How Many Years of Life Could Be Saved If Malaria Were Eliminated from a Hyperendemic Area of Northern Ghana?

Ayaga A. Bawah* and Fred N. Binka

INDEPTH Network, Accra, Ghana; School of Public Health, University of Ghana, Accra, Ghana

Abstract. Malaria is endemic in about 90 countries of the world, half of which are in Africa. Little is known about the demographic impact of the disease, however. This article uses demographic methods to examine the impact of mortality from malaria on overall mortality in a hyperendemic rural African setting. Using longitudinal demographic surveillance data from northern Ghana and applying multiple decrement and associated single-decrement life-table methods, we estimate the total number of person-years that would have been saved had malaria been eliminated from the population in 1995, given the age- and cause-specific mortality conditions of the period and gains in life expectancy that are implied. Results suggest that as many as one third of deaths in this population are attributable to malaria, depending on the age group under consideration, and that life expectancy at birth would likely increase by more than six years if malaria were eliminated as a cause of death.

INTRODUCTION

For many tropical countries, malaria remains one of the most difficult health challenges. It is endemic in about 90 countries of the world, half of which are in Africa. Malaria is estimated to affect between 300 and 500 million people worldwide every year, with 90% of all cases occurring in Africa. It is reported to be the leading cause of morbidity and mortality in Africa, accounting for about 20–30% of all infant deaths. Apart from the heavy toll in human lives, the medical costs and number of workdays lost to malaria in many African countries are enormous. In Ghana, malaria is reported to account for about 40% of all outpatient cases in hospitals and other health institutions. According to the Ghanaian Ministry of Health about 25% of all deaths among children below age 5 in the country are attributable to malaria.

The social and economic costs of malaria in Africa are huge. The World Health Organization (WHO) estimates that malaria retards African economic growth by 1.3% points per year. The benefits of controlling the disease would, therefore, be great. According to the WHO, sub-Saharan Africa’s gross domestic product (GDP) in 2000 might have been 32% greater had malaria been eliminated 35 years ago, an estimated increase of $100 billion in the region’s current GDP of $300 billion.

The disturbing issue, however, is that all efforts to eliminate or even control the disease to date have virtually failed in Africa. Modest successes that were made in central and southern Africa in reducing the vector population through mass spraying in the late 1950s and 1960s have reversed in many cases. In countries of Asia and parts of Latin America where malaria was reportedly eradicated, the disease has also reemerged as a major public health problem. Even more disturbing is the fact that the new strains of malaria parasites emerging in Africa and elsewhere are becoming resistant to the known and common forms of treatment. The emergence of these drug-resistant strains poses a further threat to efforts aimed at curtailing the disease not only in Africa, but worldwide.

Although Africa is known to have the highest level of malaria endemicity in the world, investigators have paid little attention to the measurement of the demographic impact of the disease in the region. The present analysis is aimed at bridging this void by estimating the total number of person-years that might be saved if malaria were eliminated from the population. We apply multiple-decrement life-table techniques to estimate malaria and all-cause mortality using longitudinal data. Multiple-decrement life tables refer to situations in which individuals have more than one mode of exit from a certain defined state. Multiple-decrement is appropriate for this analysis because we are dealing with a situation of competing risk—risk of dying from malaria or some other causes. Assuming a hypothetical situation in which malaria is eliminated, we estimate the expected reduced mortality that could result and the consequent increases in life expectancy.

DATA

Data come from the Navrongo Health Research Center (NHRC) in the Kasena-Nankana district of northern Ghana. Since 1993, the NHRC has maintained a Demographic Surveillance System (NDSS) that monitors demographic events—pregnancies, births, deaths, and migrations into and out of Kassena-Nankana District. Currently, the total population under surveillance is about 143,000. This article uses data for 1995 and restricts the analysis to the rural segment of the population, which in 1995 was estimated at 126,000. We excluded the urban population because it was not integrated into the NDSS until the end of 1995. Also, at the time of this analysis the 1995 data comprised the only data set for which verbal autopsies conducted were fully coded. The total of deaths was 2,193.

All deaths recorded in the NDSS are followed up with a verbal autopsy to ascertain the possible cause of death. Verbal autopsy involves interviewing relatives or caregivers who were closely associated with the deceased during the period leading to his or her death. Three independent physicians code the data, and for each death, a minimum of two must agree for a particular cause to be assigned as the most probable cause of death. If there is disagreement among the physicians, the cause of death is coded as undetermined. For this analysis, we have included all such cases in the unknown category. Through this procedure, about 17 different specific causes of deaths were identified among children and 22 causes identified among adults in the NDSS (see Figures 1 and 2).

