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ORIGINAL ARTICLE

LIFE EXPECTANCY OF PERSONS WITH CHRONIC DISABILITIES

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Summary: The life expectancy is an important summary measure of an individual's prognosis for survival. The life table is the preferred method for computing life expectancies, but it is not always feasible. We show that for several chronic disabilities, the logarithms of the age-specific mortality ratios (relative to the general population) decline linearly with age, reaching parity at age 85 or older. This, combined with a standard modeling of an individual's current mortality rate, yields a set of age-specific mortality rates that can be used to produce a "customized" life table. The life expectancy is then immediately available. In a series of empirical comparisons the method performed better than an assumption of constant excess death rate (EDR), and much better than one of constant mortality ratio (MR). The method may be useful for a variety of non-progressive disabilities, such as cerebral palsy and injuries of the brain or spinal cord.

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1. Introduction

The chronic disabilities considered here include cerebral palsy, Down's syndrome, and spinal cord injury. Information on long-term prognosis for survival can be valuable for counseling persons with these disabilities and their family members, for planning purposes, and in medico-legal work. Of the numerous summary measures of long-term prognoses, one of the most widely used is the remaining life expectation. Life expectation may be the measure of choice in medico-legal applications because settlements are frequently based on the product of the annual cost of compensation to the plaintiff and the remaining life expectancy. By contrast, the median survival time lacks a direct application of this kind.

The study period for most databases on persons with disability typically ranges from a few years to a few decades. For example, the California Mental Retardation Database, which was used in many of the applications reported here, tracks some 194,000 subjects during the 17-year period 1980 to 1996. Thus the age at death will not be known for the majority of subjects, and methods of analysis must take account of withdrawal of subjects from observation. Indeed, even if complete life-span information were available, it would be of limited use in most applications because it would reflect historical conditions of medical care that are no longer relevant.

If we are working with a group of individuals with *fixed* characteristics, such as males, female Hispanics, or persons with Down's syndrome, the computation of a life expectancy from a large database represents no particular problem. Generally, the method of choice is the period life table.[1] For example, life tables for persons with Down's syndrome, stratified by severity of mental retardation, have been developed from the California Mental Retardation Database[2] and other sources.[3,4] Often, however, the current condition of a person with disability must be taken into account. For example, we may require the life expectancy

of a five year-old child who is currently fed by gastrostomy tube and can roll over but not sit unaided. The latter characteristics may change over time. Although life tables for persons with potentially time-varying characteristics have been presented in the literature,[5] their interpretation should be restricted to a hypothetical population whose condition does not change, something that could not be known in advance for a given individual.

In view of the unsuitability of the standard life table when the subject's characteristics are potentially time-varying, statistical survival modeling[6] will generally be required. It will usually not be possible to work with a simple survivorship estimator (such as that of Kaplan & Meier[7]), even if the study period is very long, because there will seldom be a sufficiently large number of subjects in the data base that closely match the patient's characteristics. In general, a life expectancy calculation requires the combination of (a) multivariable survival analysis on a sufficiently large sample, to estimate the patient's mortality rate during the study period, and (b) a method of extrapolating the rate over the whole life span. Methods such as the Cox model[8] for the former task are highly developed, but there is little guidance in the literature on the latter, or on how the two should be integrated.

The main purpose of the present article is to develop and test a method for computing the life expectancy of an individual with a profile of possibly time-varying covariates. We begin in Section 2 by reviewing the methods needed for the present work, and develop a simple model for extrapolating mortality risk over the life span. Section 3 presents age-specific mortality rates for various conditions, and models them. Section 4 gives an example of how the methods are used to compute a life expectancy for a person with a specific profile of disabilities. Section 5 presents some empirical comparisons of the proposed approach with the other methods.

2. Methods and longitudinal models of mortality.

We are concerned with the estimation of the remaining life expectancy of an individual who is currently of age x and whose covariate values are z. Covariates will generally include sex, together with potential risk factors such as medical conditions and lack of mobility. Data on subjects will be available only during a study period, or window, typically ranging from a few years to a few decades. In principle, z = z(t) will be observed at all times throughout the subject's participation in the study, though in practice it will be feasible to observe z only on certain occasions, such as at an annual evaluation.

In some situations standard methods are available for the estimation of the life expectancy. In the simplest case, if a large cohort of individuals with the same characteristics z at age x can be followed until time of death (i.e., there is no censoring), a *generation life table*[1] may be constructed. Such a table will provide a life expectancy. As noted, however, even if feasible this may not be useful in practice because it may correspond to a historic period with outdated medical care.

If the study period is short (e.g., a single year) it may still be feasible to work with a conventional *period life table*[1] provided that z represents *fixed* risk factors, such as sex and permanent medical conditions (Down syndrome, cerebral palsy, etc.). Of course, adequate numbers of individuals with the specific z at *all* relevant ages must be available.

If the risk factors in z are time-varying, a life expectancy may be derived from a *multistate life table*, which generalizes the usual period life table by allowing several live states and modeling the transitions between them (and to the dead state).[1,9,10] The multistate life table, which provides a rich variety of age- and state-specific life expectancies and transition probabilities, has had many applications, such as labor mobility,[11] migration,[12] and marital status.[13] The method has severe limitations for

the computation of covariate-specific life expectancies, however. Firstly, it is only computationally feasible if the number of possible states is quite small, typically no more than three to five. This means that the domain of z must be partitioned into a small number of "homogeneous" regions. This will often be artificial and lead to substantial loss of information. Secondly, the method relies heavily on a Markov assumption: the transition probabilities for an individual with covariates z at time t do not depend on the values of z at earlier times. This is well known to be unreasonable in many situations.[14-16]

A quite different approach to computation of life expectancy is through parametric modeling of the survival time. Survival times may, for example, be modeled as exponential or Weibull, with parameters estimated empirically under assumptions such as that of proportional hazards or accelerated failure times.[17] Life expectancies are then obtained as known functions of the parameters.[18] This approach may be suitable when survival is typically short, as for patients with metastasized cancer. Survival distributions such as the Weibull will not, however, be appropriate for chronic conditions such as cerebral palsy, where the known human aging and mortality patterns play a significant role.

