Extrapolating published survival curves to obtain evidence-based estimates of life expectancy in cerebral palsy

STEVEN M DAY[1] | ROBERT J REYNOLDS[1] | SCOTT J KUSH[2]

1 Mortality Research & Consulting Inc., City of Industry, CA; **2** Life Expectancy Group, Menlo Park, CA, USA.

Correspondence to Steven M Day at Mortality Research & Consulting, Inc., 17700 Castleton Street, City of Industry, CA 91748, USA. E-mail: sday@mortalityresearch.com

Studies reporting long-term survival probabilities for cohorts of persons with cerebral palsy provide evidence-based information on the life expectancy of those cohorts. Some studies have provided estimates of life expectancy based on extrapolation of such evidence, whereas many others have opted not to do so. Here we review the basic methods of life table analysis necessary for performing such extrapolations, and apply these methods to obtain evidence-based estimates of life expectancy from several studies that do not report such estimates themselves.

Numerous studies have been published about life expectancy of persons with cerebral palsy (CP). A search on PubMed for articles including both 'life expectancy' and 'cerebral palsy' as Medical Subject Headings (MeSH) returned 17 articles (excluding letters to editors and commentaries).[1–17] Only six of the 17 report actual estimates of life expectancy.[1,2,4,6,11,14] Two of these six are reviews that re-state life expectancy numbers from other studies, leaving only four that report life expectancy numbers based on original research.[1,4,6,14] The four studies that have reported life expectancy estimates were all based on the same database of the California Department of Developmental Disabilities. The life expectancy estimates reported were obtained by two different, though similar, methods for extrapolating survival probabilities and mortality rates beyond the period of follow-up for each study. Such extrapolation is a necessary step in estimating life expectancy, and one that many authors opt not to take. As many of these studies note, the question of life expectancy is of great importance to persons with CP, their families, and their care providers.[2,7,11,15] The issue also has important implications for annuity companies,[18] forensic economists,[19,20] life care planners,[2,11,21] and in litigation involving allegations of malpractice as a possible cause of CP.[22]

Our goal here is to provide evidence-based estimates of life expectancy for CP cohorts that have been studied and for which long-term survival probabilities have been previously published. As we have noted, this requires extrapolation of mortality rates beyond the necessarily limited follow-up time for a given study. Several possible methods for such extrapolation have been described.[18,19,23–25] In this article we discuss briefly a few of these methods, ultimately using one of them (the method of proportional life expec-

tancy [PLE] as described in Anderson and Marion[24] and Strauss et al.[25]) to obtain evidence-based estimates of life expectancy. This method has some empirically based underpinnings, and it has been the method of choice in the most recently published work to have provided estimates of life expectancy in CP. Certainly other methods could be considered, and indeed it would be prudent to compare and contrast results of such methods in examples beyond the limited examples that have been compared in publication so far. Such a critical comparison is beyond the scope of the present work.

There may be many reasons for opting not to calculate such estimates of life expectancy, and we will discuss a few of these below. We wish to emphasize, however, that there is nothing special about the data or methods of survival analysis involved in the California studies that allowed the calculation of life expectancy;[1,4,6,14] many other studies could have used the same methods to obtain such estimates of life expectancy, and indeed we will do so here.

Our focus is on CP, but the general methods extend to other populations whose survival probabilities have been studied. For some populations, modifications to the specific methodology we will use for CP may be necessary. For example, it has been noted that there is a late-onset progressive nature to mortality in Down syndrome.[26,27] As a result, the method of PLE will tend to underestimate mortality rates beyond age 40 years, and thus overestimate life expectancy for Down syndrome. In older ages, an assumption of constant relative risk may be more appropriate for this population.[26] While our focus here is on CP, the general method of extrapolating mortality rates beyond the time frame of follow-up for a given study would apply even in Down syndrome or any other population with

developmental disability. Depending on the nature of the disability, some adjustments to the method of achieving the extrapolation may be necessary.

We will not dwell on the mathematical complexities of the methods, but will describe them somewhat heuristically. It will be helpful, however, to review in some detail the scientific concept of life expectancy and how it is estimated in general populations of humans. This will allow us to discuss clearly the reasons suggested by some researchers for not calculating or publishing life expectancy numbers for CP, and will help the reader appreciate the efforts involved in a wide variety of medical disciplines that have overcome such objections and reported life expectancy estimates from data limited in duration of follow-up. Then we will describe briefly three methods of extrapolation that actuaries, insurance underwriters, demographers, and statisticians have used to calculate life expectancy for persons with various medical conditions or disabilities, including CP.

This is not a systematic review. We will provide some information on the data involved in the studies upon which our estimates of life expectancy are based, and we will exclude from consideration studies with clear errors or serious deficiencies of analysis; however, we will not formally assess the quality of the studies we ultimately include in our analyses. Our goal here is to provide a missing summary measure of the survival of CP reported in various studies, namely life expectancy. Among other things, this will provide another meaningful way of comparing results between studies and between cohorts within a given study. Interpretation of such comparisons will require careful consideration of the source articles. How were the various cohorts defined? Were some groups more severely disabled than others? How was CP defined? At what age was CP confirmed, if it was? What variables were not controlled for that may impact mortality, survival, and life expectancy? These are a few of the questions that should be considered when comparing the life expectancy estimates reported for the various studies and cohorts. The applicability of our results to outside individuals or cohorts of persons with CP will depend largely on the data and methods used in each study. The original articles will remain the best source of information on the underlying data and methods.

SELECTION OF STUDIES
We sought studies of survival in CP that provided information sufficient to allow use of standard methods to extend survival curves and thus to estimate life expectancy. Thus we consider studies that focus on mortality as an outcome and include long-term follow-up (generally 3y or more) of persons with CP. Such studies provide information that is useful for determining long-term mortality rates and life expectancy. We exclude studies of acute mortality, for example during hospitalization for acute illnesses or medical procedures. We also exclude studies that focus primarily on preterm births, with CP as a secondary consideration in long-term follow-up. Such studies have

What this paper adds
- An explanation of life table methods for the non-statistician.
- The application of life table methods to studies of cerebral palsy (CP) survival.
- A heuristic explanation of one method used for reported life expectancies of persons with CP.
- Evidence-based estimates of life expectancy for CP sub-cohorts from several studies that do not report such estimates themselves.

been very numerous in recent years, and are beyond the scope of the present report. We identified potential studies by considering (1) our past experience reviewing such studies, which is extensive for each author, (2) a search of PubMed using 'life expectancy' and 'cerebral palsy' as MeSH terms, and (3) the list of references cited in previous reviews.[2,4,7,8,11] Ultimately we identified 20 original studies that included information on long-term survival probabilities of children or adolescents with CP that we used to produce more than 60 different estimates of life expectancy.[1,8–10,12,14–16,28–39]

As we have indicated, we use the method of PLE to extrapolate mortality rates beyond the time frame of a given study's follow-up. To understand why such extrapolation is necessary, and how it has been accomplished in this and other studies of life expectancy, we must examine in some detail the definition of life expectancy and its connection to survival curves and life tables.

LIFE TABLE METHODS
Definition of life expectancy and methods of its computation
Life expectancy, or the statistical expectation of remaining years of life, is the mean survival time remaining for a cohort. Alternatively, one can think of it as the average for an individual represented by a given cohort if such an individual could (hypothetically) live life repeatedly. We refer the reader to Table I. The remainder of this section will explain this table and illustrate the connection between it and a corresponding survival curve. The main thrust of this discussion will be (1) if a cohort is followed from a starting time until all members have died, then life expectancy is the area under the survival curve, and (2) corresponding to every such survival curve is a life table that serves to calculate that area. This visual connection between a survival curve and life expectancy can be very useful.

Table I is an abbreviated version of the latest life table for all US persons from the National Center for Health Statistics – USA (NCHS).[40] Life expectancy in the table is given in the column labeled $e(x)$. Reading from Table I we can see that that life expectancy in the USA is 78.7 years at birth; 50.0 remaining years at age 30 years; 23.1 remaining years at age 60; and 4.6 remaining years at age 90. Note that life expectancy is the average remaining lifespan from a given age. Thus while life expectancy at birth is 78.7 remaining years to age 78.7, for those who have already survived to age 90 years, life expectancy is 4.6 remaining years to age 94.6.

