person's sex and the country in which the death occurs.

The appropriate counterfactual to use will depend on the purpose of the evaluative exercise. For certain purposes it may be appropriate to use a fixed counterfactual length-of-life *T*, or more generally a fixed life table.[5] If our interest is to quantify the disease burden suffered in different countries in relation to a normative benchmark which reflects the lowest risks that individuals can expect to face anywhere in the world, then a fixed life table reflecting these risks might offer the appropriate counterfactual, as would a hypothesized maximum length-of-life *T* to which all individuals might aspire.

For normative assessment of certain kinds the appropriate counterfactual may be the lowest risks of death or the highest length-of-life observed,[6] even if the conditions for bringing this about are not readily – or even in principle – attainable in all countries. Disease burden calculated in this way may be a relevant factor in determining corrective resource transfers that accord with a conception of global justice – for example, one that seeks to reduce the difference in life chances

[5] The fixed length-of-life *T* case is also interpretable as a fixed life table: viz. one in which the age-specific mortality rates are all 0 below age *T*, and at *T* the age-specific mortality rate is 1.

[6] For example, in the GBD 1990 study, the life table used – separate for males and females – was linked to the highest observed life expectancy at the time, viz. Japanese females with a life expectancy at birth of 82.5 years.

that results from the brute luck of having been born in, say, Japan rather than Mozambique, even if the life expectancy of Japan cannot be attained in Mozambique.[7]

In contrast, if the purpose is to estimate the expected years of life that will be lost from a death in the *actual* conditions of Mozambique, then the life table of Mozambique – and not Japan – is the appropriate one to use. This loss is of interest if our goal is to choose between alternative disease interventions in Mozambique. We might also wish to know how many expected years of life are lost to each disease in the conditions actually prevailing in Mozambique – rather than those prevailing in Japan or those reflected in the synthetic GBD 2010 life table.

We can further distinguish between two types of question concerning expected years of life lost in the actual conditions in a country. A first question is: 'How many potential years of life are lost as a result of the deaths from malaria in Mozambique?'. The appropriate counterfactual implied by this question is the scenario that the dead individuals would have expected to face if they had not died of malaria. A second, distinct question is: 'How many potential years of life are lost due to the *existence* of malaria in Mozambique?'. The appropriate counterfactual in this latter case is the scenario that would be expected to exist if malaria were absent in the country. The two counterfactuals are different for the reason that if an individual did not die of malaria at a particular age, she would nevertheless face some risk of contracting it in the future. In contrast, the complete absence of malaria requires us to recalculate the life table by deleting malaria as a risk factor for death when estimating expected life-years lost. The counterfactual used to calculate DALYs arising from malaria, or any other disease, employs the first approach.

2.1 THE LIFE TABLES OF GBD 1990 AND GBD 2010 ONWARDS

The GBD 1990 exercise used a standardized life table with separate life expectancies of 82.5 years for women and 80 years for men, respectively, to calculate life-years lost from female and male deaths anywhere in the world. This life table was based on the highest observed life

[7] A more direct way of measuring the difference in life chances between persons born in Mozambique and Japan (than comparing their respective per capita DALY totals) would be to compare their life expectancies at birth. The latter also has the merit of not being sensitive to the age structure of deaths in the two populations, which affect the measured DALY totals.

expectancy at the time – that of Japanese females. The assumed gender gap in life expectancy of 2.5 years was considerably smaller than that observed in low mortality populations then *and* now. Thus Japan had a gender gap in life expectancy at birth of 6 years in 1990, and still of 6 years in 2016 (World Health Organization 2019a). The gender gap of 2.5 years in the GBD 1990 life table was argued to correspond to the "biological difference in survival potential between males and females" (Murray 1994, p. 434) and exclude the effects on life expectancy of males' greater exposure to social and behavioural risk factors. According to the updated figures for 2012 from the GBD 2010 study, the gender gap in Japan was 6.6 years and the world average gender gap (across all countries) was 5.8 years.[8]

Unlike GBD 1990, the GBD 2010 study used a *common* reference life table – the *same* for males and females – with "a life expectancy at birth of 86.0 years for males and females" (Murray, Ezzati, Flaxman, et al. 2012a, p. 2064). The authors state that in the two decades since 1990, "life expectancy has steadily improved in the countries with the lowest mortality", so that it is "appropriate to extend the normative goal for life expectancy" (Murray, Ezzati, Flaxman, et al. 2012b, p. 13). They claim that "the reference standard life table is meant to represent the aspiration for healthy lifespan for all individuals", so they have "developed a new reference standard life table by identifying the lowest observed death rate for any age-group in countries with more than five million in population – to avoid chance fluctuations in death rates due to small sample size" (Ibid., pp. 13-14). Their Web Table 5 (Ibid., p. 14) and Web Table 6 (Ibid., pp. 139-140) provide the new abridged and complete reference life tables, respectively, with a life expectancy at birth of 86.02 years for males and females *alike*.

Remarkably, this new standard reference life table in GBD 2010 takes no account of the biological and genetic differences in life expectancy between females and males which, unlike social and (possibly) behavioural differences, would seem difficult to eliminate. There is a large literature on the female-male biological gap in life expectancy, which goes back at least as far as

[8] In Anand and Sen (1993, 1995) a life expectancy gap between females and males of 5 years is assumed in constructing measures of gender inequality in longevity. These measures are motivated by considering *shortfall* rather than *attainment* inequality, with the maximal values of life expectancy set at 87.5 and 82.5 years for females and males, respectively. The UNDP's Human Development Index (HDI) and Gender-related Development Index (GDI) were constructed on this basis. See Sen (1992) for further discussion on the conception of, and approaches to, shortfall versus attainment equality.

the classic article by Madigan (1957).[9] We cannot review this literature here but there are well-established biological and genetic reasons for the gap, which include hormonal and chromosomal differences between the sexes.[10]

Murray, Ezzati, Flaxman, et al. (2012b, p. 14) justify their new standard reference life table for GBD 2010 (onwards) as follows:

"At the Critical Ethical Choices for DALYs meeting, there was a consensus that using a different standard for males and females was inappropriate. Several arguments contributed to the view that the same reference standard should be used for males and females. First, the empirically observed gap in life expectancy between males and females continues to narrow. Within high-income countries, the gaps between male and female life expectancies especially for the lowest mortality communities have also narrowed. Second, there is no reason that society should have lower aspirations for health for males than females. In fact, with advances in medical science, it is likely the mechanisms through which males tend to have higher mortality for some causes of death will eventually be understood. Interventions to equalize life expectancy for males and females are conceivable. Simply because male life expectancy has lagged behind female life expectancy for many decades in the best-off countries is not a reason to say there is not burden of disease imposed on males by this difference."

We are not aware of the detailed arguments presented at the 'Critical Ethical Choices for DALYs' meeting, and could not find any documentation relating to it. The GBD 2010 data show that female life expectancy is greater than male life expectancy in *every* country in the world

[9] See also Waldron (1976, 1983), and more recent reviews by Perls and Fretts (1997) and Kalben (2000).

[10] For example, the male hormone testosterone is associated both with risky behaviours and with biological risks – such as increasing the levels of bad cholesterol (low-density lipoprotein or LDL) and decreasing the levels of good cholesterol (high-density lipoprotein or HDL) – which put men at greater risk of heart disease and stroke. By contrast the female hormone oestrogen has beneficial effects on cardiovascular health; it lowers LDL cholesterol and increases HDL cholesterol. Oestrogen also has an antioxidant role, and can help maintain normal healthy cell function. Chromosomal differences between men and women can also affect their respective mortality rates. Men have one X and one Y chromosome, whereas women have two X chromosomes. A female with an abnormal gene on an X chromosome can use the normal gene on the other to avoid the expression of disease – which men cannot do.

(except Afghanistan), with the average gap large in high-income low-mortality countries.[11] We are not sure *what* interventions are being conceived "to equalize life expectancy for males and females". Interventions that favour men and discriminate against women, such as providing preferential access to health care to men over women for a similar ailment, would be difficult to defend.[12] As far as we can tell, modern medicine does not currently have the technology to redress the unavoidable *biological-genetic gap* in longevity. Even if such technology might conceivably develop in the future, the time horizon involved is very long and highly uncertain. In the meantime, however, the *equalized* life expectancy assumption has been built into each successive GBD update (every 2-3 years) from 2010 onwards, and continues to be used to measure the relative burden of disease of women and men – with its inequitable descriptive and policy implications.