Our proposed approach to computation of life expectancies has three stages. Firstly, one estimates the individual's mortality risk over the study period using a standard survival method, such as the Kaplan-Meier estimator or the proportional hazards model. Next, the mortality rates over subsequent ages is expressed as a function of the known rates in the general population. Finally, a life table specific to the individual is constructed from the modeled rates, and this provides a remaining life expectancy and other statistics. To illustrate, if a child with cerebral palsy currently has a mortality rate that exceeds that of the general population by c, and this EDR is assumed constant over the subsequent lifespan, then a life table for that child is obtained by increasing all the age-specific rates in a standard life table by c. A similar procedure is possible if the MR rather than the EDR were assumed constant throughout the life span.

As we shall see, in many groups of persons with disability the mortality ratio declines rapidly with age. The reason is that with advanced age mortality is dominated by conditions such as heart disease and cancer, which are often no more common in the disabled group than in the general population. The assumption of constant MR over the entire lifespan is therefore unsuitable, although it is often used in insurance applications. An improved version of the method, however, has been adopted in the literature on spinal cord injury.[19,20] More appealing is the assumption of constant *excess* death rate. This would be appropriate if the disabled population were subject to excess risk specific to their condition in addition to the risks common to the general population, and if the former risks did not change with age. Again, however, it has been found empirically in many populations that the EDR is not constant, but instead may vary with age.

In many populations (including the general population), age specific mortality over the age-range of $30 \le t \le 75$, say, roughly follows the Gompertz Law[21]:

$$h(t) = \exp(\gamma + \delta t). \qquad (1)$$

If we denote the general population by the subscript 0 and the disabled group of interest by g, it follows that:

$$\ln(h_g(t)) - \ln(h_0(t)) = \alpha + \beta t, \qquad (2)$$

for some constants α and β, and a suitable range of ages t. The Gompertz law (1) is thus sufficient, but not necessary, for equation (2) to hold. The mortality rates $h_0(t)$ are known from standard sources.[22] Equation (2) provides a convenient basis for examining empirical age-specific mortality rates $h_g(t)$: they can be fitted by least squares, with weights depen-

dent on the age specific numbers of deaths, and departures from linearity in (2) are easily assessed by the inclusion of quadratic or other terms.

3. Empirical mortality rates

In this section we examine age-specific mortality rates for four types of chronic disability: cerebral palsy, spinal cord injury, Down's syndrome, and developmental disabilities (including mental retardation) other than cerebral palsy or Down syndrome. Apart from spinal cord injury, data were taken from the California Mental Retardation Database, which tracks the 194,000 persons with developmental disability who received services from the state of California at any time since 1980. The data have been extensively described elsewhere.[5,23-24]

Although time-varying characteristics such as motor skills are important predictive factors for survival,[23-24] our focus in this section is on populations defined by time-invariant characteristics. Consequently we stratify only on essentially fixed covariates, such as type of disability (cerebral palsy, Down's syndrome, etc.) and presence of quadriplegia or severe mental retardation.

3.1. Cerebral Palsy

The California data base includes 42,371 persons with cerebral palsy. Of these, 52% were reported to be quadriplegic. The remainder fell into a variety of categories, such as hemiplegia (17%), diplegia (11%), and paraplegia (6%). We chose to stratify on presence/absence of quadriplegia, as this was the single most important risk factor. Although male sex is known to be a risk factor in cerebral palsy[25] its effect is quite small, and for simplicity we do not consider sex here. There were 300,855 person-years of exposure and 3,938 deaths, for a crude mortality rate of 13 per thousand person-years. Empirical age-specific rates were computed as occurrence-exposure ratios in the standard way, using five-year intervals.[26]

Figure 1a shows the rates for quadriplegics and non-quadriplegics with cerebral palsy, and the general population, for ages 10 to 80. The plots show the familiar steady increase in mortality at later ages. Figures 1b and 1c show the age-specific EDR's and relative risks (MR/100). The relative risks decline steadily, appearing to approach unity (MR = 100) at very advanced ages. For an essentially non-progressive condition such as cerebral palsy, this may be biologically plausible, because ultimately the risks associated with old age may dominate. The EDR is more stable, but it does increase substantially with age. For example, the EDR for quadriplegics was 1.2% at age 30 (standard error = 0.09%) and 2.5% at age 60 (standard error = 0.5%). The difference between the two proved to be statistically significant at the 5% level.

Figure 1d is a plot of the logarithm of the relative risk against age, separately for persons with and without quadriplegia. These would be linear according to the model (2). The weighted least squares method was used to fit each regression line; to maximize precision we used weights that were the inverse of the variances, the latter estimated as the reciprocal of the observed numbers of deaths.[27] In both cases the fit appears to be satisfactory, with no obvious systematic departures from linearity. For quadriplegics the regression line intersects the horizontal axis, corresponding to parity (MR = 100) between quadriplegics and the general population, at age 85. The corresponding age is 95 for the non-quadriplegics.

In subsequent work we have used the midpoint of the two parity ages, namely 90 years, as the parity age for both groups. The reasons were (1) the two parity ages proved not to be significantly different from each other, according to a standard Normal test on the difference, and (2) it is implausible that quadriplegics achieve parity with the general population at a younger age than non-quadriplegics. As we shall see, the effect of such a choice on the life expectancy is quite modest.