Age	$l(x)$	$d(x)$	$q(x)$	$m(x)$	$L(x)$	$T(x)$	$e(x)$
0	100000	612	0.006	0.0061	99694	7866328	78.7
1	99388	43	0.000	0.0004	99366	7766634	78.1
2	99345	27	0.000	0.0003	99332	7667268	77.2
3	99318	21	0.000	0.0002	99307	7567936	76.2
4	99297	16	0.000	0.0002	99289	7468629	75.2
5	99281	14	0.000	0.0001	99274	7369340	74.2
6	99267	13	0.000	0.0001	99260	7270066	73.2
7	99254	11	0.000	0.0001	99248	7170805	72.2
8	99243	10	0.000	0.0001	99238	7071557	71.3
9	99233	9	0.000	0.0001	99229	6972319	70.3
10	99224	8	0.000	0.0001	99220	6873090	69.3
11	99216	9	0.000	0.0001	99212	6773870	68.3
12	99208	12	0.000	0.0001	99202	6674658	67.3
13	99196	17	0.000	0.0002	99188	6575456	66.3
14	99179	25	0.000	0.0003	99166	6476268	65.3
15	99154	33	0.000	0.0003	99137	6377102	64.3
16	99121	41	0.000	0.0004	99101	6277964	63.3
17	99080	49	0.000	0.0005	99056	6178864	62.4
18	99031	57	0.001	0.0006	99003	6079808	61.4
19	98975	65	0.001	0.0007	98942	5980805	60.4
20	98910	74	0.001	0.0007	98873	5881863	59.5
30	98011	101	0.001	0.0010	97961	4897086	50.0
40	96798	161	0.002	0.0017	96718	3922589	40.5
50	94295	394	0.004	0.0042	94098	2965247	31.4
60	88770	778	0.009	0.0088	88381	2046832	23.1
70	78069	1526	0.020	0.0197	77306	1206570	15.5
80	57188	2868	0.050	0.0514	55755	519263	9.1
90	23619	3375	0.143	0.1542	21932	108501	4.6
100	1968	692	0.352	0.4334	1622	4611	2.3

Age=x, the age at the beginning of each 1y time interval; $l(x)$, the number of persons alive at the beginning of age x; $d(x)$, the number dying during age x; $q(x)$, the probability of dying during age x; $m(x)$, the instantaneous mortality rate during age x (assumed to be constant during a given integer age x, except at age 0); $L(x)$, the number of person-years lived by the people alive at the beginning of age x through the end of age x, which is less than $l(x)$ owing to some persons dying during the age and who are assumed to have died (on average) halfway through the age; $T(x)$, the grand total number of person-years lived by the original hypothetical cohort of 100 000 persons until all have died, which is the sum of figures in the $L(x)$ column from age x to the end of the unabbreviated table; $e(x)$, the life expectancy, equal to $T(x)$ divided by $l(x)$ at each age x.

The life expectancy figures in the NCHS table represent the average remaining number of years that will be lived by the cohort of the respective age in the USA until all have died. The life table used to calculate such figures is a period life table. The period life table uses current mortality rates as the input, which are calculated on the basis of numbers of persons alive and numbers of deaths observed at a given age and during a recent, relatively short period of time. Mortality rates are the key input for any life table, including those used to estimate life expectancy of persons with specific medical conditions including neurological injuries resulting in CP. The period life table follows a hypothetical cohort, typically but arbitrarily of 100 000 persons, as it moves from year to year. The empirically determined mortality rates then determine mathematically the number of persons surviving from 1 year to the next, the number dying at each age, and the proportions dying at each age. The life table tallies the total number of

person-years lived by the hypothetical cohort through some old age beyond which likelihoods of survival are so small as to make negligible the impact of the few who might survive beyond this age on the overall average survival time. Typically this age is 110 years or so.

The life expectancy is one output of the life table. Other information provided by the table includes (1) the likelihood that a person will be alive at age 50, 80, or 100, (2) the probability of dying before age 65, (3) the probability of surviving beyond age 70, and (4) the median survival time, namely the time at which half of the hypothetical cohort will have died and beyond which half will continue to live. Depending on the context, any of these figures may be of greater interest or importance than the life expectancy at a given age; however, life expectancy is perhaps the most often cited summary measure of survival.

The columns in Table I are the following, from left to right: x, the age at the beginning of each 1-year time interval; $l(x)$, the number of persons alive at the beginning of age x; $d(x)$, the number dying during age x; $q(x)$, the probability of dying during age x; $m(x)$, the instantaneous mortality rate during age x (assumed to be constant during a given integer age x, except at age 0); $L(x)$, the number of person-years lived by the people alive at the beginning of age x through the end of age x, which is less than $l(x)$ owing to some persons dying during the age and who are assumed to have died (on average) halfway through the age; $T(x)$, the grand total number of person-years lived by the original hypothetical cohort of 100 000 persons until all have died, which is the sum of figures in the $L(x)$ column from age x to the end of the unabbreviated table; and $e(x)$, the life expectancy, equal to $T(x)$ divided by $l(x)$ at each age x.

It is important to understand that life expectancy is never a prediction of the actual number of years that any individual will ultimately live. We see in Table I for example that while the life expectancy from birth is 78.7 remaining years, more than 20% $(1-78\ 069 \div 100\ 000)$ of the hypothetical population will not live beyond age 70, while more than 20% $(23\ 619 \div 100\ 000)$ will survive to age 90 or beyond. We refer the reader to the NCHS publication for further details on this standard life table.[40]

Figure 1 shows the survival curve corresponding to the full US life table (males and females combined). The unabbreviated version of the life table and the survival curve provide essentially the same information, though in substantially different formats. The area under the survival curve equals the life expectancy calculated in the life table. An alternative way of conceptualizing this is to estimate that area by summing up a series of rectangles of width one unit and heights varying with the vertical height to the survival curve. The $L(x)$ numbers, suitably scaled by dividing by 100 000, give the areas of those rectangles. The sum of these scaled numbers thus provides an approximation of the area under the curve, which is the life expectancy. In Table I, the (unscaled) sum is given in the $T(x)$ column. At age 0, this (unscaled) sum is 7 866 328, which upon division by 100 000 gives the life expectancy 78.7.
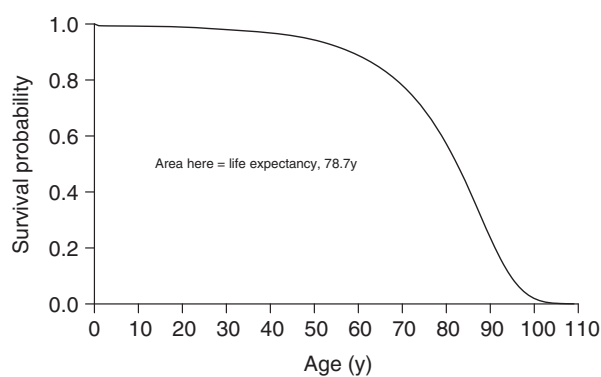
Figure 1: Survival curve for US males and females based on Arias.[40] Area bounded by the curve and the horizontal and vertical axes is the life expectancy, 78.7 total years, which is estimated by the period life table.

The full survival curve and the area under it provide a useful visual representation of life expectancy. If the survival curve for a study population (e.g. persons with CP) tracks below that of an age- and sex-matched general population, the life expectancy of the study population must be less than that of the general population; this visualization of the area under the curves can give a clue as to how much less. Since results of studies of survival of persons with significant medical conditions are often provided in the form of Kaplan–Meier survival curves (or actuarial survival curves), this visual connection with life expectancy can be illuminating.