In our opinion, as long as there is a *biological* or *genetic* reason for the gender gap in longevity, a different standard *should* be applied in determining life-years lost for males and females – as was the case in GBD 1990. If a woman dies at the same age as a man, but for biological and genetic reasons women have a higher life expectancy at that age than men, then more life years *would* be lost for the woman than for the man. However, the approach of GBD 2010 onwards is to treat the number of life-years lost for women and men as being *identical*. By failing to account for the *additional* life years lost by women relative to those lost by men, the approach of GBD 2010 onwards leads to underestimation of the disease burden of women relative to that of men. The new standard reference life table of GBD 2010 and subsequent GBDs – which is common to males and females – seems to have little normative salience or predictive power in determining life-years lost by women and men under the conditions that prevail in the world today, and are likely to prevail for a long time in the future.

3. TWO TYPES OF LIFE TABLE

[11] Other data sources for life expectancy at birth, such as WHO and UN World Population Prospects, show very similar estimates.

[12] See Sen (1992, 2002) for a discussion of violations of 'procedural fairness' and 'process equity' in discriminating against women to redress the life expectancy gap between males and females.

We distinguish between two types of life table that may be invoked to identify life-years lost upon the death of an individual: 'exogenous' and 'endogenous'. As defined they constitute a mutually exclusive and exhaustive partition of the class of life tables that may be used for this purpose. In other words, every life table used must, logically, belong to one and only one of these types.

The life table used to calculate potential years of life lost in a population could comprise, or more generally include, mortality risks that are exogenous to – i.e., not experienced by – that population. For instance, the life table based on Japan (as in GBD 1990) or a synthetically constructed reference life table (as in GBD 2010) might be used to determine the life-years lost when an individual dies in Mozambique. An exogenous life table for a population is wholly or partially made up of mortality risks that are *external* to the population.

Alternatively, the life table used to calculate potential years of life lost in a population could consist only of the actual mortality risks that are observed *in* that population. An endogenous life table for a population is made up exclusively of the mortality risks that are experienced by – and hence internal to – it.

It is, of course, possible to identify multiple populations to which an individual belongs. For example, an individual may belong to the population of Mozambique, to the population of Mozambican females, and to the population of Mozambicans with a per capita income less than US$500 per annum. An endogenous life table for each of these populations comprises the mortality risks that are experienced by *it*. To calculate the years of life lost from mortality in any of these populations, we should use the distinct mortality risks that are endogenous to it.

We can thus distinguish between two different ways of identifying potential life-years lost – through the use of an exogenous or an endogenous life table. Below we offer more formal definitions of 'exogenous' and 'endogenous' life table.

3.1 DEFINITION OF EXOGENOUS AND ENDOGENOUS LIFE TABLE

Exogenous life table: Its information set does *not* consist of the age-specific mortality rates observed in the population whose health (longevity) is being assessed.

Endogenous life table: Its information set consists of the age-specific mortality rates observed in the population whose health (longevity) is being assessed.

When life-years lost due to mortality in Mozambique are determined through the GBD 2010 life table or that of Japan, or with respect to a fixed maximum length-of-life T, an exogenous life table is being used. When life-years lost due to mortality in a country are determined through the life table of a different population, including that of the same country at a different point in time, an exogenous life table is being used.

When life-years lost due to mortality in a population are determined through the life table of the population itself, an endogenous life table is being used. In the endogenous case, the life table of Mozambique is used in determining the life-years lost due to mortality in Mozambique.

Our distinction between the exogenous and endogenous cases captures the alternative methods of calculating years of life lost in estimating DALYs that are described by Murray (1994, pp. 432-4), and are reproduced in Tan-Torres Edejer et al. (2003, Annex E, pp. 113-4). The latter volume also discusses in some detail the estimation of DALYs averted, or years of life gained, through *health interventions*. Since we are concerned in this paper with life tables used both to measure the 'burden of disease' *and* to prioritize health interventions, we will refer mainly to the Tan-Torres Edejer et al. (2003) volume here.

Murray (1994) and Tan-Torres Edejer et al. (2003) divide the methods of estimating the duration of time lost due to premature death into four families: 'potential years of life lost' (PYLL); 'standard expected years of life lost' (SEYLL); 'period expected years of life lost' (PEYLL); and 'cohort expected years of life lost'.

In the PYLL measure, the years of life lost are estimated with reference to a potential limit to life which is "chosen arbitrarily" and "the duration of life lost due to a death is simply the potential limit to life minus the age at death" (Tan-Torres Edejer et al. 2003, p. 113). This is our fixed *T* case.

In the SEYLL measure, the number of years of life lost is determined "by using a standard expectation of life at each age as the reference norm" (Tan-Torres Edejer et al. 2003, pp. 113-4). The authors state that: "For measuring the global burden of disease due to premature mortality, the SEYLL method has been adopted. To define the standard, the highest national life expectancy observed was taken. Based on the observation that Japanese females achieve a period life expectancy at birth higher than 82 years, the standard expectations were based on model life table which has a life expectancy at birth for females of 82.5 years. Note that this is not the approach used to measure DALYs averted by interventions which requires a different calculus." (Ibid., p. 114).

In the PEYLL measure, the number of years of life lost are determined by the "local period life expectancy at each age". In PEYLL, "a population's current mortality level is being used as the 'ideal' against which it is compared", and "[O]ver time and across communities, local life expectancies vary and thus the reference standards vary" (Ibid., p. 113).

The 'cohort expected years of life lost' measures the duration of life lost due to a death by using the cohort life expectancy at that age. However, by definition, cohort life expectancy is very difficult to estimate empirically. In any GBD type of exercise, it does not constitute a realistic method for determining years of life lost from deaths in the world.

It is evident from these alternative specifications of life-years lost that the PYLL and SEYLL measures rely on an 'exogenous' life table, whereas the PEYLL measure relies on an 'endogenous' life table.

Now the information set used to determine the loss of potential life-years due to premature mortality in a population either *does* consist of the mortality risks experienced by the population,

or it does *not*. If the information set includes any mortality risks that are not experienced by the population, then the life table is exogenous. The identification of life-years lost must therefore be based on either an endogenous or an exogenous life table.

In the remainder of this paper, we attempt to identify the implications of the life table that is chosen, and the dilemmas that can arise from each choice. We consider in turn the implications that arise in the exogenous case and those that arise in the endogenous case.

4. IMPLICATIONS OF USING EACH TYPE OF LIFE TABLE

4.1 EXOGENOUS LIFE TABLE

In the exogenous case, the information set used to determine the loss of potential life-years due to premature mortality in a population is not the set of age-specific mortality risks experienced by the population.

The counterfactual assumption made in estimating the 'burden of disease' in the GBD 1990 and GBD 2010 exercises is that the life-years lost from mortality in any population in the world are determined by the exogenous standard reference life table rather than by the life table of the population itself (e.g. Mozambique). The GBD 1990 standard reference life table used to determine life-years lost is the *same* for all countries but *different* for females and males, whereas the GBD 2010 standard reference life table is the *same* for all countries *and* for both sexes.

It is straightforward to argue that the use of an exogenous life table is inappropriate for certain purposes. Below we offer examples of how the use of an exogenous life table can lead to misleading description or quantification, and to misleading evaluation, of health states. As a consequence, if an exogenous life table is used for the latter purpose, it will provide inappropriate guidance for health interventions.

4.1.1 Description with Exogenous Life Table

One purpose to which DALYs are put is to describe the 'burden of disease' in different countries and regions of the world and to quantify its attribution to different diseases, injuries and risk factors – called "global descriptive epidemiology" by Murray, Ezzati, Flaxman, et al. (2012b, p. 2). They state explicitly that "[I]t is a systematic, scientific effort to quantify the comparative magnitude of health loss due to diseases, injuries, and risk factors by age, sex, and geographies for specific points in time" (Ibid., p. 2).

In assessing the magnitude of health loss – specifically the number of life-years lost – what is the rationale for choosing one exogenous life table rather than another? We shall argue in this section that there is no *unique* life table which is appropriate for this purpose. There are diverse reasons that can be advanced for the selection of a specific exogenous life table. The particular life table that is appropriate to use will depend on the judgements made and the purposes at hand.