3.2 Other types of developmental disability.

Figure 1a

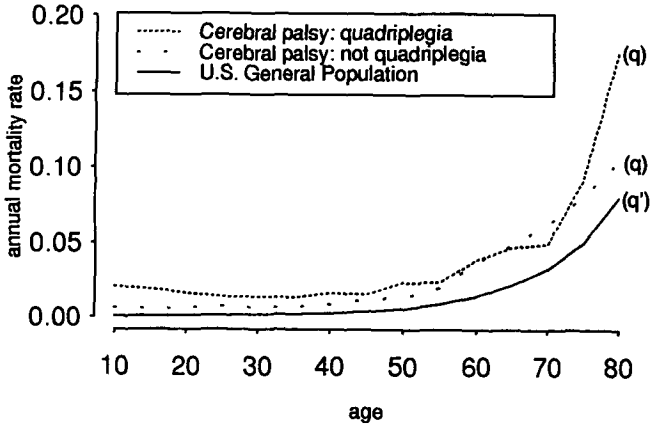


Figure 1b

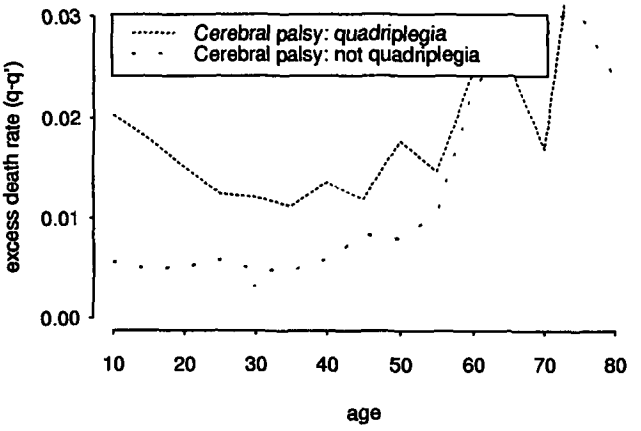


Figure 1c

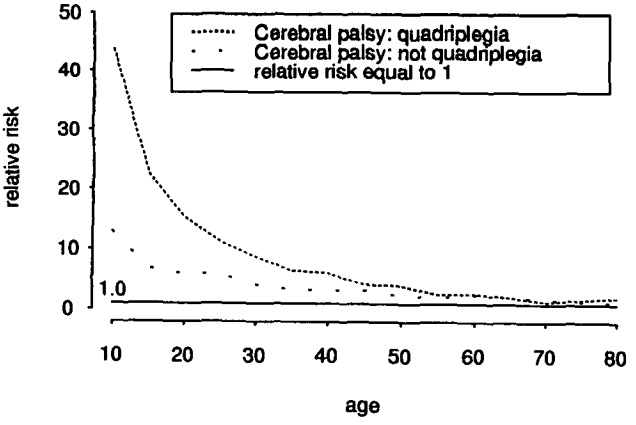
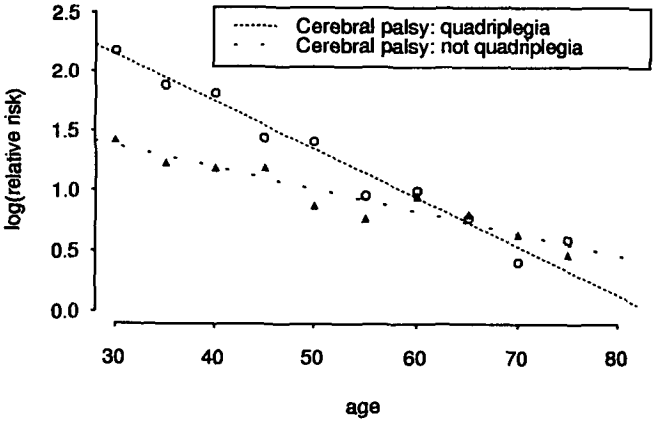


Figure 1d



Cerebral palsy. (a) Annual mortality rates in cerebral palsy, stratified by presence or absence of quadriplegia, and in the general population. Rates for the general population are averages of male and female rates. (b) Excess death rate, compared to general population. (c) Relative risk (MR/100), compared to general population. The horizontal line at 1 corresponds to parity of risk (MR = 100). (d) Plots of log(relative risk) against age. Fitted lines obtained from weighted least-squares regression. The intercepts on the horizontal axis are the parity ages.

Cerebral palsy and Down's syndrome are the two most common of the known etiologies of developmental disability. The California Mental Retardation Database also contains 130,670 persons with other types of mental retardation or disability. Identifiable groups include traumatic brain injury and chromosomal anomalies such as Klinefelter's and Fragile X syndrome. In the majority of cases, however, the etiology is unknown.

Figures 2a-d correspond to Figures 1a-d. Following earlier work[2,28] we stratified the subjects as "mild or moderate" or "severe, profound, or unspecified" level of mental retardation. For simplicity, we shall refer to the two groups as "mild/moderate" and "severe." The categories are based primarily on IQ scores, the cut point between the two being an IQ score of approximately 4 standard deviations below average.[29]

The pattern is similar to that of cerebral palsy. In particular, the logarithms of the MR's

