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The evolution of the disability-adjusted life year (DALY)

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ABSTRACT

The disability-adjusted life year (DALY) is a summary health measure that combines mortality and morbidity into a single measure as a way to estimate global disease burden and the effectiveness of health interventions. We review the methodological progression of the DALY, focusing on how the use of life expectancy estimates, disability weights, age weighting, and discounting has evolved since the first DALY reports were published in 1993. These changes have generally improved the metric but have made it difficult for researchers to interpret, compare, and conduct DALY studies.

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1. Introduction

The disability-adjusted life year (DALY) made waves in the international development community when it was introduced in the 1993 *World Development Report* [1]. Previous estimates of global burden of disease generally focused on mortality rates, both because reducing fatalities was a top public health priority and because deaths are easy to count [2]. However, mortality data alone are not sufficient for painting a picture of the state of health in a community, nation, or region. As mortality rates began to level off in industrialized nations toward the late twentieth century, researchers from a variety of disciplinary perspectives created new health metrics that incorporated physical and psychological morbidity and disability in addition to mortality, including the quality-adjusted life year (QALY) [3] and the healthy year equivalent (HYE) [4]. The DALY, which estimates the gap between a population's health status and an "ideal" level of health and survival, emerged as a commonly used tool. Economists, epidemiologists, and policy experts, especially those who work on health issues in low- and middle-income countries, frequently use the DALY for population health assessments, priority setting, and program evaluation. By contrast, decision scientists, health economists, and policymakers in high-income countries more frequently use the QALY metric.

The conceptual framework for the DALY uses the term "disability" to refer to any acute or chronic illness that reduces physical or mental health status in the short-term or the long-term. "Disabilities" in DALY models include conditions such as quadriplegia, total blindness, and developmental disorders as well as infectious and parasitic diseases, nutritional deficiencies, maternal and perinatal conditions, a diversity of non-communicable and neuropsychiatric conditions, and injuries. DALYs aim to quantify at the population level the total years of life lost to premature death and the years of life lived with suboptimal health due to any condition that reduces functioning partially or fully for a short period of time or a long duration.

While the underlying conceptual model for the DALY remains unchanged, the DALY has been under continuous revision since it was first developed by World Health Organization and World Bank collaborators in 1993 [1]. Major changes to DALY estimation methods were made for the Global Burden of Disease (GBD) estimates for 1990 [5–9] and 2010 [10–16]. In the intervening years, updated GBD estimates were published annually from 1999 to 2004, [17–27] and several major regional European studies were published in the 2000s [28–31]. DALY methods have also been used for cost-effectiveness analysis in low- and middle-income countries

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[32–35]. DALYs represented a major step forward for population health metrics [36]. However, as researchers have tweaked the equations used for estimating the DALY and have challenged some of the assumptions underlying these calculations, comparing DALY estimates across time has become difficult.

All versions of the DALY quantify the burden of disease by combining mortality and morbidity in a single metric. The basic equation for the DALY is the sum of a population's years of the life lost (YLL) to premature death and the years lived with disability (YLD):

$$DALY = YLL + YLD$$

The most basic equation for the YLLs lost in a population during a particular time period, such as one year, is:

$$YLL = N \times L$$

where N is the number of deaths in the population and L is the population's average remaining life expectancy, in years, at the age of death. The basic equation for YLDs in a population is:

$$YLD = (I \times L) \times W = P \times W$$

where I is the number of incident cases of a particular condition in the population, L is the average length (duration) of disability from a particular condition, P is the prevalence of the condition, and W is the disability weight associated with the condition.

However, neither YLLs nor YLDs can be directly measured. The YLL is dependent on the researcher's selection of the total years a member of the population is, on average, "expected" to live. The YLD depends on how disability weights are assigned for various health conditions or consequences. Additionally, some DALY models apply discounting and age weighting functions that generally apportion higher YLL and YLD values to current health problems and those that affect the young, and assign lower values to future health concerns and ones that primarily affect older adults. Thus, the number of DALYs estimated for a population may be vastly different depending on the assumptions made. Two research groups working with the same population data about births, deaths, incidence, and prevalence could arrive at very different sets of DALY estimates.