As mentioned earlier, the life table based on Japanese female life expectancy was chosen as the appropriate exogenous life table for calculating DALYs in GBD 1990. What rationales could be offered for this choice? It was argued that a common exogenous life table should be used to calculate DALYs in all countries so that the loss due to deaths was measured in the same way regardless of where the deaths occur.[13] However, this does not uniquely identify a life table for the purpose.

The reasons that could be offered for the selection of the life table are of two kinds: normative and empirical. We have mentioned above a normative rationale for choosing the life table, namely that it is the pertinent life table for assessing the difference in life chances that results from the brute luck of having been born in Japan rather than in Mozambique. But why Japan? The life table of Sweden could be used instead. It may be argued that Japan is the uniquely appropriate comparator for Mozambique and other countries because it is the country in the world with the highest length-of-life achievements. The reason offered in the GBD 1990 study was that Japan possessed a higher female life expectancy than any other country.

[13] Murray (1994, p. 431) refers to this idea as "treating like health outcomes as like".

An empirical rationale for choosing this life table could be that because Japan has the highest life expectancy in the world it may be thought to be the appropriate comparator for determining the lowest mortality risks that are *actually* attainable in Mozambique. Thus, the life table based on mortality risks in Japan may be viewed as the appropriate one to use in assessing the number of life-years actually lost in Mozambique *relative to* what could be achieved there through economic, human and health-systems development.

However, it is possible to imagine reasons for choosing exogenous life tables of countries other than Japan to assess the burden of disease in Mozambique. These reasons could be either normative or empirical in character.[14]

Why should Japan – rather than some other country with high health status – be used to assess the relative health disadvantage associated with being born in Mozambique? Why not pick Sweden for this purpose? The fact that Japan has the highest life expectancy in the world may not be sufficient reason to select it because it may not have the lowest mortality risks in the world in *all* age brackets, even if it has the highest life expectancy overall. It may be appropriate to use the life table of some other country (namely one with lower mortality risks in some age brackets, even if it has higher mortality risks in others) or indeed to use a *synthetic* life table consisting of the lowest current age-specific mortality risks experienced anywhere in the world. If the motivation for choosing Japan was to assess relative health disadvantage (DALYs) suffered, then why not choose the life table of the most advantaged sub-groups anywhere – within or outside Japan? This is indeed the basis on which the standard reference life table in GBD 2010 has been constructed by Murray, Ezzati, Flaxman, et al. (2012a, b).

An alternative rationale for the choice of an exogenous life table is to gauge the shortfall of healthy life-years in a given country relative to the reduction in mortalities that the country *could* attain over a specified time period. It is not necessary that the life table representing the

[14] There could be different normative reasons for choosing an exogenous life table. For instance, in assessing the health status of Mozambique, there may be special interest in calculating the life-years lost relative to the mortality risks prevailing in Portugal, the former colonial power in Mozambique.

mortality rates that could be achieved in the country (Mozambique) corresponds to the life table of some other country. For example, judgements concerning achievable reductions in mortality risks may depend on information concerning health interventions that have not yet been adopted in any country. However, the life table of a particular country, say Kenya, may be relevant to use in identifying the mortality risks that it is *feasible* to attain in Mozambique over the time horizon in question.

The assumptions made in judging the constraints facing Mozambique and the time frame of the assessment will influence the choice of the life table (e.g. that of Kenya or Japan) used to identify the mortality rates that it is feasible for Mozambique to attain.[15] The choice of the counterfactual life table will be based on a judgement of what the country *can* actually attain – in the sense that it could take measures to enable it to attain the lower mortality risks in the target life table over the specified time period. If it is thought that all countries can attain the same mortality risks – e.g. those of Japan – *over the time period in question*, then it is appropriate to use the same life table – that of Japan – to describe the shortfall in potential life-years lived in each country.

The magnitude of the disease burden and its share attributed to different diseases *and* populations – e.g. female and male – will be dependent on the life table that is used, whether exogenous or endogenous.[16] In measuring the burden of disease in a poor country (Mozambique) by use of a life table based on a rich country (Japan), or by use of the synthetic life table in GBD 2010, what is being measured is the "*burden of disease and underdevelopment*, and not that of disease alone" (Anand and Hanson 1997, p. 690). The sense in which we refer to the burden of disease

[15] Note that it is not possible to infer the life-years lost in Mozambique with respect to Japan by adding the life-years lost in Mozambique with respect to Kenya to those lost in Kenya with respect to Japan: transitivity does not obtain. Thus, the choice of exogenous life table is one of real significance and is not merely a matter of normalization.

[16] A separate point is that the burden of disease may be considered by some to be an ambiguous concept. This is because the 'burden of disease' must be assessed against background conditions that would exist in the absence of the disease(s), and each way of looking at these conditions involves a *different counterfactual*. As already noted, the DALY total arising from the individual deaths caused by a disease is different from the DALYs averted if the disease were absent – calculated by deleting the mortality risks associated with the disease from the life table. However, in this case the DALY total and its attribution to different diseases will depend on the order in which the diseases are 'suppressed', and whether each disease is re-introduced as a risk factor in estimating the contribution of the other diseases to DALYs.

and underdevelopment is that this burden is calculated using an exogenous life table for a country in GBD 1990 (or countries in GBD 2010 onwards) that is (are) *developed*, and which for that reason in large part exhibit lower mortality rates. In contrast, the burden of disease *alone* for any country may be calculated using its own (endogenous) life table.

If we wish to empirically determine the loss of potential life-years due to deaths in Mozambique, we should use Mozambique's own life table. The life-years lost from disease in Mozambique will depend on the empirical disease risks faced in Mozambique. Therefore, mortality information pertaining to Mozambique and not to some exogenous life table, e.g. the reference life table in GBD 2010, should be used for this purpose.

4.1.2 Ranking and Attribution of Disease Burden depend on Choice of Life Table

The quantification of the share of the total burden attributable to each disease, age group, and sex will also depend critically on the choice of life table. The level and share of the disease burden attributed to different diseases and populations – e.g. the young and the elderly, or women and men – will vary with the life table that is chosen. For instance, consider two diseases, D1 and D2, in a developing country, which respectively affect children and middle-aged individuals. Suppose that D1 results in the loss of more life-years than D2 when the endogenous life table of the developing country (say with life expectancy of 60 years) is used. Now if some other life table, say the exogenous life table of GBD 2010 (with life expectancy of 86 years) is used instead, it could turn out that D2 results in the loss of more life-years than D1.

This point can be illustrated easily by using the fixed T case as the counterfactual. Suppose that $T = 60$ and a male infant dies of malaria at age 0 (D1) and two adult males die of AIDS at age 40 (D2). Then life-years lost from malaria are 60, and those lost from AIDS are 40 (20 for each adult). Suppose instead that the exogenous fixed T is raised to $T = 86$. Then life-years lost from malaria are 86, and those lost from AIDS are 92 (46 for each adult). For $T = 60$, D1 results in

more DALYs than D2; but for $T = 86$, D2 results in more DALYs than D1.[17] Hence, the relative ranking of the disease burden attributed to D1 and D2 will depend on the life table chosen.

This suggests that using an exogenous life table with an 86-year life expectancy, as is done in GBD 2010, may lead to underestimation of the burden of disease for children *relative* to adults, when compared to using an alternative life table with a lower life expectancy. The latter, for instance, might be chosen as one reflecting the actual mortality risks in the developing country – an endogenous life table.

Lest the reader think that the reversal shown above arises because we have used a fixed T case to illustrate it, we can easily demonstrate similar reversals with respect to the GBD 2016 or GBD 2010 reference life table, and actual life tables from developing countries. Let us compare the losses arising from an infant death at age 0 and the death of two adults at age 40, using the GBD 2016 reference life table and the actual life table of South Africa for males in 2016 (from World Health Organization, 2019b), which shows male life expectancy at birth close to 60 years (it is 60.2 years).

The WHO abridged life tables show the life expectancy (LE) for countries at age <1 and at age 40-44 years. For South Africa in 2016 the male life expectancy at age <1 is 60.2 years and at age 40-44 years it is 27.6 years (World Health Organization, 2019b). So the death of a male infant from malaria at age 0 (D1) results in 60.2 DALYs, and the death of two males at age 40 (D2) results in 2x27.6 = 55.2 DALYs.