Figure 2a

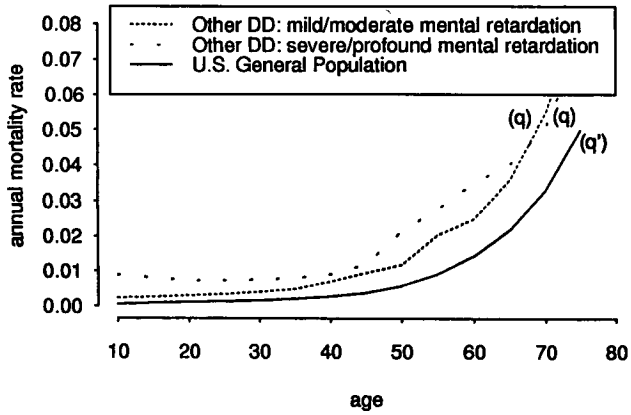


Figure 2c

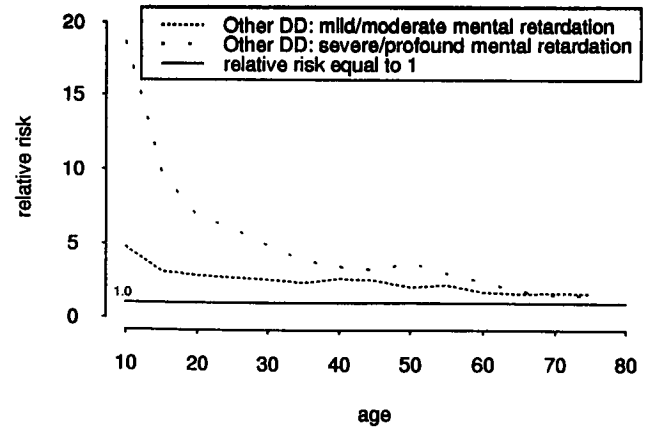


Figure 2b

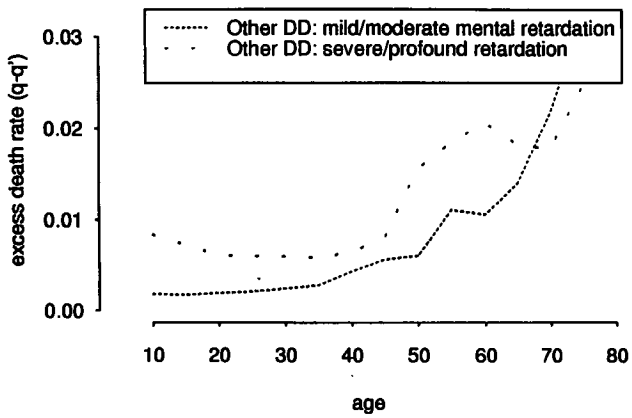
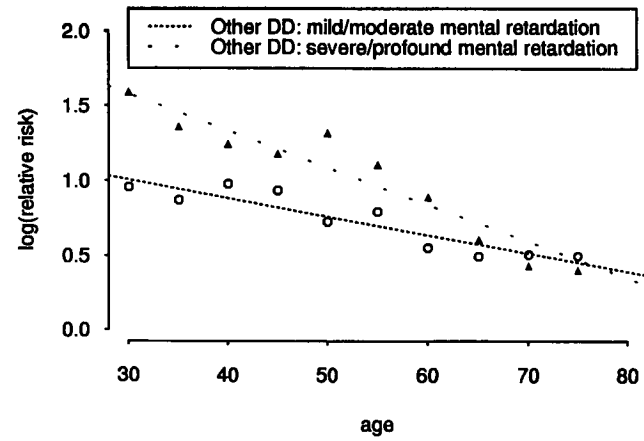


Figure 2d



Developmental disabilities other than cerebral palsy or Down's syndrome. (a) Annual mortality rates, stratified by severity of mental retardation, and for the general population. Rates for the general population are averages of male and female rates. (b) EDR compared to general population. (c) MR compared to general population. The horizontal line at 1 corresponds to parity of risk. (d) Plots of log(relative risk) against age. Fitted lines obtained from weighted least-squares regression. The intercepts on the horizontal axis are the parity ages.

decline linearly. According to the linear model (2), parity of mortality rates with those of the general population occurs at age 110 (mild/moderate) or 95 (severe).

3.3 Spinal cord injury.

The spinal cord data presented in Figures 3a-d were computed from information given by Whiteneck et al., who computed age-specific mortality rates based on 832 persons whose injury occurred 20 years or more previously.[30] Their study was thus consistent with our focus on chronic, relatively stable conditions. Disabilities ranged from partial paraplegia to complete quadriplegia, with the majority being complete paraplegia. The general population in the study was that of England and Wales, 1970, with the same sex ratio as their 832 subjects. The pattern of excess mortality is very much like that observed for the other disabilities, with a roughly linear trend in the logarithm of the MR. By extrapolation, parity of risk with the general population occurs at age 86.