Most DALY estimates are derived from complex mathematical models that account for age distributions, population dynamics such as birth and age-specific death rates, and even socioeconomic strata. These more computationally intense approaches require more cumbersome equations. A discounted, age-weighted YLL can be calculated within a model by an equation such as this one [5]:

$$YLL = \frac{KCe^{ra}}{(r+\beta)^2}\left\{e^{-(r+\beta)(L+a)}[-(r+\beta)(L+a)-1] - e^{-(r+\beta)a}[-(r+\beta)a-1]\right\} + \frac{1-K}{r}\left(1-e^{-rL}\right)$$

where K is an age weighting value, C is a constant that ensures that the total number of DALYs worldwide remains the same with and without age weighting, a is the age at death, r is the discount rate, β is a constant that adjusts the shape of the age weighting curve, and L is the standard expectation of remaining years of life at the time of death at age a. The expanded equation for YLD is similarly unwieldy [5].

These models require assumptions about life expectancy, disability weights for numerous causes of reduced health status, discount rates, and age weighting. Each of these assumptions requires careful consideration when attempting to estimate the DALYs in a population or interpreting reports of DALYs. This paper summarizes the evolution of the DALY, focusing on how the use of these four particular components has changed over time. Knowledge of the history of the DALY is a necessary foundation for calculating, interpreting, and comparing DALY estimates.

2. Life expectancy

Life expectancy in the DALY context is sometimes an "aspirational" target population value rather than one based solely on current metrics in the population being studied [5]. The WHO *Guide to Cost-Effectiveness Analysis*, published in 2003, outlined four different measures that could be used to estimate life expectancy for DALYs [37]. The simplest is a potential years of life lost (PYLL) approach in which a target population life expectancy is selected and used for all age groups. For example, the target life expectancy could be set at 80 years of age. A man who dies at age 75 will be considered to have died 5 years prematurely, and will contribute 5 YLLs to the population's total count of YLLs. A child who dies at age 5 will contribute 75 YLLs to the population total. Together these two individuals will account for 80 YLLs. A woman who dies at age 85 will contribute 0 YLLs to the population, because she will be considered to have exceeded her life expectancy. There are two major limitations to a PYLL approach. One is that interventions that extend years of healthy life for those over the target age have no effect on reducing the population DALYs. This may not align with the values and health priorities of communities, especially in aging populations in which older adults bear nearly the entire burden of disease. The other is that the selection of the target age group can seem somewhat arbitrary but can have a major impact on the total DALYs in a population. If the targeted life expectancy is raised from 80 years to 85 years, a substantial number of DALYs would be added to the population's total.

Variations on the PYLL include period expected YLLs (PEYLLs), cohort expected YLLs (CEYLLs), and standard expected YLLs (SEYLL) [37]. All of these approaches use conditional life expectancies rather than life expectancies at birth. For PEYLLs and CEYLLs, current conditional life expectancies in the population for which DALYs are being estimated are determined for each age group. If an 80-year-old woman can expect to live to age 85 in that population, her death at age 80 would contribute 5 YLLs to the population total, even if the overall life expectancy in the population is only 80 years. Both PEYLLs and CEYLLs therefore provide more nuanced measures of the DALYs contributed by older adults than are possible with the PYLL approach.

The main difference between PEYLLs and CEYLLs is that the PEYLL approach assumes that age-specific life expectancies remain constant over time while the CEYLL approach assumes that life expectancies in places that currently have low life expectancies will increase over time. Under the PEYLL approach, the death of a 40-year-old woman in a low-income, high-mortality country with a conditional life expectancy of 20 additional years (until age 60) will contribute far fewer DALYs to her population's total DALYs than the death of a 40-year-old woman from a high-income, low-mortality country with a conditional life expectancy of 40 additional years (until age 80). A CEYLL approach would reduce that 20-year DALY gap between low-income and high-income countries by assuming that the low-income country will improve live expectancies for the 40-year-old's birth cohort as they age. The PEYLL approach is appropriate for studies that examine short-term effects and for some studies in high-income regions [5], but the CEYLL approach is generally a better estimator when mortality rates are changing over time or when comparative studies include populations from low-income regions [5].

Rather than using local data, the SEYLL approach uses a global life expectancy curve based on the world's longest observed life

expectancies. The SEYLL approach has been used by most global burden of disease studies because it allows for more direct comparisons of model results across regions and countries [5,37]. The GBD results published in the 1993 *World Development Report* and 1990 GBD assumed an 82.5 year life expectancy at birth for women, based on the rates in Japan at the time, and an 80 year life expectancy for men [1,5]. These standards are not fixed in time and do not represent an "ideal" life expectancy. The 2010 GBD models were updated to use a global standard based on the lowest observed death rate for each age group in countries around the world [38]. The life expectancy for this new reference life table is 86 years at birth for both males and females [15]. The reference volume *National Burden of Disease Studies: A Practical Guide*, published in 2001 by the same team leading the GBD project also recommended that regional studies use SEYLLs to facilitate the comparability of results [39]. However, the Dutch Public Health Status and Forecast Study, the first major national study to apply DALY methods, used age-specific life expectancies based on Dutch life tables from 1994 [28].