* Address correspondence to Ayaga A. Bawah, INDEPTH Network Secretariat, 11 Mensah Wood Road, East Legon, P.O. Box KD 213, Accra, Ghana. E-mail: bawah.ayaga@indepth-network.org
As the two figures show, nearly one third of all childhood deaths and about one-fifth of adult deaths are attributable to malaria in this setting. Although the major causes of childhood deaths differ from the adult deaths, malaria tends to dominate as the reported main cause of death for both children and adults (if unknown causes of death are excluded). A large proportion of causes of death are reported as unknown, indicating either that a number of the interviews did not elicit adequate information from the respondents to allow the physicians to make informed diagnoses or that the three physicians differed in their assessment of the probable cause of death in many cases. Physicians’ disagreement is more likely to occur in cases of adult deaths; more than 35% of these are coded as unknown, as opposed to 15% for child deaths. The data presented here have been evaluated thoroughly and found to be of good quality.16

Figure 1. Diagnosed causes of death among children, Kassena-Nankana District, Ghana, 1995. ALRI = acute lower respiratory infection; Chichuru = child with congenital problems considered as deviant and killed.

Figure 2. Diagnosed causes of death among adults, Kassena-Nankana District, Ghana, 1995.
ESTIMATION PROCEDURE

Direct estimation of the impact of malaria on mortality would be possible if clinical records were available for deaths from the disease for the entire population or if epidemiologic morbidity and mortality were precisely assessed. Neither of these approaches is possible in most African settings because clinical records concerning the disease are nonexistent for most episodes of illness and because the hyperendemicity of malaria maintains its high and stable cycles of morbidity from year to year. By hyperendemicity we refer to situations of intense transmission such that immunity is insufficient to prevent the effects of the disease. Therefore, we evaluate malaria’s effect on overall mortality by estimating the number of person-years that could be saved assuming malaria was eliminated as a major cause of death in this population. We then estimated its impact using multiple-decrement and associated single-decrement life-table techniques. These methods rely on estimating the net effect of competing risks from different causes—that is, from malaria versus from other causes, under the assumption that different causes operate independently of each other. Although the assumption of independence may be unrealistic in some situations, determining the nature of dependencies is often difficult, especially in the case of malaria, which can manifest a number of signs. We evaluate the extent to which mortality could be reduced if malaria were eliminated from the population and decomposed this reduction by age. This way, we are able to determine the ages for which a decline in mortality from malaria would make the greatest impact on survival. (For detailed exposition of the methodology refer to Appendix 1.)

DATA LIMITATIONS

Some of the deaths for which we have data have causes that have been coded as “unknown.” In other studies, such deaths often have been considered as a separate category, and “unknown” has been designated as one of the causes. Because our interest is to estimate the impact of mortality resulting from malaria, treating the unknown deaths as a separate category implicitly assumes that they are the result of a competing cause to malaria. Some of the deaths in this category, however, may indeed be the result of malaria. In response to this dilemma, we first treated them as a separate category by adding them to the rest of the causes other than malaria and then estimated the impact of malaria deaths on overall mortality.

Subsequently, we assumed that some of the deaths from the unknown causes could in fact be malaria deaths, and thus allocated them proportionately among the known causes and re-performed the analysis. We adopted this approach because treating the unknowns as a competing cause of death may produce a conservative estimate if some of the deaths resulted from malaria. Allocating them among known causes, however, may overestimate the number of malaria deaths and its mortality impact. Estimating the impact of the disease before and after the reallocation of the unknown deaths approximates the possible range in the magnitude of mortality due to malaria in the study population.