Figure 3a

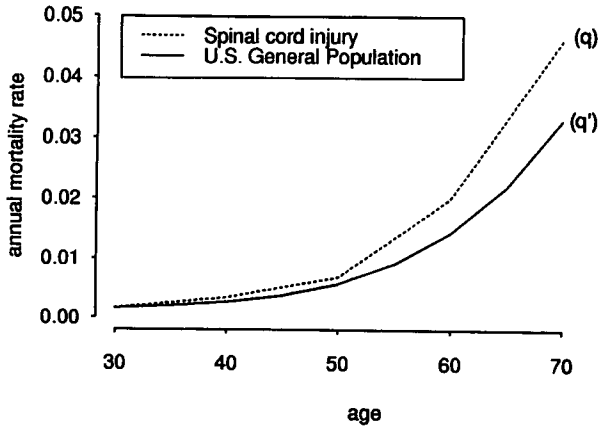


Figure 3b

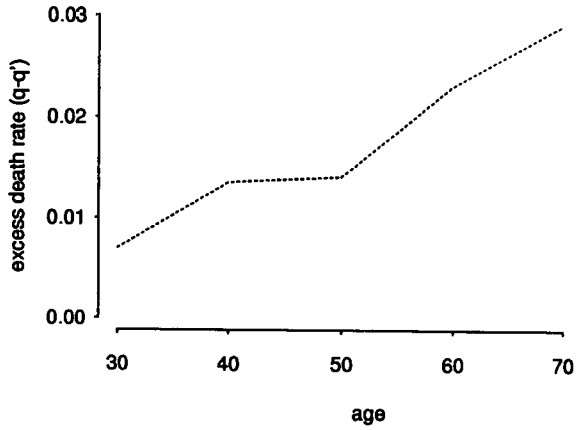


Figure 3c

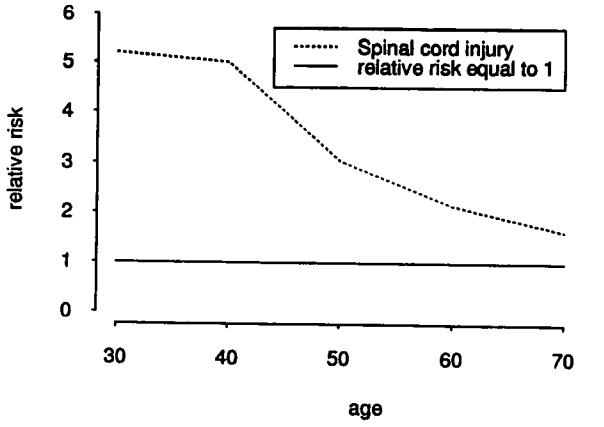
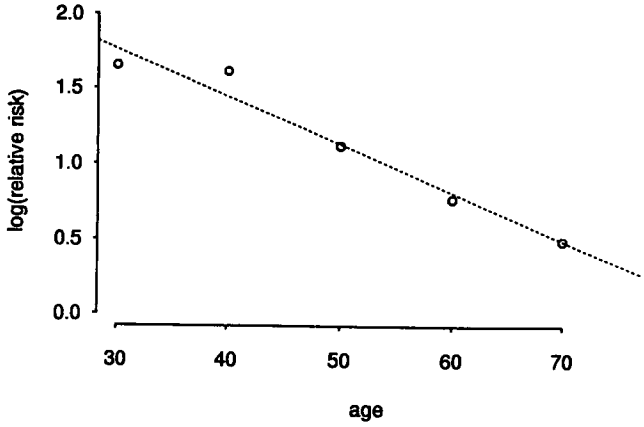


Figure 3d



Spinal cord injury. Data based on Figure 1 of Whiteneck et al.[30] (a) Annual mortality rates in the spinal cord group, and in the general population. (b) EDR compared to general population. (c) Relative risk compared to general population. The horizontal line at 1 corresponds to parity of risk. (d) Plot of log(relative risk) against age. Fitted line obtained from ordinary least-squares regression. The intercept on the horizontal axis, 86 years, is the parity age.

3.4 Down's Syndrome

The California database contains 13,265 persons with Down's syndrome, as indicated by the International Classification of Diseases code 758.0.[31] We again stratified subjects by whether their mental retardation level was mild/moderate or severe. The mortality rates (Figure 4a) show the well-known steep increase in mortality with age in Down's syndrome.[2] In contrast with the situation for cerebral palsy, the relative risk (Figure 4b) shows no tendency to decline with age. The EDR (Figure 4c) increases markedly. These patterns probably reflect the onset of Alzheimer-type dementia in adults with Down's syndrome;[32] in this sense Down's syndrome is a progressive disease, and there is no trend towards parity with the general population as age increases.

4. Computation of a "customized" life expectancy: an example.

As an example, we consider an 11-year old boy with cerebral palsy and quadriplegia. The time-varying covariates are functional skills, and we assume the child can lift his head but

Figure 4a

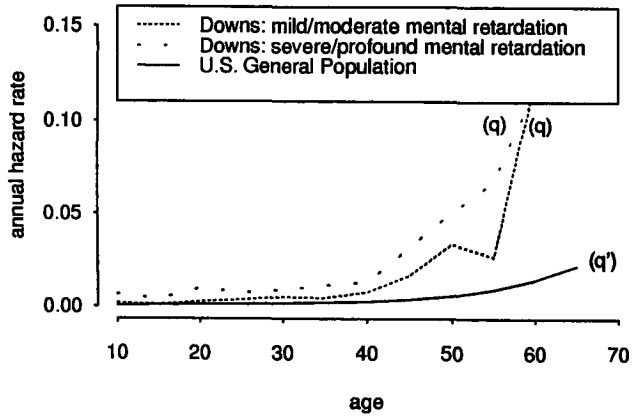


Figure 4b

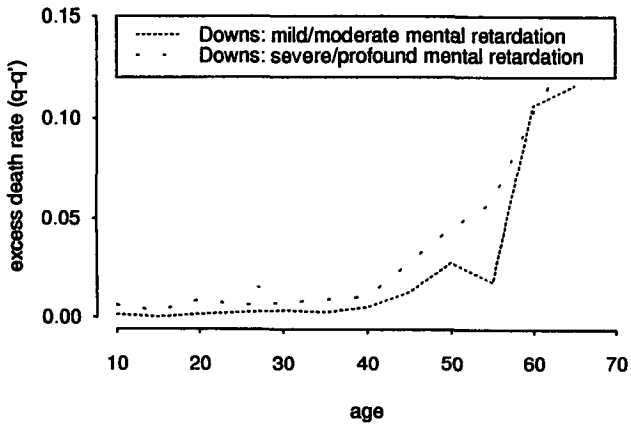
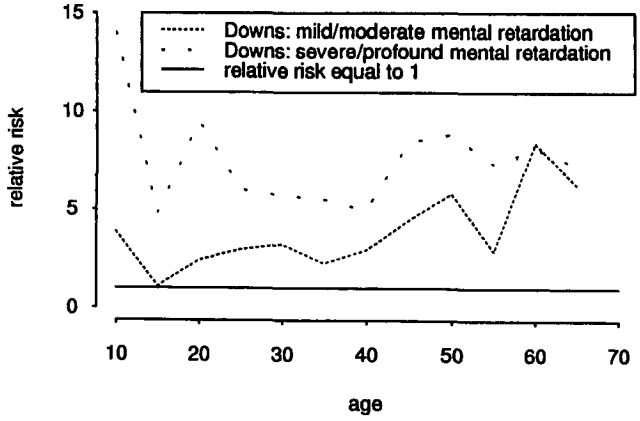


Figure 4c



Down's syndrome (a) Annual morality rates, stratified by severity of mental retardation, and for the general population. Rates for the general population are averages of male and female rates. (b) EDR compared to general population. (c) Relative risk compared to general population. The horizontal line at 1 corresponds to parity of risk.

not roll over, and is fed by others (but not by gastrostomy feeding). These factors are known to be important predictors of survival or mortality.[23,24] For the first fifteen years we used the empirical mortality rates.