In the GBD 2016 standard reference life table, the common male and female life expectancy at age 0 is 86.60 years and that at age 40 is 47.21 years (Global Burden of Disease Collaborative Network, 2017). If we calculate the losses from the same deaths with respect to the GBD 2016 life table, we see that the loss from the male infant death is 86.60 years whereas the loss from

[17] The reason this occurs is that a higher T leads to a *larger* percentage increase in life-years lost for those who die in middle age than for those who die as children. So a higher T increases the burden of disease for adults relatively *more* than for children. Formally, the years of life lost from a death at age x, YLL(x), is the life expectancy at age x, e_x. In the case of fixed T, the ratio YLL(x)/YLL(0) = $e_x/e_0 = (T - x)/T$, which for $x > 0$ is clearly larger the larger is T.

two male deaths at age 40 is 2x47.21 = 94.42 years.[18] For the South African 2016 life table, D1 results in more DALYs than D2 (60.2 compared to 55.2), but for the GBD 2016 life table, D2 results in more DALYs than D1 (94.42 compared to 86.60). Hence the relative burden of disease attributable to D1 and D2 does depend critically on the life table used to calculate life-years lost.[19] In this example, the DALYs arising from infant deaths are greater than those arising from deaths of the middle-aged when the country's own life table was used, the reverse of the case when the GBD 2016 standard reference life table is used.

A second important example of the ranking and reversal of disease burden which we wish to emphasize is that between women and men – through use of a common exogenous life table for the sexes (from GBD 2010 onwards) as compared to using separate life tables for females and males. As mentioned in Section 2.1, failure to account for the survival advantage of women, by failing to use different life tables for women and men, leads to an underestimation of the disease burden of women relative to that of men.

Consider two different disease conditions, D*f* and D*m*, in a developing country which respectively affect females and males. For instance, let D*f* refer to maternal mortality and D*m* to prostate cancer in men. Suppose one female of age 25 dies at childbirth (D*f*), and two males of age 50 die from prostate cancer (D*m*). As in the case of D1 and D2, we calculate the loss of life-years for D*f* and D*m* using the life table for South Africa in 2016 and the reference life table of GBD 2016. For South Africa in 2016 the WHO life table shows female life expectancy at age 25-29 to be 46.0 years, and male life expectancy at age 50-54 to be 20.4 years. (At age <1 female life expectancy in South Africa is 67.0 and male life expectancy is 60.2.) In contrast, in

[18] As in the fixed T case, the ratio e_x/e_0 is larger for the GBD 2016 reference life table than for the actual South African 2016 life table for males (and for females), for x = 20, 30, 40, 50, 60, etc. A larger weight is given to an adult relative to an infant (age 0) death in the GBD reference life table with e_0 = 86.60 years than in the South African life table with e_0 = 60.2 years for males (and 67.0 years for females).

[19] Similar calculations were done for the GBD 2010 standard reference life table (Murray, Ezzati, Flaxman, et al. 2012b, pp. 13-14 and pp. 139-140), the *first* GBD exogenous life table common for the sexes, and the South Africa 2010 separate life tables for males and females (World Health Organization, 2019b**)**. The corresponding figures for 2010 show a very similar reversal to that for 2016, with fractionally lower life expectancies in the 2010 life tables at each comparable age.

the GBD 2016 reference life table, life expectancy for both women and men at age 25 is 61.98 years and at age 50 it is 37.59 years.

So according to the life table for South Africa, D*f* results in 46.0 DALYs and D*m* results in 2x20.4 = 40.8 DALYs. If we calculate the same losses using the GBD 2016 reference life table, D*f* results in 61.98 DALYs and D*m* in 2x37.59 = 75.18 DALYs. Hence, the ranking of the disease burden attributed to D*f* and D*m* is *reversed* depending on the choice of a separate or common life table for females and males. The separate life table yields a larger number of DALYs for women relative to men, whereas the common life table ranks the disease burden higher for men relative to women.[20]

Even when the rankings of the disease burden do not change, the relative *shares* – or attribution of the total burden – will alter, which will change the evaluation of the relative seriousness of different diseases. For this reason, caution is required in speaking of *the* disease burden attributable to a specific cause (disease or risk factor) – because it can be sensitive to the particular counterfactual that is adopted.

There are many different life tables that could be used in an exogenous approach to calculating DALYs. The judgement as to which of these should be used, if any, needs to be defended and justified rigorously (including the life tables selected for the GBD 2010 and later exercises). The choice must be based explicitly on the ends of the exercise. In general, there will exist multiple relevant life tables that can serve as counterfactuals, none of which will be uniquely appropriate.

4.1.3 Health Intervention with Exogenous Life Table

[20] There is a 6.8 year gap in life expectancy at age <1 between females and males in South Africa in 2016. If we consider a single male death and a single female death at any age, life expectancy at that age is larger for females than for males – but it is the *same* for the GBD 2016 common life table. Hence, for death at the same age, more DALYs arise for females than for males using the South African separate life table for women and men, but the *same* number of DALYs arise using the GBD common life table. Given the gender gap of 6.8 years in life expectancy at birth in South Africa, even if we consider a female dying 5 years *later* than a male (at any age), there turns out to be a reversal in DALYs estimated for women and men using the separate life table for South Africa in 2016 and the GBD 2016 common reference life table.

In addition to description or quantification, it may be sought to use DALYs to prioritize or choose health interventions.[21] In particular, DALYs may be used to rank interventions in a country with the intent of minimizing potential healthy life-years lost. In this case, a life table based on the *actual* mortality risks experienced in the country – i.e. an endogenous life table – will be the appropriate one to use. The selection of interventions must be based on an assessment of the empirical *consequences* of the interventions, which requires reliance on an endogenous life table.

Using an exogenous life table to choose interventions will not minimize healthy life-years lost given the mortality risks *actually* faced by the population. The disease reduction priorities corresponding to the use of an exogenous life table (e.g. that of GBD 2016) may be the *reverse* of those that correspond to an endogenous life table or to a different exogenous life table. This was illustrated above using the example of diseases D1 and D2.[22] The example of disease conditions D*f* and D*m*, affecting women and men, respectively, is another illustration.

We have tried to show that the use of an exogenous life table in the global burden of disease for description *or* for prioritizing health interventions can have anomalous consequences. The reason is that the information in such a life table is not information about the country in question. It could be by fluke only that the exogenous life table gives the same ranking of disease burdens and interventions as the country's own life table. We are led to conclude that the only fitting use

[21] The interventions considered in the DALY approach are those which reduce disease prevalence and not those which reduce disability weights. However, interventions that help to lower disability weights could be cost-effective in averting DALYs, through a reduction in YLD. Such interventions would therefore also have to be considered within a comprehensive application of the DALY approach.

[22] The reversal of disease priorities between D1 and D2 occurs because of differences in the age structure of the prevalence of D1 and D2. The reversal of burdens and priorities can also occur because diseases and injuries differ in the *disability weights* attached to them. To see why, consider again the case of a fixed *T* as the counterfactual length-of-life applied to all individuals. Suppose an injury leads to a person being confined *permanently* to a wheelchair, with a disability weight of, say, ½, as in the example in Anand and Hanson (1997, p. 700). Now if *T* is raised, given that the disability is irreversible, there will be only half as many healthy life-years lost (DALYs) from this person's death compared with the death of a person who has a disability weight of 0, i.e. is in perfect health. (But see footnote 2 on the assumed separability of YLD and YLL, and the construction of YLL.) The handicap from a disease or injury could have resulted in *permanent blindness*, with a still different disability weight. Raising *T* can therefore result in a *differential* increase in healthy life-years lost (DALYs) to distinct diseases and injuries. Hence a different *T* can lead to different relative burdens attributed to different diseases and injuries, and even bring about the reversal of burdens depending on the ages at their onset. The *level* of *T* chosen can affect the *rank-ordering* of burdens attributable to different diseases and injuries.

of an exogenous reference life table is to enable a description of what a country *misses out,* in terms of potential healthy life-years, by *not* experiencing the mortality risks in the synthetically constructed reference life table.