3. Disability weights

Disability weighting assigns a value between 0 and 1 that approximates the decrease in health and function associated with various illnesses and impairments. A weight of 0 indicates no disability; a weight of 1 indicates full disability equivalent to death [1]. In this context, "disability" refers to any state of diminished health, whether due to an acute or chronic infection, noncommunicable disease, neuropsychiatric condition, injury, physical impairment, or any other cause [39].

Disability weights (D) are used to calculate the YLD component of the DALY. A disability weight of 0.920 ($D = 0.92$)—one that would add 0.92 YLDs to a population for each year lived with the condition—does not mean that a person is "92% dead" or "8% of a person." A health condition with $D = 0.92$ is one that the general public considers to be less preferable than a health condition with $D < 0.92$. If it would cost the same to restore to full health a person with a health condition of $D = 0.92$ or a person with a health condition of $D = 0.09$, the condition with the higher disability weight—the one with $D = 0.92$—would be the higher priority for intervention. The numeric value of the disability weight indicates that a typical member of the population would rank 12.5 years (1/(1−0.92) years) with a health condition of $D = 0.92$ followed by death as being of roughly equal preference to living only 1 year in perfect health and then dying [37,39].

The 1993 *World Development Report* used six severity classes to assign weights ranging from 0.096 for Class 1 disabilities that cause a decrease in ability related to education, occupation, recreation, and/or procreation to 0.920 for Class 6 disabilities that interfere with ability to independently complete activities of daily living (ADLs) such as eating and hygiene [3]. Individual disabilities had to be assigned to one of these six categories. The 1990 GBD assigned weights to 22 indicator conditions that served as the basis for assigning weights to other health states [5]. The Dutch Public Health Status and Forecast Study published in 1994 introduced different weights for mild, moderate, and severe cases of particular conditions [29]. The 2010 GBD determined weights for 220 unique health states, allowing some diseases and disabilities to have different disability weights for mild, moderate, and severe presentations of the condition [10]. Having disability weights for a wider diversity of conditions and severity levels is an improvement, but the availability of lengthy lists of disability weights that appear to be very precise based on the use of numbers reported to several decimal places has led to some confusion about how these weights are assigned, applied, and interpreted.

A variety of approaches for assigning values to health states have been used in DALY studies, including the visual analogue scale (VAS), standard gamble, time trade-off, and person trade-off (PTO) methods [5,17,39,40]. VAS asks respondents to place a mark on a line with endpoints of death and perfect health that represents their value of the time spent in each of several health states [39]. The standard gamble method asks respondents to choose between living a certain amount of time with a particular type of reduced health or living the same amount of time with perfect health but having some risk of dying during those years [39]. The time trade-off (TTO) method asks respondents to choose between living a certain time in perfect health or living a longer time in a state of lesser health [39]. The person trade-off (PTO) method compares the utility of different groups of individuals so that decisions about the rankings of disability weights can be made [39,41].

The GBD 1990 studies (published in 1996–1997) used two PTO exercises to establish disability weights [5]. First, panelists decided, in a theoretical exercise, between extending the lives of healthy individuals or, instead, saving the lives of individuals living with a given condition. Second, panelists decided between extending the lives of healthy people or raising the quality of life for those with a particular disability, not just extending those lives [36]. Critics have posited that these exercises force panelists to express discriminatory attitudes toward people living with disabilities by counting them as less valuable to society than healthy people [42].

Early DALY studies relied solely on medical experts as sources of PTO ratings [3,5,40], but there has been a movement toward basing disability weights on population-based surveys. The argument for using this approach is that in a democratic society the views of the general public are most applicable in comparative appraisal and societal decision making [43]. In the early 2000s, the GBD method began to include the use of population-based surveys in a diversity of countries rather than relying on expert panelists [17,44]. These surveys used a multiple-methods approach that combined a number of health state valuation techniques [17,45]. Survey participants from the general population used VAS to value health states [17]. Respondents with higher education backgrounds took a more detailed survey that incorporated PTO, standard gamble, and TTO methods [17,44]. Statistical methods were used to examine the relationship between the results from each technique and to determine the underlying health state severity [17]. Although these types of surveys began in the early 2000s [17,44], disability weights based on population surveys were not utilized for global DALY estimates until GBD 2010 [10].