We carried out a proportional hazards survival analysis, using the above items plus sex, type of cerebral palsy (quadriplegia, paraplegia, etc.), and severity of mental retardation. There were 9,230 children with cerebral palsy at age 11, of whom 55% were quadriplegic. The factor with the largest effect was the inability to lift head, which increased the mortality rate by a factor of 5.4 in comparison to the referent group (children able to sit unaided). All the above factors contributed significantly to the model, with the exception of sex. Tests for interactions of factors and for non-proportionality of mortality rates over time did not suggest that such additional terms were necessary.

The mortality rate for males with the given profile was computed from the proportional hazards model in the standard way.[6] The result was a mean annual rate of 0.0262 over the first five-year period, corresponding to a roughly 2.6% chance of dying in a given year. From the standard 1989-1991 Life Table[22] the male mortality rate was 0.00017, for a relative risk of 15.4. We then constructed a new life table specifically for the given profile of covariates. The rates for this were computed from the log-linear model of equation (2), so that the rate in the 10-15 age range was the observed value of 0.0262 and the rate at the parity age of 90 was the same as that of the general population. Table 1 shows the resulting age-specific rates and life expectancies. For comparison, the corresponding figures for the general population are also shown. According to the life table, the residual life expectancies at ages 10 and 15 are 30.1 years and 29.0 years, respectively. By interpolation, the required life expectancy at age 11 is 29.9 years.

Under the assumptions of the model, a confi-

Table 1

Age-specific annual mortality rates and life expectancies for 11-year-old male with cerebral palsy, quadriplegia, able to lift head but not to roll over (Columns 2 and 3), compared to the general population (Columns 4 and 5).

			US general population, males	
age	(2) Annual Mortality Rate	(3) Life Exp. (years)	(4) Annual Mortality Rate	(5) Life Exp. (years)
10	0.0262	30.1	0.0002	62.8
15	0.0267	29.0	0.0009	57.9
20	0.0279	27.7	0.0016	53.2
25	0.0268	26.5	0.0017	48.7
30	0.0255	24.8	0.0021	44.1
35	0.0260	22.9	0.0026	39.6
40	0.0258	20.8	0.0032	35.1
45	0.0280	18.3	0.0042	30.7
50	0.0339	15.9	0.0063	26.4
55	0.0435	13.7	0.0100	22.3
60	0.0566	11.7	0.0160	18.5
65	0.0694	10.1	0.0243	15.1
70	0.0851	8.5	0.0367	12.1
75	0.1061	7.2	0.0565	9.4
80	0.1316	6.0	0.0865	7.1
85	0.1630	5.0	0.1321	5.3
90	0.2041	3.9	0.2041	3.9

dence interval for the life expectancy may be constructed. For simplicity we worked with the 15-year annual mortality rate, which was 0.0269. A 95% confidence interval for the rate may be obtained from the estimated variance of the survival function. This is, for example, provided in version 6.11 of the SAS software package, which was used here. The upper and lower limits may then be used to construct two new life tables, and the corresponding life expectancies obtained as before. Here the 95% limits for the rate were 0.01893 and 0.03356, leading to the confidence interval 25.4 to 34.4 years.

5. Comparison of the method with some others.

Here we examine the performance of the proposed method in some situations where the true result is known, at least approximately. As we have seen, the true result cannot be obtained from a conventional life table if we are working with time-varying characteristics, such as mobility: such a table would only apply to a hypothetical group with those characteristics throughout the life span. We therefore worked with cases where the characteristics are constant throughout the life span, or constant after the injury if an acquired one. This is so for cerebral palsy, chronic spinal cord or traumatic brain injury, and for conditions such as paraplegia or quadriplegia. When the characteristics are fixed ones such as these and the group is sufficiently large, the ordinary life table is the method of choice. We use these life tables results as "truth" for our

Table 2

Illustrative example of life expectancy calculations: 10- year olds with cerebral palsy but not quadriplegia.

Model Life Table Method	Life Expectancy (at age 10) Observed (1)	Modeled (2)	Difference (2) - (1)
Observed mortality rates	51.8	51.8	(0.0)
Declining log relative risk *	51.8	50.1	-1.7
Constant EDR *	51.8	49.1	-2.8
Constant MR *	51.8	34.2	-17.6
Declining log relative risk, 10 years added to parity age*	51.8	48.6	-3.2

*Based on data for the initial age group (10-15 years).

purposes here.[a]

Eight groups were considered. These were the combinations of three binary characteristics:

1. Current age of subject: 10 or 30;
2. Cerebral palsy versus neither cerebral palsy nor Down's syndrome;
3. Quadriplegic versus not quadriplegic (in the case of cerebral palsy), or mild/moderate versus severe/profound mental retardation in the group without cerebral palsy.

Before presenting the full results, we illustrate the procedure, using as an example the case of 10-year olds with cerebral palsy but not quadriplegia (Table 2). Using data on such persons of all ages, we constructed a life table and found the life expectancy at 10 years to be 51.8 (Column (1)). This is taken to be "truth." We then constructed three additional life tables, using the assumptions of constant EDR, constant MR, and linearly declining log relative risk (Column (2)). To check on the sensitivity of the last of these to changes in the assumed parity ages, we also constructed a fourth life table based on the declining log relative risk assumption but with 10 years added to the assumed parity age.