In general, there is a cost to adopting an exogenous life table, which is that it constrains us to overlook empirical information concerning the actual mortality risks present in a population, which may be relevant to both normative and empirical assessment. Applying the same exogenous life table (e.g. the GBD 2010 or later GBD reference life tables) to groups that face *different* mortality risks, such as women and men, may appear to be treating 'like' (a given death) with 'like' (another death). But such an approach in fact treats the *losses* from deaths identically, when the losses *should* be treated differently.[23] This leads to a cost in terms of moral assessment – by distorting our quantification of the number of life-years lost due to premature death. It also leads to a cost in terms of empirical assessment – by providing a misleading picture of how many life-years lost would *actually* be averted as a result of an intervention that reduced mortality risks in one group as opposed to another, e.g. interventions that benefit women relative to those that benefit men.

4.2. ENDOGENOUS LIFE TABLE

An endogenous life table, like an exogenous life table, might plausibly be used for two purposes – description and the guidance of health interventions. We consider them both below.

4.2.1 Description with Endogenous Life Table

If we are interested in the years that an individual would have expected to live if she had not died, then we should use the life table of the population that identifies the mortality risks she would actually have faced. Therefore, as argued above, an endogenous life table should be used for this purpose.

[23] See Anand and Hanson (1997) for a discussion of the treatment of persons *unlike* along dimensions outside the DALY information set. In the GBD 2010 and later GBD studies, the information set for YLL only includes the age, but not the sex, of an individual.

This concept is appropriate to answering the question (discussed earlier) 'How many potential years of life are lost as a result of deaths from malaria in Mozambique?'. The appropriate counterfactual implied by this question is the scenario that the individuals who died from malaria would have expected to face if they had not died. The life table that reflects this counterfactual refers to the age-specific mortality rates in Mozambique itself – i.e. an endogenous life table.

There are a number of issues that arise in applying an endogenous life table for the purposes of description. We consider three of these here.

First, we could have asked the same question of a sub-population, viz. 'How many potential years of life are lost as a result of deaths of *women* from malaria in Mozambique?'. In this case, the endogenous life table comprising the age-specific mortality risks of the *female* population of Mozambique should be used to answer the question, rather than that of the male and female populations combined. The appropriate counterfactual will be different for different sub-populations whose health is being assessed, just as it will be different for different populations of countries.

Second, for each disease, we could also consider how reducing its prevalence will affect the prevalence of *other* diseases. The DALYs that are averted due to a reduction in the prevalence of a disease depend on the resulting decrease in the number of deaths at each age, and on the life expectancy at each age. However, the life expectancy at each age may *change* as a result of a reduction in disease prevalence – causing non-constancy of the yardstick. This is because a reduction in the prevalence of a particular disease may have a direct effect on the life expectancy at each age, and also an indirect effect brought about through changes in the prevalence of *other* diseases. As a result, failure to consider the effect of a reduction in the prevalence of a particular disease on the prevalence of other diseases may lead to an incorrect estimate of the benefits arising from the reduction.

Third, if we are interested in the question 'How many potential years of life are lost due to the *existence* of malaria in Mozambique?', then a distinct endogenous life table which deletes

malaria as a risk factor (thereby eliminating deaths from malaria and possibly changing the mortality risks from other diseases) would be the appropriate one to use.[24] This counterfactual is different from that involved in assessing the sum total of life-years lost due to *individuals* dying of malaria. The latter requires retaining malaria as a risk factor in determining the life-years a person would have expected to live if they had not died.

4.2.2 Anomalies in the Use of an Endogenous Life Table

An obvious requirement of any measure of ill-health is that it should be *monotonic* increasing in disease risk, i.e. when risk of disease increases the measure of ill-health increases. Does the DALY, constructed using an endogenous life table, satisfy this basic requirement?

For example, it would be natural to expect that the quantity of ill-health would be greater in a situation in which life expectancies were low, public health measures were few, antibiotics non-existent and infectious diseases ubiquitous than it would in contemporary advanced societies – where life expectancies are relatively high, public health measures numerous, medical experience substantial, and infectious disease prevalence low.

The number of DALYs arising in a particular situation is determined by the number of deaths that take place at each age and the potential life-years assumed to have been lost due to those deaths. When an exogenous life table is used to calculate DALYs, the number of potential life-years assumed to have been lost due to a death at any age is determined by this *fixed* life table, and is therefore not influenced by the mortality risks actually experienced by the population under consideration. In contrast, when an endogenous life table is used to calculate DALYs, the number of potential life-years assumed to have been lost due to a death at any age is determined by the mortality risks actually experienced in the population under consideration.

In the endogenous case there are two different effects of an increase in mortality rates (or risks) on the number of DALYs arising. First, an increase in mortality risks at a given age *increases*

[24] This consideration seems potentially relevant to all the four cases considered in this paper: description or health intervention, using an exogenous or endogenous life table.

the number of deaths occurring among persons of that age and thereby increases the number of DALYs arising due to deaths at that age. Second, an increase in mortality risks *decreases* the age-specific life expectancy of persons at *earlier* ages, and thereby decreases the number of potential life-years assumed to have been lost due to deaths at those earlier ages. The first effect of an increase in mortality risks is to increase the number of DALYs whereas the second effect is to *decrease* the number of DALYs.

Is the net effect of an increase in mortality risks always to increase the number of DALYs, i.e. the 'burden of disease'? Since in the endogenous case an increase in mortality has two distinct effects of *opposite* sign on the number of DALYs, it is not clear that the net effect of an increase in mortality risks will always be to increase the DALY total. Indeed, a number of examples can be found in which the effect of an increase in mortality risks is to *decrease* the number of DALYs.[25] We discuss these examples in what follows. However, regardless of whether the net effect of an increase in mortality risks is to decrease the DALY total, the impact of the second effect identified above is always that an increase in mortality risks *reduces* DALYs arising from deaths due to the same or other causes at earlier ages. Thus there is a component of the DALY, constructed using an endogenous life table, which always responds perversely, even if the net effect turns out to be as expected.

Suppose that the mortality rate increases for a middle age-group in a population. The magnitude of the increase in DALYs arising through the first effect will depend on the number of persons at that age and the size of the increase in the mortality rate. The magnitude of the decrease in DALYs through the second effect will depend on the number of persons dying at each earlier age and on the size of the decrease in age-specific life expectancies at those earlier ages caused by the increase in the mortality rate for the middle age-group. A 'perverse' effect of the DALY total decreasing when a mortality risk increases is thus most likely when the number of persons dying at earlier ages is large, and the reduction in age-specific life expectancies at those earlier

[25] An example of this kind seems to have been recognized by Preston (1993) and is mentioned by Murray (1996, p. 21). However, the relevance of the phenomenon appears in general not to have been adequately appreciated or explored.

ages is also large. It is possible to demonstrate the existence of such effects in empirical cases: see Examples 1 and 2 in the 'Appendix on Non-Monotonicity' in this paper.

Two instances in which perverse results of this kind might arise are of particular interest. The first is that of historical comparisons, e.g. between populations from an earlier century afflicted with disease and populations in contemporary advanced societies. There is no guarantee that the 'burden of disease' would be found to be lower in the more advanced society with lower mortality rates. The second is that of cross-sectional comparisons, such as that between a contemporary poor country and a contemporary rich country with lower mortality rates. There is similarly no guarantee that the 'burden of disease' would be found to be lower in the rich country than in the poor country. The possibility that DALY-based analysis of the 'burden of disease' using an endogenous life table can be *non-monotonic* in mortality risks makes it difficult to see how such analysis can provide a basis for description, evaluation, or resource allocation.

In the 'Appendix on Non-Monotonicity', we present an example involving historical comparisons in which such perverse results arise. In particular, we use data from a very high mortality population beset by infectious diseases, namely that of Liberian immigrant ex-slaves from the United States in the early 19th century, and compare the DALY total in this population with that of USA in 2001. To illustrate possibilities, we use only the respective life tables to calculate DALYs in the two cases, and not the actual age distribution of deaths. In calculating DALYs from a life table alone, we assume a population with an age structure that corresponds to that of the life table.[26] The population of Liberian ex-slaves has age-specific mortality risks which *dominate* those of contemporary societies, in the sense that the mortality risk is higher in *every* age bracket in the former. In the 'Appendix on Non-Monotonicity' we demonstrate that the DALY total arising for this Liberian population is a small fraction of that arising in USA in 2001.