Mortality rates in a period life table provide sufficient information to calculate the life expectancy of a person (or group of persons) alive today even though no one has died. An assumption underlies this: that the age-specific mortality rates observed recently will hold for a hypothetical cohort until all have died. We will consider later whether this assumption is reasonable, and discuss briefly possible alternatives.

The period life table is a standard and widely used method for calculating life expectancy, but it is not the only method. Cohort life tables offer another approach. In a historical cohort life table, information on an actual cohort of persons is collected and analyzed from their birth until the last member of the cohort has died. A period life table and a cohort life table may produce different life expectancies. The Human Mortality Database[41] provides both period and historical cohort life expectancies for several European countries. For example, in 1900 the period life table for the Netherlands gives a life expectancy at birth of 48.4 years, while the corresponding cohort table gives a life expectancy of 55.1 years. Since historical cohort life tables become available only after every member of a cohort has died, they have limited value for the calculation of the life expectancy of a living person.

To examine differences between today's period and cohort life tables is problematical because today's cohort tables will not be completed for many years. Historical

trends are often indicative of future patterns, however, and several demographers, actuaries, and other scientists have attempted to project what may happen to mortality rates in the next 50 or 100 years.[42–44] This work has led to what are called projected mortality rates. When used in a life table, projected mortality rates produce a future cohort life table. Projected rates are generally developed on the basis of an assumption of a fixed annual decline in mortality rates, or in some cases a gradually diminishing annual decline, over the next several decades or more. Resulting life expectancies vary.

For example, in the UK, a period life table analysis for males born in 2012 yields a life expectancy of 79.0, while the principal projected mortality rates produced by the UK Office for National Statistics result in a future cohort life expectancy of 90.6 years, a 15% increase.[42] Similarly, the United States Social Security Administration has developed projections for future mortality rates, and the cohort tables for males in 2010 produce a 7% increase in life expectancy compared with period tables.[44] Such future cohort analyses include a fair amount of speculation, as it is uncertain whether historical trends in reduced mortality rates will continue for another 50 or 100 years. As the UK Office for National Statistics cautions, 'When using the cohort expectation of life the user should be aware that the calculation includes 50 years of assumed future mortality improvements and that these become less reliable the further into the future from the projections base year.'[42]

Further discussion about the issues of projected mortality rates are beyond the scope of this review. The interested reader will find a wealth of information and many further references on the topic of projected mortality rates in the cited references.[42–44] For analyses involving general population life expectancies (e.g. when we report that the general population life expectancy of 4-year-olds in the USA is 75.2 remaining years), we will be referring to period life table calculations. Important implications arise from recent evidence that mortality rates have fallen during the past 20 or 30 years for some CP populations[1,4,6,45] since information we will be using to estimate CP mortality rates and life expectancies may therefore be dated. In the table of life expectancy estimates, we have included numbers based on the latest information on declining mortality rates in the California CP population as reported by Brooks et al.,[1,45] with unadjusted estimates provided for comparison.

Extrapolating information on survival of CP cohorts to complete a life table and survival curve

The reasons some authors of studies of survival in CP report life expectancies and others do not are complex. Of course, some studies of survival are just that, and there is no reason that life expectancy needs to be a focus of such a study. Reporting 5-, 10-, or 20-year survival probabilities is common, and sufficient for many purposes. Yet many studies that have titles suggesting that life expectancy is a focus nevertheless do not report any life expectancy estimates.

The key input to national life tables such as those published by the NCHS is the column of age-specific mortality rates. The NCHS determines age-specific mortality rates from population data and national death statistics, and the resulting mortality rates at all ages allow for the calculation of life expectancy. Studies of survival of persons with CP provide information about mortality rates, but this information is generally limited to only a few decades (if that). During these few decades, mortality rates for CP typically differ from those in standard tables. Adjustments can be made to the mortality rates in standard tables to reflect the differences, and the resulting tables can thus provide information on the life expectancy of a particular study population. The information does not address mortality rates at all ages, however, which is one reason that calculations of life expectancy are reported infrequently in studies of CP. The rare study that does report life expectancies for CP must overcome these limitations somehow. Two examples of studies that do not report any life expectancy estimates, and one that does, illustrate these points and raise several important issues.

(1) Crichton et al.[15] report no life expectancy estimates, and explain that, 'Because all the cases were born within a 38-year period and the data were heavily right-censored (i.e. the fate of each individual surviving beyond the date of the study was not known) there is no information on the risks for the longer-surviving cases. Since nothing can be inferred about the risks in later life, it is not possible to estimate an average life-expectancy.'

(2) Hutton and Pharoah[8] also provide no estimates of life expectancy, explaining that, 'When life expectancy is quoted, it generally refers to the mean life expectancy, the calculation of which requires every member of the cohort to have died.' Since not every member of any cohort considered in the study had died, estimation of life expectancy was problematic. However, the authors saw a possible way forward: 'Alternatively, survival curves have to be extrapolated and the assumptions made must be specified.' They explain briefly how this extrapolation might be done, but do not provide details or examples.

(3) Strauss et al.[6] report two estimates of life expectancy. These appear in a figure illustrating the impact of an observed trend of falling mortality rates from 1983 to 2002. For a particular group of males with CP, they report life expectancies of 14 (on the basis of survival probabilities derived from 1983–1995 data) and 20 (adjusted to mortality rates in 2002) remaining years. The authors note that these figures result from the 'use of standard methods.' They elaborate only briefly on these standard methods, directing the reader to an article with a detailed explanation.[25]

The studies by Crichton et al. and Hutton and Pharoah highlight important limitations of all studies of survival of persons with CP, and, in fact, of nearly all studies of human survival. While these limitations present important challenges for estimating the life expectancy of the cohorts studied, they are not insurmountable. The life insurance industry has long been interested in this basic problem, and textbooks and many articles have been written about the subject.[18,19,24,25,46–51] Life expectancy estimates of persons with CP have been reported on the basis of several of these methods.[1,4,6,13,50] We will describe three methods using a visual representation of each, and we will use one of them, the method of PLE, to provide life expectancy estimates for more than 60 different sub-cohorts of children and adolescents with CP on the basis of reports from 17 original studies (Table II). (It should be noted that several of these original studies were based on analyses of overlapping databases, or in some cases subsets or supersets of a common database of persons with CP. For example, the studies by Strauss et al.[4,6,9,13,14] and by Brooks et al.[1,36,37] were all based on different eras of the California Department of Developmental Disabilities database, although in each study the inclusion and exclusion criteria varied. Similarly, studies by Hutton et al.[16,31] and Hemming et al.[33] involved data sets that overlapped considerably.) The method (PLE) performed relatively well in situations where it was tested empirically, and was particularly good in an application to CP survival.[25]

An obvious question must be posed and dispensed with at this point: why not use the same methods used by the NCHS[40] to determine the life expectancy of persons with CP? This period life table method could, in principle, be used. If we had a registry of persons with CP at all ages, for example, we could count persons and deaths at each age, determine age-specific mortality rates, and use them in the life table exactly as the NCHS does for the general population of males and females in the USA. We would then have an estimate of the life expectancy of persons with CP at all ages.