Each life table gave an estimated life expectancy at age 10, which could then be compared to the truth. The difference between the two (last column of the Table) may be regarded as the "error." In this illustration, the smallest error (1.7 years) was obtained with the declining log relative risk, while the constant MR assumption resulted in much the largest error (17.6 years).

Table 3 summarizes data on the errors for all eight cases described above. Each row corresponds to one of the cases. At the foot of the table we give the square root of the mean squared error (a common summary measure of accuracy), together with the maximum error over the eight cases and the mean absolute error (i.e., with signs ignored).

Table 3 indicates that the declining log relative risk method, column (2), performed best in this study. On average it underestimated the life expectancies by 1.3 years, compared to an underestimation of 12.1 years with the constant MR model (column (5)) and an overestimation of 12.1 years with the constant EDR model (column (4)). When 10 years were added to the parity ages in the declining log relative risk method, the results (column (3)) were slightly worse than those of column (2),

Table 3

Comparison of life expectancy methods for eight groups. All figures are years.
Difference from Life Table Computation[a]

Age	CP	Group	(1) Life Table[b] Method[c]	(2) Present Method, increased parity age[d]	(3) Present EDR[e]	(4) Constant MR[f]	(5) Constant
10	Yes	Quad	40.0	-2.0	-5.1	-4.3	-20.4
30	Yes	Quad	33.0	-0.4	-2.3	11.8	-9.2
10	Yes	Not Quad	51.8	-1.7	-3.2	2.8	-17.6
30	Yes	Not Quad	37.4	0.2	-0.7	4.4	-5.8
10	No	Mild/Mod	58.8	-1.8	-2.3	3.4	-11.8
30	No	Mild/Mod	41.6	-1.3	-1.7	2.8	-4.9
10	No	Severe	49.9	-3.1	-4.9	0.2	-20.3
30	No	Severe	36.9	-0.6	-1.6	3.8	-7.0
Root mean squared error				1.7	3.1	5.2	-13.5
Maximum error[g]				-3.1	-5.1	11.8	-20.4
Mean error (= "bias")[h]				-1.3	-2.7	3.1	-12.1

Notes

[a] Entries in columns (2) - (5) were obtained by subtracting life table values (column 1) from the computed life expectancies.

[b] Computations from a conventional life table. These values are taken as "truth," as this is the method of choice for groups defined by fixed characteristics, as here.

[c] The "present method" estimates the mortality rate over the first five years, and then uses rates computed from the declining log relative risk method, equation (2). The parity ages used were empirically determined as in Section 3.

[d] The computational method for column (3) was the same as for column (2) except that, as a sensitivity check, 10 years were added to all the parity ages.

[e] Based on the EDR as determined over the first five years.

[f] Based on the MR as determined over the first five years.

[g] Maximum error when signs were ignored.

[h] The quotation marks around "bias" acknowledge that the statistic is specific to the set of eight

but still better than the other methods. The addition of 10 years to the parity age typically increased life expectancies by about 1 year, which is relatively little.

6. Conclusions

Life expectancies are a widely used summary measure of an individual's prognosis for survival. They are, for example, generally the appropriate measure in medico-legal applications. These applications arise frequently for persons with chronic disability, such as cerebral palsy or traumatic injury of the brain or the spinal cord. The conventional life table is the method of choice for computing an individual's life expectancy based on fixed characteristics. Frequently, however, potentially time-varying covariates such as current level of functioning must be taken into account. Methods for computing life expectancies in

such cases have not been widely explored.

Our proposed approach combines multivariate modeling to assess the individual's current mortality rate with a method for extrapolating the rate over the whole life span. The former can be based on a suitable data registry, even if the study period is only a few years. In this way the full profile of an individual's current functioning and medical condition can be taken into account. We have seen that extrapolation can be accomplished by modeling the mortality rate over the life span as a multiple of the rate in the general population. The logarithm of the MR appears to decline linearly after age 30, reaching parity (i.e., MR = 100) at age 85 or older. This may be biologically plausible for non-progressive conditions such as cerebral palsy or spinal cord injury, and when the Gompertz law for age-specific mortality rates applies the linear decline is actually a mathematical consequence. The method is not suitable for progressive conditions; Down's syndrome, for example, is associated with early onset of Alzheimer's disease and the MR does not tend to 100% as age increases.

The method worked well in a number of cases where the "true" life expectancy was known, and appeared to be relatively robust against perturbations of the assumed parity age. It was superior to the assumption of EDR, which generally overestimates life expectancies. In this connection we note the work of Singer,[33] who uses known mortality rates to the latest age for which follow-up data are available and makes the assumption of constant EDR thereafter.

By contrast, the assumption of constant MR leads to gross underestimates. This finding may be especially noteworthy because a constant MR is assumed by many practitioners when computing life expectancies in structured settlements.

The findings shown in Figure 3 suggest that the method would be suitable for persons with spinal cord injury, once the condition has stabilized. Regarding traumatic brain injury, it appears that the data necessary for computation of age-specific mortality rates have unfortunately never been published, so it is not feasible to test the method directly.[b]

We close on a cautionary note regarding the range of applicability of the proposed method. As the data on Down's syndrome demonstrate, the method is does not apply to all congenital conditions. Regarding acquired conditions, the spinal cord data refer to a period at least twenty years after the injury, and the mortality rate during the earlier period requires further investigation. The method is unlikely to apply to common acquired conditions such as stroke, cancer, and myocardial infarction, in which the risk is very much elevated in the early phases. Finally, rather little is known about the reduction in life expectancy resulting from risk factors such as hypertension and obesity. Age- and duration-specific mortality data for these conditions is available, however, and further work on the patterns of EDR and MR would be valuable.