As part of GBD 2010, population-based household surveys were conducted in each world region [10]. These surveys used paired comparison questions that asked participants to indicate which of two health scenarios represented a greater level of overall health [10]. The focus was on "health loss" rather than "welfare loss". "Health loss" focuses on the changes in wellbeing due to physical and mental health while "welfare loss" is a broader concept that includes additional factors, including social considerations that alter wellbeing [10]. The strength of preference for one health state over another across survey participants was used to adjust disability weights for those conditions [10]. Data were collected from both household and open-access web-based surveys [10]. The web-based survey was available to anyone visiting the GBD site, even though GBD leaders have long cautioned about allowing advocacy groups to influence the process of weighting various disabilities [15,39]. The vast majority of the internet survey participants were from high-income countries, but the household surveys included data collection in Bangladesh, Indonesia, Peru, and Tanzania, among other sites [10].

From the time the early DALY estimates were released, concerns have been raised about whether disability weights can be

considered universal [46–48]. Critics have questioned whether health status can be removed from a social context and a resource environment [49,50]. The decrease in quality of life associated with blindness or paraplegia or other impairments might be quite different in a rural community in a low-income country and in an urban area of a high-income country where assistive technologies and public transportation are readily available. Some critics have challenged disability weights for being too Western to be universal [47,48]; others have deemed them too universal to be accurate in Western Europe [29]. Studies of the disability rankings resulting from population-based studies in different countries show generally consistent ratings across diverse countries [10,46,51–53], but that does not prove universality. The *National Burden of Disease Studies*: *A Practical Guide* took a moderate position of suggesting that either international standard disability weights could be used for national-level studies or local weights could be determined [39]. The WHO *Guide to Cost-Effectiveness Analysis* similarly recommended that independent groups use weights from the GBD or develop their own regional values [37].

A remaining challenge for disability weighting is adjusting for comorbidities and co-disabilities. No individual should contribute more than 1 year of disability to any model. When one person has an impairment with a disability weight of 0.8 and another with a disability weight of 0.5, then summing these weights to 1.3 would violate the rule that no individual should contribute more than 1.0 years to the model annually. Since most mathematical models used to estimate DALYs are not individual events history models, there is no simple way to account for overlapping disabilities. One way to adjust for this is for researchers to decide ahead of time how to apportion the YLDs and YLLs resulting from common comorbidities. For example, research teams can agree to assign a fraction of YLLs attributable to HIV and tuberculosis co-infection to the HIV category of the model with the remaining YLLs to the tuberculosis category. Similarly, a set fraction of YLDs resulting from hepatocellular carcinoma can be assigned to the hepatitis C virus that is a frequent cause of liver cancer. These decisions should be carefully documented and disseminated with the model results.

4. Discounting

Discounting is an economic concept that assigns greater value to near-term benefits than ones that might accrue in the future. With discounting, an intervention that prevents 1000 cases of cancer this year will remove more DALYs from a population's total count of DALYs than an intervention expected to prevent 1000 cases of cancer from occurring 50 years from now. Discounting provides an incentive for policymakers and practitioners to focus on health interventions that can be implemented right away for immediate benefit. In the equations used to estimate DALYs, discounting assigns greater value to YLL reductions in the present than to years of life gained in future years.

The developers of the 1993 report selected a 3% discount rate that was based on the rates of return on long-term investments and the values used in cost-effectiveness analyses [3]. The report's authors suggested that discounting was important for providing a justification for investing in health projects now rather than postponing them until costs might be lower in the future while, at the same time, removing a bias in the model that rewarded heavy investment in disease eradication plans that would have the most significant gains for future YLLs even at the expense of ignoring all other current health needs [3]. Others have raised concerns about considering future health congruent to future money, arguing that discounting the DALY would benefit lives now at the expense of future lives [54].

DALY guidelines and GBD studies from the 1990s and early 2000s generally recommended using a 3% discount rate and also presenting the results that would occur with a 0% discount rate and with a 6% rate [36,37,39]. However, some European studies, such as the Dutch Public Health Status and Forecast Study and the European Disabilities Weight Project, opted not to use discounting because of the controversies associated with it [28,30]. The GBD 2010 update simplified the model by removing discounting from the equations [15].