This would be enlightening to a point, but it would not account for the level of disability. It is clear from an extensive literature on survival in CP that level of disability has a profound impact on survival probabilities and thus on life expectancy.[1,2,4,6–9,11–17,25,31–33,35,36,38,39] For example, Brooks et al. recently reported life expectancy for 15-year-old females with CP that ranged from as low as 21% to as high as 83% of the corresponding general population life expectancy, depending on level of gross motor functioning and feeding ability.[1]

We could, then, go a step further and restrict our attention for a period analysis of mortality rates to one particular level of disability, for example using only data on persons able to roll over and sit independently, but unable to walk. Resulting estimates of life expectancy would then be based not on a natural progression of a cohort initially meeting these criteria, but rather on data from different sets of persons at each age, effectively removing from consideration persons from prior ages who improved or declined in function beyond the initial criteria. As applied to a cohort or individual, such a period or person-year calculation of life expectancy effectively assumes that the

Table II: Life expectancy estimates based on the method of proportional life expectancy

Study	Cohort/group	Number in cohort	Age (y)[a]	Life expectancy (95% CI)[b]	Comments
Evans et al.[28]	Dyskinesia, with or without spasticity	119	2	59	England (South East Thames). Would be an overestimate of life expectancy for a child with spasticity and severe limitations in motor function or feeding ability; an underestimate if especially high functioning
	Quadriplegia	144	2	37	May be an overestimate or underestimate of life expectancy for a particular child with quadriplegia depending on actual level of functional ability, feeding status, etc.
McGrath et al.[29]	Status post-gastrostomy	61	5	12	USA (Wisconsin). Motor function was not controlled for, but most were non-ambulatory and had severe cognitive impairment
Hutton et al.[16]	1. Severe disability	189	2	67 (60–76)	England (Mersey region). Baseline survival probabilities for the general population are provided in Table III of this study and these were used to determine excess death rates during the study follow-up
	2. Severe disabilities	63	2	55 (43–71)	
	3. Severe disabilities	188	2	27 (22–32)	
	Severe ambulatory disability	274	1	29	
	Severe manual disability	255	1	28	
	Severe cognitive disability	398	1	40	
Crichton et al.[15]	Quadriplegia	757	2	56	Canada (British Columbia)
	Diplegia	412	2	75	
	Severe or profound intellectual disability	517	2	46	
	Mild or no intellectual disability	2552	2	73	
Strauss et al.[14]	ULH, tube fed	557	2	10	USA (California). These estimates were re-evaluated by Brooks et al.,[1] albeit for a slightly different starting age. In addition to beginning the cohort analyses at age 4 in the 2014 study, two other changes were made. First, the methodology used in this 1998 study (an assumption of linearly declining logarithm of relative risk between the CP cohorts and the US GP) was abandoned, and the method of proportional life expectancy was used instead. Second, evidence for falling mortality rates from the 1983–2010 period were used to arrive at higher life expectancies in the 2014 study: see below
	ULH, FBO	977	2	19	
	ULH, self-feeding	37	2	35	
	Lift head/chest, partial rolling, tube fed	136	2	25 (19–32)	
	Lift head/chest, partial rolling, FBO	1403	2	38 (35–43)	
	Lift head/chest, partial rolling, self-feeding	382	2	54 (45–70)	
Smith et al.[30]	Tube fed	65	5	15	Canada (Nova Scotia)
Hutton et al.[31]					England (North of England Collaborative CP Survey)
	LAS≤30	129	5	—[c]	
	30<LAS<70	164	5	59	
	LAS≥70	62	5	35	

Study	Cohort/group	Number in cohort	Age (y)[a]	Life expectancy (95% CI)[b]	Comments
Blair et al.[12]	IQ<20	N/A	0	25	Australia (Western Australia)
	IQ 20–34	N/A	0	48	
	IQ 35–49	N/A	0	77	
	IQ 50–69	N/A	0	—[c]	
	Mild CP	732	0	77	
	Moderate CP	584	0	71	
	Severe CP	470	0	41	
Hutton and Pharoah[32]		1942			England (Merseyside and Cheshire regions). The survival probabilities used in these analyses are based on a multivariate accelerated life model that presumably used all 1942 participants (with some possible exclusions because of missing values)
	No severe disabilities, low birthweight	N/A	2	—[c]	
	Severe ambulatory disability only; low birthweight	N/A	2	72	
	Severe ambulatory disability only; normal birthweight	N/A	2	68	
	Severe motor, low birthweight	N/A	2	54	
	Severe motor, normal birthweight	N/A	2	48	
	Severe motor and cognitive, low birthweight	N/A	2	38	
	Severe motor and cognitive, normal birthweight	N/A	2	32	
	Severe motor, cognitive and visual, low birthweight	N/A	2	25	
	Severe motor, cognitive, visual, normal birthweight	N/A	2	21	
Tsirikos et al.[10]		288	15	24	Greece
Strauss et al.[9]	Some walking	540	60	20	
	No walking, some mobility	345	60	14	
	No mobility	19	60	9	UK (United Kingdom Collaborative Network of Cerebral Palsy Registers)
Hemming et al.[33]	2. Severe disabilities	194	2	55	
	3. Severe disabilities	265	2	34	
	4. Severe disabilities	211	2	18	
Wockenforth et al.[34]	Status-post Nissen fundoplication and gastrostomy	61	5	15	
Westbom et al.[35]	GMFCS level V	102	2	29 (20–39)	Sweden
Westbom et al.[35]	GMFCS level V, tube fed	N/A	2	20	With adjustment for feeding tube, based on relative risk derived from results in Brooks et al.[36]
Westbom et al.[35]	GMFCS level V, not tube fed	N/A	2	31	With adjustment for no feeding tube, based on relative risk derived from results in Brooks et al.[36]
Reid et al.[38]	Mild+no additional impairments	1478	0	—[c]	Australia (Victoria)
	Mild+three additional impairments	41	0	68 (51–78)	
	Moderate+three additional impairments	39	0	72 (54–80)	
	Severe+three additional impairments	352	0	25 (22–28)	
Touyama et al.[39]	GMFCS level V	166	4	36	Japan

Table II: Continued

Study	Cohort/group	Number in cohort	Age (y)[a]	Life expectancy (95% CI)[b]	Comments
Brooks et al.[1]					USA (California). This study reported life expectancies for adolescents and adults at ages 15y, 30y, and 45y, and we do not repeat those in this table. The study also reported survival probabilities but no life expectancies for 15 cohorts of children aged 4y with CP, and we provide here estimates of life expectancy for 14 of them (one cohort, that of children unable to lift their heads from a prone position and fed by a feeding tube, was too small to warrant analysis). The figures given are based on survival probabilities adjusted to 2010, with unadjusted figures (based on Kaplan–Meier survival from 1983 to 2010) given in parentheses for comparison. No confidence intervals on survival probabilities were reported, thus no confidence intervals on life expectancy are reported here
	ULH, tube fed	482	4	18 (16)	
	ULH, FBO	615	4	26 (24)	
	LH, tube fed	303	4	21 (19)	
	LH, FBO	795	4	28 (26)	
	LH, feeds self orally	103	4	48 (46)	
	LH/chest, partial rolling, tube fed	265	4	24 (22)	
	LH/chest, partial rolling, FBO	962	4	33 (31)	
	LH/chest, partial rolling, feeds self orally	329	4	49 (47)	
	Full rolling, does not walk unaided, tube fed	475	4	33 (31)	
	Full rolling, does not walk unaided, fed orally by others	1643	4	49 (48)	
	Full rolling, does not walk unaided, feeds self orally	4906	4	65 (64)	
	Walks unaided, tube fed	125	4	48 (46)	
	Walks unaided, fed orally by others	188	4	59 (58)	
	Walks unaided, feeds self orally	5199	4	68 (68)	

[a]Age represents the age at the beginning of follow-up for those studies in which the baseline for follow-up was a fixed starting age, or the mean age at start of follow-up for those studies in which the baseline for follow-up was time at entry into the study for an age-heterogeneous cohort. [b]Remaining years of life expectancy, with 95% CI based on the respective 95% CI on estimates of survival probabilities reported in some studies given in parentheses. (Note that for Brooks et al.[1] the single number in parentheses is the unadjusted estimate of life expectancy, as explained in the table comment.) [c]Life expectancy essentially normal for respective country of study. LAS, Lifestyle Assessment Score; GMFCS, Gross Motor Function Classification System; ULH, unable to lift head from prone; FBO, fed orally by others; LH, lifts head, but not chest.