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Reference

1. Schoen R. Modeling multigroup populations. New York: Plenum, 1988.
2. Strauss DJ, Eyman RK. "Mortality of people with mental retardation in California with and Without Down Syndrome, 1986-91," Am J on Mental Retardation, 1996;100, 643-653.
3. Baird PA, Sadovnik AD. "Life Expectancy in Down Syndrome". The Journal of Pediatrics, 1987;110,849-54.
4. Dupont A, Vaeth M, Videbech P. "Mortality and life expectancy of Down's syndrome in Denmark," Journal of Mental Deficiency Research, 1986;30,111-120.
5. Eyman RK, Grossman HJ, Chaney RH, Call TL. "The life expectancy of profoundly handicapped people with mental retardation," N Eng J Med, 1990;323, 584-589.
6. Collett D. Modeling Survival Data in Medical Research. Chapman & Hall, London 1994.

7. Kaplan EL, Meier P. "Nonparametric estimation from incomplete observations," Journal of the Am Statistical Association, 1958;53,457-481.
8. Cox DR. "Regression model and life tables," Journal of the Royal Statistical Society, 1972;B,34,187-220.
9. Keyfitz N. Applied Mathematical Demography, 2nd edition, Springer-Verlag, New York, 1985;ch.12.
10. Rogers A. "Introduction to multistate mathematical demography," Environment & Planning, series A, 1980;12:489-498.
11. Willekens FJ. "Multistate analysis: Table of working life," Environment & Planning, series A,1980;12,563-588.
12. Ledent J, Rees P. "Life Tables," In: A Rogers and FJ Willekens (Eds.), Migration and settlement: A multiregional comparative study, Reidel, Dordrecht, Holland, 1986.
13. Keyfitz N, "A Markov chain for calculating the durability of marriage," Mathematical Population Studies, 1988;1,101-121.
14. Shavelle RM, "The semi-longitudinal multistate life table," unpublished Ph.D. dissertation, Department of Statistics, University of California, Riverside, 1996.
15. Beck JR, Pauker SG, "The Markov process in medical prognosis," Medical Decision Making, 1983;3,419-458.
16. Hannan MT, "Multistate demography and event history analysis." In: A Diekmann and P Mitter (Eds.) Stochastic modeling of social processes, Academic Press, New York, 1984.
17. Cox DR, Oakes D. Analysis of survival data. Chapman & Hall, London, 1984;80-90.
18. Lee ET, Statistical methods for survival data analysis, Wiley, New York, 1992;200-222.
19. Smart CN, Sanders SR. "The costs of vehicle-related spinal cord injuries." Washington DC: Insurance Institute for Highway Safety, 1976.
20. DeVivo MJ, Stover SL. Long-term survival and causes of death. In: SL Stover, JA DeLisa, GG Whiteneck (Eds.), Spinal Cord Injury, Gaithersburg MD: Aspen, 1995;289-316.
21. Gompertz B, "On the nature of the function expressive of the law of human mortality and on the new mode of determining the value of life contingencies," Philosophical Transactions, 1825;513.
22. National Center For Health Statistics. Vital statistics of the United States, 1989-1991, volume II, section 6, life tables. Public Health Service, Washington, DC, (1996).
23. Strauss DJ, Eyman RK, Grossman HJ. "The prediction of mortality in children with severe mental retardation: The effect of placement," Am J of Public Health, 1996;86, 1422-1429.
24. Strauss DJ, Kastner TA. "Comparative mortality of people with mental retardation in institutions and the community," Am J on Mental Retardation, 1996;101,26-40.
25. Strauss DJ, Shavelle RM. "Life expectancy of adults with cerebral palsy," Developmental Medicine & Child Neurology, 1998:40,369-375.
26. Batten RW. Mortality table construction, Prentice-Hall, Englewood Cliffs, New Jersey, 1978.
27. Breslow NE, Day NE. Statistical methods in cancer research: Volume II The design and analysis of cohort studies, IARC, Lyon, France, 1995;67.
28. Eyman RK, Grossman HJ, Chaney RH, Call TL. "Survival of profoundly disabled people with severe mental retardation," American Journal of Diseases of Children, 1993;147,329-336.
29. Grossman HJ. Classification in Mental Retardation. American Association on Mental Deficiency, Washington DC, 1983;32.
30. Whiteneck GG, Charlifue SW, Frankel HL, Fraser BM, Gardner BP, Gerhart KA, Krishnan KR, Menter RR, Nusibeh I, Short DJ, Silver JR. "Mortality, morbidity, and psychosocial outcomes of persons spinal cord injured more than 20 years ago," Paraplegia, 1992;30,617-630.
31. International Classification of Diseases, Ninth Revision, 4th edition. McGraw-Hill, New York, 1995.
32. Strauss DJ, Zigman WB. "Behavioral capabilities and mortality risk in adults with and without Down syndrome," Am J On Mental Retardation, 1996;101,269-281.
33. Singer RB. "A method of relating life expectancy in the US population life table to excess mortality." J Ins Med, 1992;24,32-41.

End notes:

a. The period life tables we constructed used the whole study period for information on occurrence and exposure, rather than the single year period that is more common in demographic applications. By doing so we have greatly increased the sample sizes. If there were a pronounced secular trend in age-specific mortality over the study period this would pose some problems. Numerous studies with the California data base have indicated, however, that if such trends are present at all they are of small magnitude.

b. Recent unpublished work by the authors, however, suggests that after about 10 years subsequent to the injury, age-specific mortality rates for persons with traumatic brain injury are similar to those of persons with cerebral palsy who are at a comparable functional level. Under this assumption, the present method might be applied also to the brain injured-population.