RESULTS

Of the 2,193 deaths recorded for 1995, 512 were diagnosed as resulting from malaria, representing close to one fourth (23%) of all deaths in the Kassena-Nankana district. The overall crude mortality rate for the district is estimated at 17.4 deaths per 1,000 and the crude mortality rate for malaria is about 4.1 deaths per 1,000. Although these composite rates give a fair idea about the level of mortality they do not tell us anything about the age pattern of mortality. A life table representing these deaths by age is presented in Table 1. Results

Note: Not applicable. 
\( \mu_{nx} \) = Average number of person-years lived in the interval by those who have died in the interval. 
\( \mu_{mx} \) = Mortality rate for people in age group \( m \) to \( x \) n.
\( \phi_{nx} \) = Probability of dying between ages \( x \) and \( x + n \).
\( \phi_{mx} \) = Probability of surviving between ages \( m \) and \( x + n \).
\( l_{x} \) = Number surviving at each age. 
\( d_{nx} \) = Number of deaths between ages \( x \) and \( x + n \).
\( p_{nx} \) = Person-years lived between ages \( x \) and \( x + n \).
\( T_{x} \) = Person-years lived beyond age \( x \).
\( e_{x} \) = Life expectancy at age \( x \).
show that the age pattern of mortality for malaria is similar to that for all-cause mortality (Figure 3). Mortality is high at the younger and older ages, showing the typical pattern of mortality in developing countries. The infant mortality rate \( (\mu_0) \) is estimated at 0.092 and child mortality rate \( (\mu_1) \) of 0.026. The corresponding probabilities of dying before age 1 \( (q_{0}) \) and between ages 1–4 for those who survive to age 1 \( (q_{1}) \) are 0.087 and 0.097, respectively. These estimates translate into a life expectancy at birth of 48.8 years.

To evaluate the impact of malaria mortality on overall mortality, we isolated deaths due to malaria and estimated a multiple-decrement life table to answer the question, “How many newborns may eventually die from malaria if the age-specific mortality conditions of 1995 prevail?” Starting with a cohort

![Age pattern of malaria for overall mortality and malaria-specific mortality. This figure appears in color at www.ajtmh.org.](image)

**Figure 3.** Age pattern of malaria for overall mortality and malaria-specific mortality. This figure appears in color at www.ajtmh.org.

### Table 2
Associated single-decrement life table for causes of death other than malaria, Kassena-Nankana District, Ghana, 1995