cohort or individual will remain unchanged relative to the defining characteristics in question (here the ability to roll over and sit, and the inability to walk) throughout life. More likely we are interested in knowing the life expectancy of a person meeting the criteria today without the benefit of knowing what the future may hold for that person. In this case, a better approach is a cohort analysis of mortality rates that accounts for the probabilities of developmental progress (or decline) over time. The person-year approach may underestimate the life expectancy of a cohort (or of a member of it) if the likelihood of progression to a higher level of functioning is high, or overestimate life expectancy if the likelihood of decline to a lower level of functioning is high. The differences in life expectancy resulting from the two approaches can be large, especially for very young children who, on average, have a substantial probability of making significant developmental gains over time; but this is also true for adolescents or adults, who sometimes have a significant probability of decline in function over time. With regard to the cohort approach being more appropriate in the analysis of an individual's life expectancy, we agree with Strauss, who remarked in a

letter explaining some of the problems with a 1993 analysis of life expectancy by Eyman et al.,[52] 'For the estimation of a life expectancy (e.g. in litigation) the cohort approach is the correct one.'[53]

Thus we seek to extrapolate survival information for cohorts over a limited period of follow-up to obtain full survival curves and the corresponding life expectancy estimates for the cohorts. Methods of extrapolation generally rely on assumed future relationships between mortality rates in a CP cohort with the corresponding (hypothetical, period-based) mortality rates in age- and sex-matched general populations. We mentioned above a simple assumption of constant relative risk that had been used for many years in the life insurance industry.[18] For many chronic but non-progressive medical conditions (see notes above about the possible exception of Down syndrome, for example), this method results in future mortality rates that are too high, and thus life expectancies that are too low.[18,24,25,49] An alternative is the assumption of constant excess death rates (EDRs): if mortality rates for a population with CP are observed to exceed those of the general population by, for example, 100 deaths per 1000 person-years during a study's follow-up period, it might be assumed they will continue to exceed general population mortality rates by this flat amount through all remaining ages in the life table. This assumption has been observed to underestimate future mortality rates in several chronic medical conditions, including CP.[18,24,25,49] The assumption of PLE falls between these two methods. Under this method, relative risks decline with increasing age, while EDRs rise.[24,25,49] We will examine and compare these methods as applied in two examples. We will also include an illustration of two additional, extreme assumptions. The extremes are included to illustrate an important point: even under extremely conservative assumptions about our ability to know mortality rates for a CP cohort beyond the period of a given study, some bounds on the possible life expectancy of the cohort can nevertheless be determined. Full details of the mathematical calculations involved in the PLE method are provided in Strauss et al.[25]

EXAMPLE 1

Consider Figure 2a, reproduced from Strauss et al.[6] The study reported improvement in survival from 1983 to 2002 for certain CP populations. The figure illustrates survival probabilities of a sub-cohort of 4-year-old children with CP with severe limitations in independent motor functioning and self-feeding ability. The two curves illustrate the improvement in survival over the years for the defined sub-cohort. The probability of survival to age 14 years was 53% based on unadjusted 1983 to 1995 data, and 67% adjusted to 2002 mortality rates using the 3.4% per year reduction in mortality rates from 1983 to 2002 reported in the study. The figure in Strauss et al.[6] included estimates of median survival times and life expectancies. This is noteworthy, because the available follow-up was not sufficient to determine either directly (and certainly not everyone had died). The authors indicated that 'standard methods' led to the reported life expectancies of 14 (unadjusted) and 20 (adjusted) remaining years. The standard method was PLE. We will explore this visually now, alongside the alternatives discussed above. We focus on the adjusted survival curve, isolated in Figure 2b.

Figure 2c puts the curve in the context of the full survival curve for the US general population of males and females.[40] The life expectancy is the area under the curve in each case, bounded by the horizontal and vertical axes of the graph. In the case of the US general population, the area is completely determined, but for the CP curve, the area beyond the period of follow-up, in this case beyond 14 years of age, is uncertain. Given the unavoidable and irreversible nature of mortality, we do know that the CP survival curve from age 14 onwards can only continue to fall. For the children with CP, the area bounded by the curve must be smaller than that of the general population. The defined CP sub-cohort must have a lower life expectancy than that of the corresponding general population.

The CP survival curve must continue on a downward course, but many trajectories are possible. Hutton alluded to some possible actuarial assumptions for the completion of the CP curve in her 2006 review,[7] and Strauss et al.[25] examined several of these and others in their 2005 methodology review, providing details and comparison of results. In Figure 2d we provide trajectories based on assumptions that have been suggested in the literature, along with two that provide unrealistically high and low bounds on the ultimate answer we seek: the area under the CP curve from age 4 to age 110, i.e. the CP life expectancy.

The methods of extrapolation depicted in Figure 2d are (1) zero EDRs beyond the last point of available data (unrealistic, providing an unrealistically high gross upper bound on life expectancy), (2) constant EDR, (3) PLE, (4) constant relative risk, and (5) impending death, considered here to be the death of all who remain alive beyond age 14 within a year after the end of available follow-up (unrealistic, providing an unrealistically low gross lower bound on life expectancy). The assumptions of zero EDRs and impending death are both unrealistic. They are contrary to all evidence leading up to the end of available follow-up, and contrary to abundant outside evidence from other studies of survival of children with CP. The likelihood of death does not suddenly jump to near certainty after the end of an arbitrary study period (impending death); nor do EDRs drop suddenly to zero after having been substantially above that for years (zero EDRs). These two unrealistic situations illustrate, however, that even under the most extreme possibilities for what the future may hold, some clear bounds on the life expectancy can be determined.

Each method can be, and each of the more reasonable methods has been, compared with how empirical data play out in cases for which very long-term data are available. Of the five depicted in Figure 2d, PLE performed best in the case of CP.[25] Another method, the assumption of
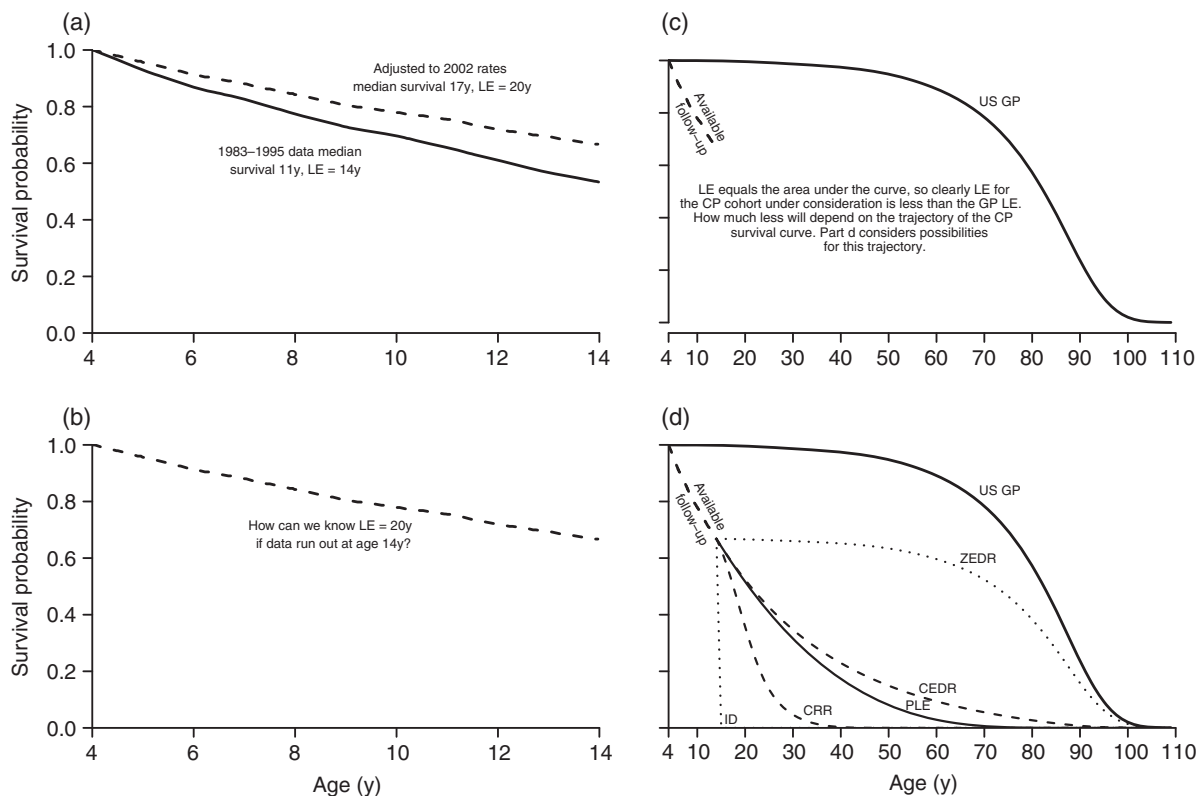
Figure 2: (a) From Strauss et al.:[6] Survival of children aged 4 years with cerebral palsy (CP), who did not lift head in prone, and who were fed by others (either orally or by gastrostomy). Curves show proportion of persons surviving to each age. Solid curve is based on 1983 to 1995 data; dotted curve is adjusted to 2002 mortality rates. Respective 10-year survival probabilities, for example, are 53% and 67%. Use of standard methods yields respective medians of 11 years and 17 years, and life expectancies of 14 years and 20 years respectively. (b) The adjusted to 2002 mortality rates curve isolated for illustration. (c) The adjusted CP survival curve superimposed on the full US GP survival curve. (d) Possible future trajectories to age 100 and beyond for the CP cohort adjusted survival curve. LE, life expectancy; GP, general population; ZEDR, zero excess death rate; CEDR, constant excess death rate; PLE, proportional life expectancy; CRR, constant relative risk; ID, immediate death (in the next year); US GP, United States general population.