5. Age weighting

Age weighting may be used to increase or decrease the DALYs contributed by various age groups within a population if some age groups are deemed more “valuable” than others. When younger adults are expected to be significantly more economically productive than older adults, a disability in a younger adult can be considered more burdensome to a population than the exact same disability in an older adult. In 2006, Sassi identified age weighting as an important component that makes the DALY unique to other summary measures [55]. Critics of age weighting have asked why only age is used to assign social value, and not also occupation and other socioeconomic characteristics [54]. Also, YLLs already favor the young, so age weighting the DALY only further emphasizes interventions for younger people [56].

The age weighting curve for 1993 *World Development Report* assumed that productivity peaked at age 25, valuing a 30-year-old with a weight of about 1.4 and a 70-year-old with a weight of about 0.7 [1]. When age weighting is applied, the YLDs per year assigned to a disabled 30-year-old are nearly twice those attributed to a 70-year-old with the same condition. Similar age weighting curves were used for most GBD studies in the 1990s and early 2000s [5,17].

As the debate over age weighting continued [57], the 2000 GBD results were published with and without age weighting. The major European studies from the early 2000s elected not to use age weighting [28,30], even though age weighting with regionally-derived weighting curves was recommended in the *National Burden of Disease Studies*: *A Practical Guide* [39]. The 2010 GBD [15] also omitted age weighting from DALY models. These alternative models assume a uniform distribution that values each age group equally.

6. Conclusions

Over the last two decades, the DALY has evolved from being a rough estimator of population health to a sophisticated summary measure of the local, regional, and global burden of disease. Life expectancy, which was based on the highest observed life expectancy in 1993, has been updated to be based on the lowest globally observed death rate at every age group. Disability weights set by panels of health experts have been replaced with rankings from large-scale population-based surveys from diverse world regions. Discounting and age weighting, which were difficult to calculate and sometimes difficult to justify, have been removed in the most recent GBD studies. Thus, many of the initial concerns about DALYs have been addressed [42–49,54,56].

One limitation of the DALY is that the method is so complicated and the models require so many inputs about population-specific age structures, life expectancies, incidence, prevalence, and other metrics that it is difficult for local research groups to apply DALY methods to their populations. The changes to the DALY over the years have decidedly not made the metric significantly less cumbersome to use, even with the removal of discounting and age weighting from some models.

The Global Burden of Disease collaborative, now led by the Institute for Health Metrics and Evaluation (IHME), has made impressive efforts to develop regional and country-level burden of disease estimates that are based on global models, systematic literature reviews, population-based surveys, and expert opinions. These studies have been extremely useful for estimating the burden of morbidity, mortality, and disability in the world and highlighting emerging health trends that require public policy considerations. However, the changes made over time to the definitions and equations used for DALY estimation mean that even relatively recent guidebooks and technical reports may be somewhat obsolete and not allow for direct comparison with the newest global estimates. Researchers aiming to create national or subnational DALY estimates and those who use the DALY for decision making would benefit from having access, in one place, to a complete set of information about the assumptions underlying current and past methods and the equations used to operationalize these assumptions.

Another challenge is that so many different versions of the DALY have been created that it might be more accurate to refer to "DALYs" in the plural. The DALY was created with the hope that the metric would be comparable across time and place. The many changes to DALY methodology since it was created—the various approaches for determining life expectancy, the evolving list of validated disability weights, and the use or non-use of discounting and age weighting—make comparisons of studies from the 1990s and early 2000s with newer studies quite difficult. The methodological changes (and model inputs) have not always been well described, and this makes all DALY studies more difficult to interpret and compare. Readers who are not aware of how the DALY has been updated over time may apply old interpretations and critiques to new models that have addressed those issues (while perhaps overlooking criticisms that should be raised about the new models). To ensure that reports using the DALY are more fully useful to and useable by the global community, future DALY reports must clearly state which methods were used for life expectancy, disability weights, discounting, and age weighting. Standardization of the components used would enhance the interpretability of the DALY between studies, but it is also important to allow the metric to continue to evolve over time as new insights are gained about how to best design and estimate global health metrics and as emerging technologies allow for more robust models to be created.

The DALY was an exciting new metric twenty years ago, and it has made a major contribution to understanding national, regional, and global disease burden, especially the burden caused by chronic conditions. However, the ongoing refinements may be confusing for researchers and others who refer to DALYs for planning, policy, and practice purposes. Improved reporting of DALY methods, including transparency about exactly what changes are made from one version to the next, will enhance the DALY's usability and applicability to local and global public health.

Contributors

All of the co-authors contributed to the preparation and critical revision of the manuscript.

Conflict of interest

The authors declare no conflicts of interest.

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