[26] This assumption is in keeping with the calculation of DALYs in the intervention exercise conducted in Tan-Torres Edejer et al. (2003, pp. 55-6). The age structure represented in a life table can arise from having a stationary (zero growth) population which faces static age-specific mortality rates enumerated in the life table.

The underlying reason for the occurrence of the perverse results identified above is that in the endogenous case the 'yardstick' (the disvaluation placed on death at any age) used to estimate the contribution of individual deaths to the DALY total is itself determined by the number of those deaths. Indeed the disvaluation of deaths at earlier ages *decreases* when the number of deaths at later ages *increases*.

4.2.3 Health Intervention with Endogenous Life Table

Is it appropriate to use an endogenous life table to calculate DALYs for the purposes of assessing and comparing the value of health interventions?

One health intervention should be judged superior to another if it improves the health that is experienced by the population of interest. In particular, an intervention should be judged desirable if it helps to increase the number of healthy life-years lived by members of that population – and undesirable if it reduces them. Accordingly, a fall in mortality rates should be deemed desirable and a rise in mortality rates should be deemed undesirable.

Can DALYs calculated using an endogenous life table provide a basis for assessing interventions in this way? From one standpoint, the endogenous approach would seem the appropriate one to employ for assessing interventions, because it uses the *actual* mortality risks experienced by the population – and hence provides an estimate of the life-years that an individual would have expected to live if she had not died. It offers a means of determining the loss experienced due to deaths (DALYs) based on *empirical* information about the population of interest. As such, in contrast to an exogenous life table, it might be thought to offer a suitable basis for the assessment of the expected actual impact of a particular intervention – and thus for the comparison of alternative interventions being considered for implementation in that population.

Yet an endogenous life table may be inappropriate to use for an entirely different reason in the assessment of the impact of an intervention. As noted above, in the case of an endogenous life table, an increase in the mortality rate at a given age leads not only to an increase in deaths at that age but also to a *decrease* in the loss of life-years arising from deaths at earlier ages. These

two effects work in the opposite direction in calculating the DALY total, and can lead to a net decrease in the number of DALYs arising from an increase in mortality. Obversely, they can lead to a net increase in the number of DALYs from a decrease in mortality. This perverse consequence stems, here as elsewhere, from the focus of the DALY on the life-years deemed to be *lost* due to a death rather than on the life-years actually *lived*. It arises directly, as we elaborate below, from this central feature that distinguishes the DALY from other measures of population health.

In the endogenous case, the DALY approach is completely indifferent to changes in life-years lived which do not affect life-years lost. As an illustration, consider a hypothetical intervention which results in the following shift of mortality risks in a life table. Suppose that a life table for a population has age-specific probabilities of dying ${}_1q_x$, where ${}_1q_x$ is the probability of dying in the age interval $[x, x+1)$. Now *translate* this life table by giving everyone an additional 5 years of healthy life at birth. In other words, construct a new life table described by the following probabilities of dying ${}_1Q_x$ in the age interval $[x, x+1)$:

${}_1Q_x = 0$ for $0 \leq x \leq 4$, and ${}_1Q_x = {}_1q_{(x-5)}$ for $x \geq 5$.

In the new life table every individual in the birth cohort will live a full 5 life-years *before* beginning to experience the sequence of age-specific mortality risks described in the old life table. The life expectancy for the population in the new life table will be exactly 5 years more than the life expectancy in the old life table. Yet the total years of life lost from deaths in *both* life tables (total DALYs) will be *exactly* the same when deaths are evaluated endogenously with respect to each life table.[27]

This phenomenon of the constancy of DALYs arising from a horizontal rightwards shift of the age-specific probabilities of death may be described as 'translation invariance'.[28] It is brought

[27] The burden of disease in the new situation would actually be *higher* if the shift is accompanied by a *small* increase in mortality risk in the penultimate age group!

[28] It occurs equally if a horizontal rightwards shift takes place at any age and the mortality rate there is replaced by 0.

about by simply adding healthy life-years at birth for everyone in the cohort. The reason for this invariance is that DALYs measure the aggregate quantity of *ill-health* rather than of *health*.

A metric that values life-years actually lived or expected to be lived – e.g. LE, HALE, or QALYs – will not face this problem. The DALY approach attempts to measure the quantity of ill-health, which in the case of endogenous life tables is *not* the obverse of measuring the quantity of *health*. The two exercises can lead to quite different results, as shown in the historical comparison of USA in 2001 with Liberian immigrants in 1820-43 (Appendix Table 2). Males in USA in 2001 had a higher life expectancy *and* suffered a larger number of DALYs per capita than Liberian male immigrants two centuries ago.

As shown in Example 1 in the 'Appendix on Non-Monotonicity', the non-monotonicity of DALYs can also occur when mortality risks are increased due to a serious disease epidemic (Appendix Table 1). This consequence likewise arises because of the focus of DALYs constructed using an endogenous life table on life-years lost (ill-health) rather than on life-years actually lived or expected to be lived (health). Again, positive measures of health such as LE or QALYs do not suffer from the non-monotonicity problem: they are uniformly monotonic decreasing in mortality risk.

The consequences of such perversities arising from the use of an endogenous life table, especially with regard to health interventions aimed at reducing the disease burden, can be serious. As we have just seen, they can result in a failure to favour interventions which *increase* healthy life-years lived.

It appears that an endogenous life table cannot provide a suitable basis for the comparison of the benefits of alternative possible interventions, because its implications can contravene our fundamental premises as to what constitutes an improvement in health. Surely, an intervention must be judged to be undesirable if it contributes to a rise in mortality risks – and to be desirable if it contributes to a reduction in mortality risks.

5. SUMMARY AND CONCLUSION

There are two main purposes to which a measure of aggregate ill-health can be put – the description or quantification of the disease burden, and the ranking or choice of interventions. The use of the DALY for the purpose of description is based on a difficult-to-justify selection of an exogenous life table, which will affect the magnitude of the disease burden and its attribution to different diseases, countries and populations – including female and male, or young and middle-aged. The use of the DALY for the ranking and choice of interventions can lead to anomalies whether an exogenous or an endogenous life table is employed.

5.1 SENSITIVITY OF THE DISEASE BURDEN TO THE LIFE TABLE CHOSEN

As we have seen in the case of historical comparisons, the use of an endogenous life table can lead to perverse description, because lower (higher) mortality risks can imply a higher (lower) measured disease burden. The use of an exogenous life table avoids this problem, but introduces others. In particular, different exogenous life tables can give rise to different conclusions concerning the relative burden among countries or regions, or attributable to different diseases, injuries and risk factors, or to different populations – female and male, young and elderly. This is because each exogenous life table implies different disvaluation weights on deaths at each age (viz. life expectancy at that age), and can therefore lead to different assessments of the relative significance of these deaths across countries or diseases or populations. The choice of any particular exogenous life table would seem difficult to rationalize uniquely, and each choice carries with it distinct normative and descriptive implications.

5.2 DILEMMAS IN USE OF THE DALY FOR HEALTH POLICY

The use of the DALY to choose interventions can be problematic because, regardless of whether an exogenous or endogenous life table is used to estimate life-years lost due to a death, it can lead to anomalous recommendations.

When an exogenous life table is used for this purpose, the number of life-years lost due to a death is estimated on the basis of the mortality risks in the exogenous life table rather than those that *actually* prevail in the population in question. Thus, an exogenous life table yields a *biased* estimate of the number of additional life-years that are expected to be lived as a result of a health intervention. The use of an exogenous life table fails to capture the expected *actual* consequences of an intervention and is therefore of limited relevance for policy.

On the other hand, when an endogenous life table is used for this purpose, reducing (increasing) the risk of disease can imply a larger (smaller) total of life-years lost (as shown in the case of a decrease in DALYs from an increase in adult mortality). The existence of this effect can give rise to perverse policy recommendations.

Thus both possibilities for defining the DALY – through an exogenous or an endogenous life table – can be problematic for the guidance of interventions.

Our conclusions concerning the use of the DALY to describe the disease burden and to choose interventions are summarized in Table 1 below.