linearly declining logarithm of relative risk of mortality rates, performed nearly as well for CP, and in fact performed better in other settings.[25] As we have indicated, we choose here to use the method of PLE in part because it performed well for CP, and in part because it is the method used in the most recent studies to report life expectancy in CP.[1,4,6] In the present case, the PLE method leads to a life expectancy of 20 remaining years for the sub-cohort whose (adjusted) survival is depicted in Figure 2b, just as the original study reported.[6]

EXAMPLE 2

Figure 3 provides another illustration of the process. We have begun with a smoothed version of the survival curve for children with severe CP depicted in Figure 3 of Blair et al.[12] (the dotted curve labeled 'available follow-up' in our Fig. 3). Trajectories are illustrated based on the same five assumptions discussed for Figure 2. In this case, the curves are superimposed on the full survival curve for the Australian general population of males and females.[41] We have used Australian general population mortality rates for

1978 (the midpoint of the study follow-up) to obtain EDRs over the 25 years of available CP follow-up. The assumption of PLE (using the latest Australian mortality rates as the baseline for the application of PLE) leads to a life expectancy estimate of 40.6 remaining years from birth for the CP sub-cohort.

RESULTS

Our review identified 17 studies including more than 60 sub-cohort estimates of long-term survival that would potentially allow for the calculation of life expectancy using the methods we have described. We have used these methods to produce the sub-cohort-based estimates of life expectancy reported in Table II. For those studies that reported 95% confidence limits on estimates of survival probabilities, we also report corresponding 95% confidence limits resulting from applying the above methods to those limits. Some further details on each calculation are provided in Table II and its footnotes. Further detailed information on the steps involved in the calculations is available on request from the first author.
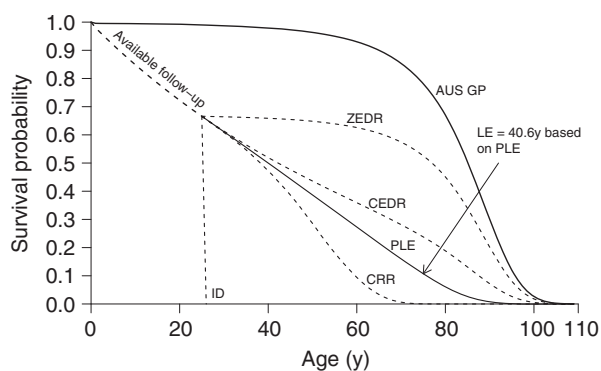
Figure 3: Survival for children with severe CP as described in Blair et al.[12] and extrapolated to complete the survival curve using the methods described in the text. GP, general population; ZEDR, zero excess death rate; LE, life expectancy; PLE, proportional life expectancy; CEDR, constant excess death rate; CRR, constant relative risk; AUS GP, Australia general population; ID, immediate death (i.e., death certain within the next year).

DISCUSSION

The life expectancy estimates provided in Table II illustrate and reinforce several important findings from numerous studies of survival of children and adolescents with CP. The table dramatically illustrates that CP is a heterogeneous condition in terms of life expectancy. For children or adolescents with CP, life expectancy may be only modestly lower than, or nearly equal to, that of age- and sex-matched general populations. It is plausible that a given individual with very mild CP may have a normal or even higher than normal life expectancy. On the other hand, Hall was absolutely correct in noting that, 'there is a subgroup (of children with CP) with profound and multiple disabilities whose life expectancy is severely curtailed.'[54] This comment was made in a letter to the editor about the Canadian study by Crichton et al.[15] Crichton replied to Hall, noting that,[54] 'Any experienced clinician will agree with Professor Hall that there is a cohort of these children who are so severely affected that they have a greatly shortened life-span.' The results in Table II identify several specific functional criteria that are predictive of life expectancy. Many of these criteria are key milestones such as the ability to lift one's head and chest, sit unsupported, roll, feed oneself, and walk (with or without assistive devices). Clearly the theme is that independent mobility is a key factor for survival. For children who are independently ambulatory, life expectancy may approach normal for age and sex. At the other end of the spectrum, children unable to lift their heads from a prone position may have life expectancies less than 20% of normal.

Feeding ability is also a critical predictor of life expectancy. For example, consider the 4-year-olds described in Brooks et al.[1] who were able to roll and sit independently. Life expectancy (adjusting to 2010 mortality rates) for those who had some ability to self-feed was 65 remaining years, whereas for those fed by others it was 49 (Table II).

The need for a feeding tube is a marker for particularly low life expectancies overall, which is largely associated with it being a marker for more severe disability overall. The results also identify several factors beyond mobility or feeding that have further impact on survival. These include epilepsy, severe visual or hearing impairment, cognitive impairment, non-verbal status, low birthweight, and low gestational age. The last two factors have been shown to have a perhaps counterintuitive association with survival: among children with CP of comparable level of severity, those of low birthweight or low gestational have lower mortality rates, and thus longer life expectancies.

There are several potential limitations to the results presented in Table II. Some limitations derive from limitations in the source reports. To point to a small example, the fact that the survival curve in Blair et al.[12] used in Example 2 begins at age 0 (Fig. 3) may be problematical. Children are generally not diagnosed with CP in infancy. If the diagnosis is not made until age 2 or later, this may introduce a bias in the survival analysis (the so-called 'immortal time bias'[55]). Starting the survival analysis at age 0 may result in 100% survival from age 0 to age 2 or older, which is unrealistic. Another important limitation is that the defined levels of disability are often unique to the given study (and perhaps a few other studies based on the same data source), thus making direct comparisons with other results difficult. In recent years, several studies have reported on the life expectancy of children with CP based on Gross Motor Function Classification System (GMFCS) level.[27–31] This is a positive development for future comparative analyses of life expectancy between CP care settings globally.

There are also limitations related to the methodology. For example, our smoothing of the curve in Example 2 (we have assumed a constant EDR compared with the Australian 1978 general population during the 25y of follow-up) may affect the calculations somewhat. In addition, the method of PLE requires a determination of an EDR as of the final year of follow-up in a given study, and there are various ways this might be achieved. In each calculation in this study, we have assumed a constant EDR during the period of a given study, determined as the difference in the average mortality rate observed in the study and that of an age-, country-, and calendar-year-matched general population of males and females from the Human Mortality Database.[41] These EDRs were then applied to the most current mortality rates from the Human Mortality Database for the country in question for males and females combined, and extrapolated using PLE. Alternative approaches to this determination of an EDR are possible. These and other considerations can, in some cases, have significant implications. In most cases, adjustments to account for such considerations will lead to fine-tuning of results, but the methodology is relatively robust to such modifications.