<table>
<thead>
<tr>
<th>Age x</th>
<th>( l_x )</th>
<th>( d_x )</th>
<th>( R_{x-0} )</th>
<th>( p_{x-0} )</th>
<th>( l_x )</th>
<th>( d_x )</th>
<th>( \mu_{x-0} )</th>
<th>( \phi_{x-0} )</th>
<th>( \phi_{x-0} )</th>
<th>( \phi_{x-0} )</th>
<th>( q_{x-0} )</th>
<th>( q_{x-0} )</th>
<th>( q_{x-0} )</th>
<th>( e_x )</th>
<th>( e_x )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>100,000</td>
<td>0.9135</td>
<td>0.7941</td>
<td>0.9307</td>
<td>100,000</td>
<td>0.0693</td>
<td>6.933</td>
<td>1.248</td>
<td>0.494</td>
<td>0.0729</td>
<td>96,491</td>
<td>5,490,315</td>
<td>54.90</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1–4</td>
<td>91,349</td>
<td>0.9029</td>
<td>0.6615</td>
<td>0.9347</td>
<td>93,067</td>
<td>0.0653</td>
<td>6.081</td>
<td>1.486</td>
<td>1.856</td>
<td>0.0169</td>
<td>395,228</td>
<td>5,393,824</td>
<td>57.96</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5–9</td>
<td>82,478</td>
<td>0.9757</td>
<td>0.7872</td>
<td>0.9808</td>
<td>86,986</td>
<td>0.0192</td>
<td>1.668</td>
<td>1.267</td>
<td>2.492</td>
<td>0.0039</td>
<td>430,746</td>
<td>5,034,596</td>
<td>57.88</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10–14</td>
<td>80,474</td>
<td>0.9833</td>
<td>0.7368</td>
<td>0.9877</td>
<td>85,318</td>
<td>0.0123</td>
<td>1.052</td>
<td>1.354</td>
<td>2.315</td>
<td>0.0025</td>
<td>423,765</td>
<td>4,803,849</td>
<td>53.96</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15–19</td>
<td>79,131</td>
<td>0.9872</td>
<td>0.6774</td>
<td>0.9913</td>
<td>84,266</td>
<td>0.0087</td>
<td>7.34</td>
<td>1.473</td>
<td>2.671</td>
<td>0.0017</td>
<td>419,620</td>
<td>4,180,085</td>
<td>49.61</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20–24</td>
<td>78,115</td>
<td>0.9622</td>
<td>0.8148</td>
<td>0.9691</td>
<td>81,877</td>
<td>0.0309</td>
<td>2.530</td>
<td>1.223</td>
<td>2.576</td>
<td>0.0063</td>
<td>403,253</td>
<td>3,346,568</td>
<td>40.87</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25–29</td>
<td>76,357</td>
<td>0.9622</td>
<td>0.8148</td>
<td>0.9691</td>
<td>81,877</td>
<td>0.0309</td>
<td>2.530</td>
<td>1.223</td>
<td>2.576</td>
<td>0.0063</td>
<td>403,253</td>
<td>3,346,568</td>
<td>40.87</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30–34</td>
<td>73,472</td>
<td>0.9632</td>
<td>0.8800</td>
<td>0.9675</td>
<td>79,347</td>
<td>0.0325</td>
<td>2.575</td>
<td>1.134</td>
<td>2.554</td>
<td>0.0066</td>
<td>390,439</td>
<td>2,943,315</td>
<td>37.09</td>
<td></td>
<td></td>
</tr>
<tr>
<td>35–39</td>
<td>70,768</td>
<td>0.9495</td>
<td>0.8219</td>
<td>0.9583</td>
<td>76,772</td>
<td>0.0417</td>
<td>3.200</td>
<td>1.211</td>
<td>2.563</td>
<td>0.0085</td>
<td>376,064</td>
<td>2,552,876</td>
<td>33.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40–44</td>
<td>67,196</td>
<td>0.9422</td>
<td>0.8308</td>
<td>0.9518</td>
<td>73,572</td>
<td>0.0482</td>
<td>3.549</td>
<td>1.198</td>
<td>2.580</td>
<td>0.0099</td>
<td>359,271</td>
<td>2,178,812</td>
<td>29.59</td>
<td></td>
<td></td>
</tr>
<tr>
<td>45–49</td>
<td>63,313</td>
<td>0.9199</td>
<td>0.8061</td>
<td>0.9349</td>
<td>70,023</td>
<td>0.0651</td>
<td>4.558</td>
<td>1.231</td>
<td>2.575</td>
<td>0.0134</td>
<td>339,063</td>
<td>1,817,541</td>
<td>25.96</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50–54</td>
<td>58,241</td>
<td>0.9072</td>
<td>0.8482</td>
<td>0.9207</td>
<td>65,465</td>
<td>0.0793</td>
<td>5.192</td>
<td>1.170</td>
<td>2.595</td>
<td>0.0165</td>
<td>314,836</td>
<td>1,478,479</td>
<td>22.58</td>
<td></td>
<td></td>
</tr>
<tr>
<td>55–59</td>
<td>52,835</td>
<td>0.8443</td>
<td>0.8788</td>
<td>0.9802</td>
<td>83,532</td>
<td>0.0198</td>
<td>1.655</td>
<td>1.136</td>
<td>2.726</td>
<td>0.0040</td>
<td>413,896</td>
<td>3,760,464</td>
<td>45.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60–64</td>
<td>48,213</td>
<td>0.8443</td>
<td>0.8788</td>
<td>0.9802</td>
<td>83,532</td>
<td>0.0198</td>
<td>1.655</td>
<td>1.136</td>
<td>2.726</td>
<td>0.0040</td>
<td>413,896</td>
<td>3,760,464</td>
<td>45.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>65–69</td>
<td>44,607</td>
<td>0.8255</td>
<td>0.8374</td>
<td>0.8517</td>
<td>53,554</td>
<td>0.1483</td>
<td>7.914</td>
<td>1.176</td>
<td>2.574</td>
<td>0.0321</td>
<td>247,572</td>
<td>879,009</td>
<td>16.47</td>
<td></td>
<td></td>
</tr>
<tr>
<td>70–74</td>
<td>36,824</td>
<td>0.7200</td>
<td>0.8058</td>
<td>0.8058</td>
<td>45,440</td>
<td>0.2143</td>
<td>9.736</td>
<td>1.307</td>
<td>2.524</td>
<td>0.0482</td>
<td>203,090</td>
<td>631,457</td>
<td>13.90</td>
<td></td>
<td></td>
</tr>
<tr>
<td>75+</td>
<td>26,514</td>
<td>0.6964</td>
<td>0.8058</td>
<td>0.7471</td>
<td>35,703</td>
<td>0.2529</td>
<td>9.030</td>
<td>1.200</td>
<td>2.379</td>
<td>0.0583</td>
<td>154,846</td>
<td>428,347</td>
<td>12.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>75+</td>
<td>18,464</td>
<td>0.0000</td>
<td>0.7662</td>
<td>0.0000</td>
<td>26,673</td>
<td>1.0000</td>
<td>26,673</td>
<td>1.000</td>
<td>10.254</td>
<td>0.0975</td>
<td>273,501</td>
<td>273,501</td>
<td>10.25</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: \( R_{x-0} \) is the proportion of deaths due to all causes other than malaria.
- \( \mu_x \) = Average number of person-years lived in the interval by those who have died in the interval.
- \( \phi_{x-0} \) = Probability of dying between ages x and x + n.
- \( q_x \) = Probability of surviving between ages x and x + n.
- \( l_x \) = Number surviving at each age.
- \( d_x \) = Number of deaths between ages x and x + n.
- \( \phi_x \) = Number of person-years lived in the interval by those who have died in the interval.
- \( e_x \) = Average number of person-years lived by those who have died in the interval.
of 100,000 new births, we estimated that 22,250 of them may eventually die of malaria by the time they reach age 75, assuming that the age-specific mortality conditions of 1995 prevailed throughout their life course. This means that more than 22% of all newborn children may eventually die of malaria by the time they reach age 75.