Table 1. Dilemmas in the Use of the DALY

	LIFE TABLE USED TO ESTIMATE LIFE-YEARS LOST (DALYs)	
	Exogenous	**Endogenous**
DOMAIN OF APPLICATION		
Description/quantification of disease burden	**Burden and ranking of diseases across and within countries and populations is sensitive to choice of life table**	**Perverse description possible: lower disease risk can result in higher disease burden (DALYs)**
Choice of interventions	**Fails to predict expected *actual* consequences within a country or a population, and hence is of no relevance for policy**	**Perverse policy recommendations possible: reducing the risk of disease can result in more life-years lost (DALYs)**

5.3 THE USE OF DIFFERENT LIFE TABLES FOR DIFFERENT PURPOSES?

Tan-Torres Edejer et al. (2003, pp. 113-4) propose that the global burden of disease be measured using an exogenous life table (with life expectancy at birth for females of 82.5 years, close to that observed for Japanese females). They add that "this is not the approach used to measure DALYs averted by interventions which requires a different calculus. Details are found in Section 4." (Ibid., p. 114). Their Section 4 (Ibid., pp. 55-6) recommends using what we call an endogenous life table to evaluate a malaria intervention (we use the same life table in Example 1 in the Appendix to evaluate our 'intervention'). But this proposal to use different life tables for different purposes cannot offer a solution to the dilemmas in the use of the DALY. There are two reasons why it cannot do so.

First, as argued above, the use of the DALY to choose health interventions can lead to anomalies, whichever life table is employed to define life-years lost and DALYs.

Secondly, using a different construction for the DALY in choosing interventions from that used in health assessment can lead to a different relative ranking of health states in the two instances – and such a discrepancy is not readily acceptable. We may be forced to conclude that health state A is superior to health state B from the standpoint of aggregate health (comparing DALY totals) but that an intervention that brings about health state B is preferred to one that brings about health state A (assuming the two interventions cost the same). However, such a perspective does not seem coherent. If there is a convincing reason to conclude that health state A is superior to health state B from the standpoint of aggregate health, then that must be a reason to intervene to bring about health state A rather than health state B. The possibility of such inconsistency renders untenable the proposal that two different versions of the DALY be used for the two different purposes.

5.4 CONCLUDING COMMENTS

The proponents of the DALY employ the metric for two separate purposes: description of ill-health and choice of interventions. As discussed in this paper, the definition of the DALY must be based on a counterfactual. The counterfactual consists of the life table to be used in estimating the life-years lost from premature mortality. This life table can be either exogenous or endogenous to the population whose ill-health is being assessed.

The use of an exogenous life table for description of ill-health is problematic because the extent of the disease burden and its attribution among diseases, countries and populations depend on the particular exogenous life table chosen. Thus the GBD 2010 and later GBD exogenous life tables understate the burden of disease for women relative to that for men compared to exogenous (or endogenous) life tables which reflect the higher life expectancy observed for women than for men, including for example the GBD 1990 exogenous life table. The use of an endogenous life table for description of ill-health is inappropriate because it can lead to perverse description – viz. lower mortality risks can imply a *higher* measured disease burden.

The use of an exogenous life table to choose interventions is problematic because it fails to reflect the actual expected health effects of an intervention, and can therefore lead to inappropriate recommendations. The use of an endogenous life table to choose interventions is problematic because it can lead to perverse prescription – viz. a decrease in mortality risks can result in an increase in the DALY total.

In this paper we have attempted to explore the implications and anomalies that can arise in the use of the DALY for different purposes – including the identification of the disease burden for women relative to that for men, and that for children relative to adults. It is unclear how the dilemmas we have noted in the application of the DALY can be resolved.

APPENDIX ON NON-MONOTONICITY

Consider two vectors of age-specific mortality risks $\langle {}_nq_x^i \rangle$, i = 1, 2, that refer to life tables 1 and 2, where ${}_nq_x$ is the probability of dying in the age interval [x, x+n). We will say that the vector $\langle {}_nq_x^2 \rangle$ *dominates* the vector $\langle {}_nq_x^1 \rangle$, written $\langle {}_nq_x^2 \rangle > \langle {}_nq_x^1 \rangle$, when each age-specific mortality risk in life table 2 is greater than or equal to that in life table 1 and at least one age-specific mortality risk in life table 2 is strictly greater than that in life table 1. Plainly, when one vector of age-specific mortality risks dominates another it describes a population with worse health.

A measure of the ill-health of a population, Δ, can be defined as a real-valued function of the mortality risks prevailing in that population, i.e. $\Delta = f(\langle {}_nq_x \rangle)$. A minimal requirement of such a measure is that ill-health should be greater for a vector of mortality risks that dominates another, i.e. if $\langle {}_nq_x^2 \rangle > \langle {}_nq_x^1 \rangle$ then $f(\langle {}_nq_x^2 \rangle) > f(\langle {}_nq_x^1 \rangle)$. We refer to this property as *monotonicity* of Δ with respect to mortality risks.

Abstracting from morbidity, DALYs are a function of the mortality risks prevailing in a population and are a measure of ill-health, Δ, as defined above. Through the following two examples we demonstrate that DALYs can fail to satisfy the minimal requirement of monotonicity.

Example 1: Change in DALYs from Increases in Adult Mortality

We adopt the life table used by Tan-Torres Edejer et al. (2003, Table 4.1, p. 56) to evaluate the effect of an intervention (in their case insecticide-treated nets for malaria) which reduces mortality (in their case infant mortality, by 50%). This life table is shown on the left-hand side of our Appendix Table 1. Tan-Torres Edejer et al. (2003, p. 55) ask us to "[I]magine that this intervention is applied to the population represented in Table 4.1". The authors state that "[I]t is commonly assumed that preventing a neonatal death (at age 0) gains years of life equal to the life expectancy at that age (74.68 years)" and that "[T]his is a good approximation as long as the changes caused by the intervention do not change age-specific and overall life expectancies substantially" (Ibid., p. 55). Here the authors are describing an approach in which the life table

used to assess life-years lost remains fixed. They go on to say that "[A] 50% reduction in infant mortality does, however, substantially change life expectancy at birth" and that, hence, "[T]his is not correct" (Ibid., p. 55). Instead, they recommend that to assess the life-years gained from the intervention, the life table "without intervention" should be compared to the life table "with intervention" (Ibid., p. 56). In our terminology, this recommendation is tantamount to the use of a life table that is *endogenous* to the intervention being evaluated.

For this purpose they present these two life tables side-by-side in Table 4.1, which show "the life expectancies without and with the intervention" (Ibid., p. 56). Using this approach the authors state that "the total number of life-years saved" (Ibid. p. 55) – i.e. DALYs averted – is larger than the number estimated using the fixed pre-intervention life table.

We will use the *same* pre-intervention life table and a different 'intervention' to demonstrate that the approach favoured by Tan-Torres Edejer et al. (2003) can lead to non-monotonicity. In particular, the intervention that we will examine is an increase in the probability of dying for persons in *five* middle age-groups (20 to 24, 25 to 29, 30 to 34, 35 to 39, and 40 to 44) to a common high level of 0.5. Such an intervention can be thought of as a large increase in the risk of mortality arising from the emergence of a serious disease such as AIDS, which disproportionately affects certain middle age-groups. As noted above, Tan Torres Edejer et al. have argued that when age-specific and overall life expectancies change "substantially", the correct approach to use for measuring the change in life years lost (i.e. "DALYs averted", Ibid., p. 114) does not involve the use of a fixed life table. Our 'intervention' does indeed involve such substantial changes in age-specific and overall life expectancies.

In Appendix Table 1 we present the pre- and post-adult mortality change life tables with the years of life lost (DALYs) arising from deaths at each age and in total.

It can be seen that DALYs are actually "averted" by the huge increase in mortality. In other words, the number of life-years lost is *lower* when disease risk is much *higher*. This is an instance of non-monotonicity.

Example 2: Historical Comparison of DALYs

It is possible to identify instances of non-monotonicity involving actual historical life tables. We present here one such instance, involving comparison between a life table for the United States in 2001 and one for a very high mortality historical population (immigrants to Liberia from the United States in the period 1820-1843). The mortality risks for the 19th century immigrants to Liberia are higher than for the United States in 2001 (indeed massively so) in every age interval, as can be seen in our Appendix Table 2.