In reviewing the results in Table II, the reader should bear in mind the specifics of the defining characteristics of

the sub-cohorts. We have described these briefly in the table; however, to make the most sense of the estimates, the original sources should be consulted for further clarification.

Applicability

In general, the defining criteria for the sub-cohorts make interpretation challenging. Consider the problem of estimating the life expectancy of a 2-year-old child with CP who is unable to walk, able to self-feed, and who has an unknown IQ. Relative to such a child, results based on Hutton et al.[16] are of interest. On the one hand, the child meets the criteria for severe ambulatory disability as defined in this study. Survival for this group leads to a life expectancy estimate of 29 remaining years (Table II). However, many of the children with severe ambulatory disability also had severe manual and cognitive disabilities, while the child in question has at most just one of these (given the unknown IQ), and may well have neither. A life expectancy of 29 remaining years is probably too low for this child. Alternatively, results for children with one severe disability are relevant, as this child may meet the study criteria for one severe disability (depending on IQ). Life expectancy for this group is 66 remaining years. However, some children in the one-severe-disability group could walk, feed, and dress themselves, and thus 66 remaining years is probably too high for the child in question. Such considerations shed light on the life expectancy of the child in question, but a wide range of possibilities remain. By considering multiple sources and results, the range can often be narrowed. Our hope for future research is that studies will routinely stratify by, or control simultaneously for, levels of functioning on the GMFCS, the Manual Ability Classification System,[56] the Communication Function Classification System,[57] and the Eating and Drinking Ability Classification System.[58] Each of these measures a different aspect of disability, and each is in some sense also a measure of overall severity of neurological injury. Accounting for all of these variables simultaneously may require large sample sizes, but the use of these uniform classification systems will make it possible to combine data from different settings for long-term cohort analyses.

Also related to applicability of results, we must comment on the those relating to observed improvement in survival in the latest studies based on the data of the California Department of Developmental Disabilities.[1,6,45] Strauss et al.,[6] in their 2008 study, originally reported an improvement in survival from 1983 to 2002 for the most severely impaired children with CP and for adults requiring tube feeding, and in 2014 Brooks et al. expanded on this and carried the analysis through to 2010.[1,45] In Brooks et al.,[1] survival probabilities for 4-year-olds in various functional ability strata are reported, both unadjusted (thus based on data running from 1983–2010) and adjusted to 2010 mortality rates based on the annual decline in mortality reported in the first part of their study.[45] Resulting life

expectancies based on the unadjusted and adjusted rates differ by a year or two in most cases (Table II). It might be argued that a similar adjustment may be needed in other reported estimates of life expectancy. However, other researchers have yet to identify a similar trend of falling mortality rates in CP. Whether the observed improvement in survival derives from real improvements on an individual basis (e.g. owing to improvements in care and treatment), or whether it may represent a change in the overall population of CP over time, is uncertain. As Reid noted in her commentary[59] on the latest research by Brooks et al., the observed improvements in survival do suggest that changes to clinical practice may be having some benefit. As Reid also notes, however, these findings of improved survival have not been replicated outside California, or through alternative methodologies.

Possibly related to the last point, it has been reported that children born prematurely or of low birthweight who are ultimately diagnosed with CP have lower mortality, other factors being equal, than children born at term or of normal birthweight.[8,32,33,38] As prematurity or low birthweight were not included as covariates in Brooks et al.,[1] it is possible that the observed improvement in survival may represent an increased proportion in recent years of children with CP who were born prematurely. This idea is not far-fetched. In 1990, Pharoah et al.[60] reported data showing a clear trend in increasing proportions of low or very low birthweight among cases of CP in the Mersey region of England from 1967 to 1984. Children of low or very low birthweight accounted for a steadily rising proportion of all cases of CP, from roughly 25% in the late 1960s to early 1970s, up to 50% in the early 1980s.[60] As Brooks et al.[1] note, there are other possible explanations for the observed trends, including shifts in medical treatment related to feeding tube placement, and general improvements in medical care and treatment mirroring those in the general population. If the observed improvements in survival are real for individuals with CP and a consequence of improvements in care and treatment, the results will undoubtedly be replicated in other settings in the near future.

CONCLUSION

Estimating life expectancy for children with CP is not always a straightforward task. Issues of incomplete follow-up necessitate extrapolation of mortality rates to ages and years that have yet to be observed. Study cohorts are often heterogeneous with respect to functional abilities, complicating interpretation of life expectancy estimates derived from these cohorts. However, much progress has been made in understanding the factors influencing life expectancy in CP. For example, it is now indisputable that the level of independent gross motor functional ability is a very strong determinant of life expectancy. It is therefore crucial to control for the level of gross motor functional ability to the extent possible when exploring the influence of other factors.

In the near future we should capitalize on the development of the GMFCS to help standardize the ways in which we study survival in CP. Combining the GMFCS with the Manual Ability Classification System or other validated measures of level of disability will undoubtedly improve the ability to estimate life expectancy accurately for persons with CP. Accounting for GMFCS level or other validated measures of abilities in studies of long-term survival in CP will allow more meaningful comparisons of results both globally and across care settings. This may in turn aid in comparing the effectiveness of treatments or therapies, and will help us understand the changing nature of mortality in CP.

REFERENCES

1. Brooks JC, Strauss DJ, Shavelle RM, Tran LM, Rosenbloom L, Wu YW. Recent trends in cerebral palsy survival. Part II: individual survival prognosis. *Dev Med Child Neurol* 2014; **56**: 1065–71.

2. Katz RT, Johnson CB. Life care planning for the child with cerebral palsy. *Phys Med Rehabil Clin N Am* 2013; **24**: 491–505.

3. Roebroeck ME, Jahnsen R, Carona C, Kent RM, Chamberlain MA. Adult outcomes and lifespan issues for people with childhood-onset physical disability. *Dev Med Child Neurol* 2009; **51**: 670–8.

4. Strauss D, Brooks J, Rosenbloom L, Shavelle R. Life expectancy in cerebral palsy: an update. *Dev Med Child Neurol* 2008; **50**: 487–93.

5. Young NL. The transition to adulthood for children with cerebral palsy: what do we know about their health care needs? *J Pediatr Orthop* 2007; **27**: 476–9.

6. Strauss D, Shavelle R, Reynolds R, Rosenbloom L, Day S. Survival in cerebral palsy in the last 20 years: signs of improvement? *Dev Med Child Neurol* 2007; **49**: 86–92.

7. Hutton JL. Cerebral palsy life expectancy. *Clin Perinatol* 2006; **33**: 545–55.

8. Hutton JL, Pharoah POD. Life expectancy in severe cerebral palsy. *Arch Dis Child* 2006; **91**: 254–8.

9. Strauss D, Ojdana K, Shavelle R, Rosenbloom L. Decline in function and life expectancy of older persons with cerebral palsy. *NeuroRehabilitation* 2004; **19**: 69–78.

10. Tsirikos AI, Chang WN, Dabney KW, Miller F, Glutting J. Life expectancy in pediatric patients with cerebral palsy and neuromuscular scoliosis who underwent spinal fusion. *Dev Med Child Neurol* 2003; **45**: 677–82.

11. Katz RT. Life expectancy for children with cerebral palsy and mental retardation: implications for life care planning. *NeuroRehabilitation* 2003; **18**: 261–70.

12. Blair E, Watson L, Badawi N, Stanley FJ. Life expectancy among people with cerebral palsy in Western Australia. *Dev Med Child Neurol* 2001; **43**: 508–15.

13. Strauss D, Shavelle R. Life expectancy of adults with cerebral palsy. *Dev Med Child Neurol* 1998; **40**: 369–75.

14. Strauss DJ, Shavelle RM, Anderson TW. Life expectancy of children with cerebral palsy. *Pediatr Neurol* 1998; **18**: 143–9.

15. Crichton JU, Mackinnon M, White CP. The life-expectancy of persons with cerebral palsy. *Dev Med Child Neurol* 1995; **37**: 567–76.