In Table 2, we show the expected gains in life expectancy if malaria were eliminated. The results show that the overall probability of surviving to age 75 is likely to increase in the absence of malaria from 0.18 to 0.27, with a corresponding increase in life expectancy at birth from 48.8 to 54.9 years, a probable gain of about 6.1 years. Figure 4 displays life expectancy at each age when all causes of death are combined and the corresponding life expectancies if malaria were absent. Results portrayed in the figure show that life expectancy is increased at every age in the absence of malaria. The increase in life expectancy is, however, more pronounced at the early ages of life than at other ages, as expected.

Results from a decomposition of the gains in life expectancy at birth discussed below show clearly that the younger age groups—those younger than 5—account for the greatest gains in life expectancy at birth. This result is expected because most deaths (36%) occur in this age group and most of these deaths (27%) are caused by malaria. Figure 5 portrays

Figure 4. Comparison of estimated life expectancy for each age group without malaria, Kassena-Nankana District, Ghana. This figure appears in color at www.ajtmh.org.

Figure 5. Estimated proportion of individuals surviving to each age with and without malaria, Kassena-Nankana District, Ghana. This figure appears in color at www.ajtmh.org.
the number of those surviving to each age ($L_x$) when all causes of death are combined and in the hypothetical situation where malaria is assumed to have been eliminated as a cause of death in the population. Thus, starting with a cohort of 100,000 new births, the figure shows that many more people would be likely to survive at every age if malaria were eradicated from the population (see also Table 2).

To answer the question as to which age group would contribute more to improvements in life expectancy at birth if malaria were eliminated, we decomposed the total change in life expectancy at birth (6.1 years) by age. Results of this decomposition are presented in Table 3. The results show that children in the 1-year and 1–4-year age groups are likely to contribute most to improvement in life expectancy if mortality from malaria were eliminated from the population. The contribution of under-5 mortality (1-year and 1–4 years) to the total change in life expectancy at birth is about 45%.

Although the results demonstrate a substantial impact of malaria mortality, it is possible that we may have underestimated the impact of the disease because a large proportion of the deaths that are diagnosed as “unknown” may, in fact, be caused by malaria. This is because the distribution of deaths from the “unknown” causes has a similar shape as those of infectious and parasitic diseases, among which malaria is the main cause of death (not shown).

In view of this circumstance, we reallocated proportionally the unknown deaths among the known causes and reperformed the analysis. Results from the reallocation show an increase in the estimated probability of survival to age 75 as 0.33, assuming that malaria was eliminated as a major cause of death in the population. The corresponding life expectancy at birth is also expected to increase further to 58.2 years from 48.8 years, representing an estimated probable gain of 9.4 years. (Without the allocation, the estimated gain in life expectancy is 6.1 years as noted above.) Thus, after the allocation, there is an estimated additional gain of 3.3 years from the initial estimate of 54.9 to 58.2 years.

**DISCUSSION**

Little systematic attention has been directed to researching the demographic impact of malaria in Africa, although the disease remains the leading cause of childhood mortality and is implicated in mortality risks at all ages. Because malaria is most severe in infancy and childhood, much of the emphasis of clinical researchers and epidemiologists tends to center on malaria occurring at these ages. Evidence from Navrongo demonstrates that the disease affects all ages, although its mortality impact diminishes with age owing to an increase in immunity that occurs over time. Findings from Navrongo support the assessment of the Multilateral Initiative on Malaria (MIM) that the burden of malaria has been grossly underestimated in Africa.