We draw our data for 19th century immigrants to Liberia from McDaniel (1995) who carefully reconstructs the mortality experience of this population from relatively high-quality historical records of the American Colonization Society. McDaniel (1995, p. xix) notes that the "colonization of Liberia resulted in extreme mortality for the immigrant population" as a result of their unfamiliarity with the disease environment in the country to which they moved. The mortality risks at each age appear to have been higher for Liberian immigrants than for the corresponding slave populations in the United States, Trinidad and Jamaica (as documented in McDaniel 1995, chapter 6). Indeed, "[T]he life tables created for the African American immigrants to Liberia appear to embody the highest mortality ever reliably recorded" although "the shape of the mortality corresponds with that for other known human populations" (Ibid., p. 104).

It is easy to check that if the number of life-years lost due to deaths in a given population is determined by reference to the life table of that *same* population – i.e. by using an endogenous life table – then the number of life-years lost (DALYs) is *lower* for the life table corresponding to 19th century immigrants to Liberia than for the life table corresponding to the United States in 2001. In Appendix Table 2 we present the life tables for the United States in 2001 and for 19th century immigrants to Liberia along with the years of life lost (DALYs) arising from deaths at each age and in total.

It is seen that the number of DALYs arising in the life table corresponding to the United States in 2001 is 4.6 times higher than the number of DALYs arising in the life table corresponding to 19th century immigrants to Liberia.[29]

The underlying reason for this marked non-monotonicity is that the age-specific life expectancies at the death of a person in Liberia are very low, due to the high mortality risks in the population at ages subsequent to the death (Appendix Table 2). Accordingly, the disvaluation weights placed on individual deaths (the life-years lost due to a death) are small, causing the number of DALYs to be small.

Note

In the examples above, we have used age-specific population numbers corresponding to a life table birth cohort of 100,000. The possibility of non-monotonicity is not contingent on these particular population numbers, and could arise with actual populations of given age structures. As stated in Tan-Torres Edejer et al. (2003, p. 55), we are simply imagining "that this intervention is applied to the population represented in [the life table shown in] Table 4.1".

[29] Our estimates of life expectancy at each age are extremely close (but not identical) to those reported by McDaniel (1995) because of minor differences in assumptions concerning the average age at death within each age interval.

Appendix Table 1. Life table without and with the mortality change

Without mortality change						With mortality change				
Age Interval (years)	Population	Deaths	Probability of dying within age interval	Life expectancy	DALYs	Population	Deaths	Probability of dying within age interval	Life expectancy	DALYs
$[x, x+n)$	(l_x)	$({}_nd_x)$	$({}_nq_x)$	(e_x)		(l_x)	$({}_nd_x)$	$({}_nq_x)$	(e_x)	
0 to 1	100,000	1,254	0.01254	74.68	93,653	100,000	1,254	0.01254	27.84	34,910
1 to 4	98,746	140	0.00142	74.63	10,448	98,746	140	0.00142	27.19	3,806
5 to 9	98,606	46	0.00047	70.73	3,254	98,606	46	0.00047	23.22	1,068
10 to 14	98,560	82	0.00083	65.76	5,393	98,560	82	0.00083	18.23	1,495
15 to 19	98,478	223	0.00226	60.82	13,562	98,478	223	0.00226	13.25	2,954
20 to 24	98,255	296	0.00301	55.95	16,561	98,255	49,128	0.50000	8.27	406,353
25 to 29	97,959	422	0.00431	51.11	21,568	49,128	24,564	0.50000	9.04	221,959
30 to 34	97,537	448	0.00459	46.32	20,751	24,564	12,282	0.50000	10.57	129,787
35 to 39	97,089	522	0.00538	41.52	21,674	12,282	6,141	0.50000	13.63	83,702
40 to 44	96,567	774	0.00802	36.73	28,431	6,141	3,070	0.50000	19.76	60,662
45 to 49	95,793	1,248	0.01303	32.01	39,947	3,070	40	0.01303	32.01	1,280
50 to 54	94,545	1,809	0.01913	27.40	49,564	3,030	58	0.01913	27.40	1,589
55 to 59	92,736	3,423	0.03691	22.88	78,333	2,972	110	0.03691	22.88	2,511
60 to 64	89,313	5,154	0.05771	18.67	96,202	2,863	165	0.05771	18.67	3,084
65 to 69	84,159	8,655	0.10284	14.66	126,842	2,698	277	0.10284	14.66	4,066
70 to 74	75,504	12,806	0.16961	11.05	141,489	2,420	410	0.16961	11.05	4,535
75 to 79	62,698	16,213	0.25859	7.79	126,374	2,010	520	0.25859	7.79	4,051
80 to 84	46,485	18,957	0.40781	4.64	87,982	1,490	608	0.40781	4.64	2,820
85+	27,528	27,528	1.00000	1.12	30,705	882	882	1.00000	1.12	984
				TOTAL DALYs	**1,012,734**				**TOTAL DALYs**	**971,615**

Source: Tan-Torres Edejer et al. (2003, Table 4.1, p. 56) and authors' calculations.

Appendix Table 2. Life Tables for USA 2001 and Liberia 1820-43

USA 2001 (MALE)						LIBERIAN IMMIGRANTS, 1820-43 (MALE)				
Age Interval (years)	Population	Deaths	Probability of dying within age interval	Life expectancy	DALYs	Population	Deaths	Probability of dying within age interval	Life expectancy	DALYs
$[x, x+n)$	(l_x)	$({}_nd_x)$	$({}_nq_x)$	(e_x)		(l_x)	$({}_nd_x)$	$({}_nq_x)$	(e_x)	
0 to 1	100,000	754	0.00754	74.42	56,113	100,000	77,900	0.77900	1.73	134,905
1 to 4	99,246	136	0.00137	73.98	10,059	22,100	16,518	0.74740	5.78	95,411
5 to 9	99,110	87	0.00088	70.08	6,112	5,582	2,368	0.42420	12.95	30,667
10 to 14	99,023	118	0.00119	65.14	7,676	3,214	803	0.24980	15.65	12,565
15 to 19	98,905	452	0.00457	60.22	27,217	2,411	536	0.22240	15.03	8,059
20 to 24	98,453	676	0.00687	55.48	37,526	1,875	540	0.28820	13.61	7,355
25 to 29	97,777	682	0.00697	50.85	34,653	1,335	379	0.28420	13.11	4,972
30 to 34	97,095	756	0.00779	46.19	34,934	955	281	0.29360	12.32	3,455
35 to 39	96,339	994	0.01032	41.53	41,290	675	196	0.29080	11.40	2,237
40 to 44	95,345	1,405	0.01474	36.94	51,910	479	149	0.31060	10.04	1,493
45 to 49	93,939	2,096	0.02231	32.45	68,012	330	116	0.35170	8.44	979
50 to 54	91,843	2,912	0.03171	28.14	81,940	214	100	0.46840	6.66	667
55 to 59	88,931	4,286	0.04820	23.97	102,767	114	71	0.62800	5.32	380
60 to 64	84,645	6,269	0.07406	20.06	125,764	42	27	0.63960	5.08	137
65 to 69	78,376	8,734	0.11144	16.47	143,823	15	9	0.57140	4.64	40
70 to 74	69,642	11,643	0.16719	13.22	153,904	7	7	1.00000	2.50	16
75 to 79	57,998	14,034	0.24198	10.37	145,534	0	0	1.00000	0.00	0
80 to 84	43,964	15,893	0.36150	7.88	125,266	0	0	1.00000	0.00	0
85 to 89	28,071	14,475	0.51567	5.93	85,820	0	0	1.00000	0.00	0
90 to 94	13,596	8,883	0.65341	4.58	40,681	0	0	1.00000	0.00	0
95 to 99	4,712	3,591	0.76203	3.50	12,566	0	0	1.00000	0.00	0
100+	1,121	1,121	1.00000	1.70	1,906	0	0	1.00000	0.00	0
				TOTAL DALYs	**1,395,471**				**TOTAL DALYs**	**303,339**

Sources: 1. WHO Statistical Information System (WHOSIS), Life Tables for 191 Countries, World Mortality in 2001.
2. McDaniel (1995, p. 78). 3. Authors' calculations.

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