16. Hutton JL, Cooke T, Pharoah POD. Life expectancy in children with cerebral palsy. *BMJ* 1994; **309**: 431–5.

17. Schlesinger ER, Allaway NC, Peltin S. Survivorship in cerebral palsy. *Am J Public Health Nations Health* 1959; **49**: 343–9.

18. Singer RB. A method of relating life expectancy in the U.S. population life table to excess mortality. *J Insur Med* 1992; **24**: 32–41.

19. Messori A. Survival curve fitting using the Gompertz function: a methodology for conducting cost-effectiveness analyses on mortality data. *Comput Methods Programs Biomed* 1997; **52**: 157–64.

20. Strauss D, Shavelle R, Pflaum C, Bruce C. Discounting the cost of future care for persons with disabilities. *J Forensic Econ* 2001; **14**: 79–87.

21. Kush SJ, Day S, Reynolds R. Life expectancy for life care planners. *J Life Care Plan* 2013; **12**: 31–49.

22. Werth B. Damages. New York, NY: Berkley, 1988.

23. Strauss D, Shavelle R. Life expectancy of persons with chronic disabilities. *J Insur Med* 1998; **30**: 96–108.

24. Anderson TW, Marion SA. Estimating mortality rates: the role of proportional life expectancy. *J Insur Med* 2005; **37**: 35–41.

25. Strauss DJ, Vachon PJ, Shavelle RM. Estimation of future mortality rates and life expectancy in chronic medical conditions. *J Insur Med* 2005; **37**: 20–34.

26. Day SM, Strauss DJ, Shavelle RM, Reynolds RJ. Mortality and causes of death in persons with Down syndrome in California. *Dev Med Child Neurol* 2005; **47**: 171–6.

27. Strauss D, Eyman RK. Mortality of people with mental retardation in California with and without Down syndrome, 1986–1991. *Am J Ment Retard* 1996; **100**: 643–53.

28. Evans PM, Evans SJ, Alberman E. Cerebral palsy: why we must plan for survival. *Arch Dis Child* 1990; **65**: 1329–33.

29. McGrath SJ, Splaingard ML, Alba HM, Kaufman BH, Glicklick M. Survival and functional outcome of children with severe cerebral palsy following gastrostomy. *Arch Phys Med Rehabil* 1992; **73**: 133–7.

30. Smith SW, Camfield C, Camfield P. Living with cerebral palsy and tube feeding: a population-based follow-up study. *J Pediatr* 1999; **135**: 307–10.

31. Hutton JL, Colver AF, Mackie PC. Effect of severity of disability on survival in north east England cerebral palsy cohort. *Arch Dis Child* 2000; **83**: 468–74.

32. Hutton JL, Pharoah POD. Effects of cognitive, motor, and sensory disabilities on survival in cerebral palsy. *Arch Dis Child* 2002; **86**: 84–9.

33. Hemming K, Hutton JL, Colver A, Platt MJ. Regional variation in survival of people with cerebral palsy in the United Kingdom. *Pediatrics* 2005; **116**: 1383–90.

34. Wockenforth R, Gillespie CS, Jaffray B. Survival of children following Nissen fundoplication. *Br J Surg* 2011; **98**: 680–5.

35. Westbom L, Bergstrand L, Wagner P, Nordmark E. Survival at 19 years of age in a total population of children and young people with cerebral palsy. *Dev Med Child Neurol* 2011; **53**: 808–14.

36. Brooks JC, Shavelle RM, Strauss DJ. Survival in children with severe cerebral palsy: a further international comparison. *Dev Med Child Neurol* 2012; **54**: 383–4.

37. Brooks J, Tran L, Shavelle R, Strauss D. Concordance of survival models for children with cerebral palsy: a 24-year follow-up in the California database. *Dev Med Child Neurol* 2012; **54**(Suppl. 6): 46–7.

38. Reid SM, Carlin JB, Reddihough DS. Survival of individuals with cerebral palsy born in Victoria, Australia, between 1970 and 2004. *Dev Med Child Neurol* 2012; **54**: 353–60.

39. Touyama M, Touyama J, Ochiai Y, Toyokawa S, Kobayashi Y. Long-term survival of children with cerebral palsy in Okinawa, Japan. *Dev Med Child Neurol* 2013; **55**: 459–63.

40. Arias E. United States life tables, 2010. *Natl Vital Stat Rep* 2014; **63**: 1–63.

41. Human Mortality Database. University of California, Berkeley and Max Planck Institute for Demographic Research. Available at http://www.mortality.org (accessed 20 April 2014).

42. Office for National Statistics. Statistical Bulletin: Historic and Projected Mortality Data from the Period and Cohort Life Tables, 2012-Based, UK 1981–2062. London: Office for National Statistics, 2013.

43. Continuous Mortality Improvement. Institute and Faculty of Actuaries. Available at http://www.actuaries.org.uk/research-and-resources/pages/continuous-mortality-investigation (accessed 16 February 2015).

44. Bell FC, Miller ML. Life tables for the United States Social Security Area 1900–2100. Actuarial Study No. 120. United States Social Security Administration. Available at http://www.ssa.gov/OACT/NOTES/as120/TOC.html (accessed on 20 April 2014).

45. Brooks JC, Strauss DJ, Shavelle RM, Tran LM, Rosenbloom L, Wu YW. Recent trends in cerebral palsy survival. Part I: period and cohort effects. *Dev Med Child Neurol* 2014; **56**: 1059–64.

46. Brackenridge RDC, Croxon R, Mackenzie BR, editors. Medical Selection of Life Risks. 5th edn. New York, NY: Palgrave Macmillan, 2006.

47. Lew EA, Gajewski J, editors. Medical Risks: Trends in Mortality by Age and Time Elapsed. New York, NY: Praeger, 1990.

48. Singer RB, Kita MW, Avery JR, editors. Medical Risks: 1991 Compend of Mortality and Morbidity. New York, NY: Praeger, 1994.

49. Anderson TW. Life Expectancy in Court: A Textbook for Doctors and Lawyers. Vancouver, BC: Teviot Press, 2002.

50. Plover C. Life expectancies for individuals with cerebral palsy. Cumpston Sarjeant. Available at http://www.cum-sar.com.au/docs/cerebral_palsy.pdf (accessed 16 February 2014).

51. Slesnick S, Thornton R. Life expectancies for persons with medical risks. *J Forensic Econ* 1994; **7**: 197–207.

52. Eyman RK, Grossman HJ, Chaney RH, Call TL. Survival of profoundly disabled people with severe mental retardation. *Am J Dis Child* 1993; **147**: 329–36.

53. Strauss D. Life expectancies in children with cerebral palsy. *Lancet* 1997; **349**: 283–4.

54. Hall DM. The life expectancy of persons with cerebral palsy. *Dev Med Child Neurol* 1995; **37**: 1032–3.

55. Lévesque LE, Hanley JA, Kezouh A, Suissa S. Problem of immortal time bias in cohort studies: example using statins for preventing progression of diabetes. *BMJ* 2010; **340**: b5087.

56. Eliasson AC, Krumlinde-Sundholm L, Rösblad B, et al. The Manual Ability Classification System (MACS) for children with cerebral palsy: scale development and evi-dence of validity and reliability. *Dev Med Child Neurol* 2006; **48**: 549–54.

57. Hidecker MJ, Paneth N, Rosenbaum PL, et al. Develop-ing and validating the Communication Function Classi-fication System for individuals with cerebral palsy. *Dev Med Child Neurol* 2011; **53**: 704–10.

58. Sellers D, Mandy A, Pennington L, Hankins M, Morris C. Development and reliability of a system to classify the eating and drinking ability of people with cerebral palsy. *Dev Med Child Neurol* 2014; **56**: 245–51.

59. Reid SM. Trends in cerebral palsy survival: are health measures really making a difference? *Dev Med Child Neurol* 2014; **56**: 1034–5.

60. Pharoah PO, Cooke T, Cooke RW, Rosenbloom L. Birthweight specific trends in cerebral palsy. *Arch Dis Child* 1990; **65**: 602–6.