This article documents the age pattern of mortality from the disease and its consequential shortening of life. Our results show that between about one fourth and one third of all deaths in this population are attributable to malaria, depending on the age group considered. Striking differences exist by age: mortality from malaria is highest in childhood—about 45% of the deaths due to malaria occur to children. Overall, the results suggest that if malaria were eliminated from this population, life expectancy at birth could be expected to increase by more than 6 years.

The effect of mortality from malaria may have been underestimated where verbal autopsy data are used, because not all deaths that are recorded for the surveillance project are followed through with successful verbal autopsy interviews.
Even in cases of deaths for which interviews were conducted, the fraction coded as “unknown” is high. If malaria deaths are assumed to represent a large proportion of the cases categorized as unknown in the reported cases, it is possible that we have underestimated malaria mortality. For example, if the deaths from unknown causes are allocated among the other categories, the expected gain in life expectancy at birth increases by 9 years, implying 3 additional years gained beyond the 6 years achieved by eliminating malaria.

It is important to note, however, that it is difficult to estimate entirely the impact of malaria mortality, partly because we are dealing with verbal autopsy data where the issues of specificity and sensitivity are clearly important. Indeed, this also raises questions about the often overplayed tune of the specificity and sensitivity are clearly important. Indeed, this also raises questions about the often overplayed tune of the

Received April 27, 2007. Accepted for publication August 31, 2007.

Acknowledgments: We thank Tukufu Zuberi, Herbert Smith, and Etienne van de Walle, all of the University of Pennsylvania, for useful comments on earlier drafts. James Phillips of the Population Council provided useful suggestions on the final version. Finally, we acknowledge the staff of Navrongo Health Research Centre—the field staff for diligently collecting the data and the physicians for coding of causes of death.

Authors’ addresses: Ayaga A. Bawah, Senior Research Associate, INDEPTH Network, 11 Mensah Wood Road, East Legon, P.O. Box KD 213, Accra, Ghana, E-mail: bawah.ayga@indepth-network.org. Fred N. Binka, School of Public Health, University of Ghana and Department of Epidemiology and Population Health, London School of Hygiene and Tropical Medicine, London.

REFERENCES


APPENDIX 1

In the analysis of causes of death, the force of the mortality function from different causes is additive because disentangling precisely the effects of other causes of death is difficult, particularly in settings where precise measurement is not possible. Thus, the sum of the different causes is equal to all causes combined as represented in equation (1) thus:

\[ \mu(x) = \sum_{i=1}^{j} \mu_i(x), \]  

where \( \mu_i(x) \) is the force of mortality from all causes combined and parameters \( \mu_i(x) \) refer to the death rate for the \( i \)th cause of death. This implies that the rates of decrements are also additive:

\[ n_m = \sum_{i=1}^{j} n_{mi}, \]

where \( n_m \) is the rate of decrement from all causes and \( n_{mi} \) in this case is the rate of decrement from malaria.

In light of the basic relationship between mortality rates \( \mu(x) \) and the probability of dying \( (d) \) as shown in the conventional life table, the transformation of the rates to probabilities of dying is shown in the following equation as:

\[ d = \frac{n_m}{1 + (n_m - d_m) n_m}, \]
where $\alpha_x$ is defined as the average number of person-years lived in the interval $x$ to $x + n$ by those who died in the interval. This relationship extends to multiple-decrement processes as follows:

$$\alpha_{x+i} = \frac{n_{x+i}m_{x+i}}{1 + (n - \alpha_{x})(n_{x+i} + nM_{x+i-1})},$$

where $m_{x+i}$ and $M_{x+i-1}$ represent decrement rates from malaria and all other causes other than malaria combined, respectively. Data concerning the causes of death by age and the corresponding number of person-years by the same subcategories define the probabilities of dying at each age ($q_{x+i}$), by cause of death. Unfortunately, the $\alpha_{x}$ values is often difficult. We employed different techniques to estimate the $\alpha_{x}$ values. We assumed, first, that those who died in the interval on average lived halfway through the interval. On the basis of this assumption, we adopted an initial value of 2.5 for all age groups with an interval of 5 years. For the younger than 1-year and 1–4-year age groups, we adopted the procedure suggested by Coale and Demeny.  

Using the $\alpha_{x}$ values of 2.5 in the $m_{x+i} \rightarrow q_{x+i}$ conversion formula, we first estimate $\alpha_{x}$, values and use these to obtain $\alpha_{x}$ (the number of deaths between age $x$ and $x + n$) in a life table. These $\alpha_{x}$ estimates are plugged into the iteration formula below to obtain new sets of $\alpha_{x}$ values. These values are subsequently reintroduced into the $m_{x+i} \rightarrow q_{x+i}$ conversion formula to re-estimate new $\alpha_{x}$ values, which are reintroduced in the iteration formula to obtain a new set of $\alpha_{x}$ values. This process is repeated until stable estimates of $\alpha_{x}$ are achieved. 

The iteration equation used is specified as follows:

$$\alpha_{x} = \frac{n_{24}d_{x-n} + n_{24}x+n}{n_{24}d_{x}}.$$  

The stable $\alpha_{x}$ values then are used to generate a life table for Kassena-Nankana District through the basic $m_{x+i} \rightarrow q_{x+i}$ conversion formula. With the overall life table generated, we can estimate the probability of dying from malaria ($q_{x}$), by applying the proportion of deaths that are due to malaria to the overall probabilities of dying for each age, $q_{x}$, as follows:

$$q_{x} = \frac{n_{x}D_{x}}{n_{x}d_{x}}.$$  

where $q_{x}$ and $D_{x}$ represent the probability of dying from malaria and the observed number of deaths from malaria, respectively. The above relationship is based on the assumption that the observed death rates for malaria ($m_{x}$) are equal to the life-table death rates for malaria ($q_{x}$), that is, $m_{x+i} = n_{x+i}$.

Estimating the contribution of mortality from malaria to overall mortality also permits us to estimate the effect of completely eliminating malaria through “cause-deleted” life-table analysis.  

If malaria were eliminated as a cause of death, survival at age interval $x$ to $x + n$, will be represented as:

$$nP_{x+n} = p_{x+n}(\alpha_{x+i} - n),$$

The approach described above assumes that the force of mortality function from each cause is proportional to all causes combined in the interval $x$ to $x + n$ and constant throughout the interval.  

The $\alpha_{x}$ values for the associated single-decrement life table were obtained using the following formula for all age groups except the first two and the last:

$$\alpha_{x} = n + R^t \frac{q_{x}}{\alpha_{x-n}} (\alpha_{x} - n),$$

where $\alpha_{x-n}$ refers to the average number of person-years lived by those dying in the interval from all causes other than malaria, and $R^t$ represents the proportion of deaths due to malaria. For the other age groups, the iteration procedure used for estimating the $\alpha_{x}$ values in the parent life table is used.

**DECOMPOSITION BY AGE**

To ascertain the age groups likely to contribute most to the total difference in life expectancy at birth as a result of the elimination of malaria, we decomposed the total difference in life expectancy into specific age groups, using the procedure proposed by Arriaga. This approach permits estimation of specific reductions in mortality due to the disease by age group and consequent increases in life expectancy in the population, allowing for malaria’s being more lethal during childhood than during adulthood:

$$\alpha_{x} = \frac{I_{x}^{all}}{I_{x}^{all}} \cdot \left( \frac{L_{x}^{malaria}}{L_{x}^{malaria}} - \frac{L_{x}^{all}}{L_{x}^{all}} \right) + \frac{T_{x}^{malaria}}{I_{x}^{all}} \cdot \left( \frac{L_{x}^{all}}{L_{x}^{all}} - \frac{L_{x}^{malaria}}{L_{x}^{malaria}} \right),$$

where the superscripts all and “malaria” indicate, respectively, with and without malaria. The first term at the right side of the equation refers to the direct effect of a change in mortality rates between ages $x$ and $x + n$, whereas the second term refers to the sum of both the indirect and interaction effects of contributions resulting from the number of person-years to be added because of additional survivors at age $x + n$ exposed to the new mortality conditions. The equation used for the open-ended interval is as follows:

$$\alpha_{x} = \frac{I_{x}^{all}}{I_{x}^{all}} \cdot \left( \frac{T_{x}^{malaria}}{T_{x}^{malaria}} - \frac{T_{x}^{all}}{T_{x}^{all}} \right).$$

Thus, the change in life expectancy ($L_{x}^{malaria} - L_{x}^{all}$) can be decomposed according to the contribution of the different age groups.