Health Expectancy: An Overview

Yasuhiko Saito
Eileen M. Crimmins
Mark D. Hayward

NUPRI Research Paper Series No.67

March 1999

Yasuhiko Saito

Associate Professor
Center for Information Networking
Nihon University
Japan

Eileen M. Crimmins

Edna M. Jones Professor of Gerontology
Andrus Gerontology Center
University of Southern California
USA

Mark D. Hayward

Professor
Population Research Institute
The Pennsylvania State University
USA

CONTENTS

FIGURE AND TABLES

I. Introduction

This article provides a general description of the concept of **health expectancy**, which aims to explain its meaning and the methods of calculation to researchers who are interested in studying this topic. Health expectancy is a general term for the portions of life expectancy divided into healthy years and unhealthy years (Mathers, Robine, and Wilkins, 1994). Depending on the measures used to indicate health, healthy years can be called "healthy life expectancy", "disability-free life expectancy" or "active life expectancy". The development of this measure represents an increased emphasis on quality of life (proportion of healthy years) rather than just quantity of life (length of life expectancy). In the following sections, definitional issues, computational methods, and issues encountered in estimating health expectancy are discussed.

Nihon University Population Research Institute (NUPRI) held an international academic meeting in 1997 entitled "Disseminating the concept of health expectancy in Asia" as the 10th meeting of REVES (Réseau Espérance de Vie en Santé: International Network on Health Expectancy or The International Research Network for Observed Values of Healthy Life Expectancy). REVES is an international organization of researchers and health planners from universities, governments, and international agencies dedicated to understanding the use of health expectancy as an indicator of population health and as a tool for health planning. Publication of this article is part of the continuing effort of NUPRI to promote the concept of health expectancy. This paper will begin a series of health expectancy related articles to be published by NUPRI.

II. Background

The concept of health expectancy was introduced in the 1960s (Sanders, 1964) and developed in the 1970s (Sullivan, 1966, 1971a, 1971b). Recently, there has been great interest in the estimation of health expectancy among both policy makers and members of the research community. This interest arises from the fact that measures of health expectancy potentially offer easily comprehensible indicators of both the level of, and change in, physical and/or mental well-being among a population. Because these measures incorporate indicators of both mortality and morbidity, they seem highly appropriate as summary measures of the effects of changing health status and mortality schedules in populations where mortality decline is dominated by declining death rates due to chronic diseases among the older population. Much of the recent interest in health expectancy has been generated by interest in the issue of the "Compression of Morbidity" (Fries, 1981). James Fries theorized that we should begin to observe improvements in health because he assumed a decrease in the incidence of disease was the cause of mortality decline. He conjectured that people were living longer, healthy lives. In contrast, Morton Kramer (1980) and Ernest Gruenberg (1977) conjectured that the incidence of ill health and disability should increase because, in their view, the recent mortality decline resulted from prolonging the lives of people who have relatively debilitating diseases. Measures of health expectancy can provide empirical evidence to address this debate on the expected relationship between mortality decline and population health.

Testimony to the interest of researchers in the concept of health expectancy is provided by the large number of articles published over the last 15 years which contain estimates of health expectancy and/or discussions of alternative computational strategies for obtaining these estimates (A sampling includes: Barendregt et al., 1994; Bebbington, 1988, 1991; Branch et al., 1991; Colvez and Robine, 1986; Crimmins, Hayward and Saito, 1994, 1996; Crimmins, Saito, and Ingegneri, 1989, 1997; Guralnik at al., 1993; Katz, et al., 1983, 1985; Land et al.,

1994; Liu et al., 1995; Mathers, 1991; Manton and Stallard, 1990, 1991; Manton, Stallard and Liu, 1993; Robine, 1986; Robine and Ritchie, 1991; A. Rogers et al., 1989, 1990; R. Rogers et al. 1989; Tsuji et al., 1995; Nusselder, 1998). There have been eight volumes of proceedings from meetings of REVES, of which at least three are available from publishers (Robine, Blanchet, and Dowd, 1992; Robine, Mathers, Bone and Romieu, 1993; Mathers, McCallum and Robine, 1994), and one is published as a special issue of a journal (*Journal of Aging and Health*, Vol. 10, No. 2, 1998). In addition, a special issue on health expectancy was published in *Cahiers Québécois de Démographie* (Vol. 20, No. 2, 1991). Periodically REVES has also produced bibliographies of relevant literature. Finally a number of governments and international agencies have prepared reports that either address methodological and theoretical issues or provide empirical estimates for individual or multiple countries (Mathers, 1991; Bone et al., 1995; TNO Health Research, 1994; World Health Organization, 1995).

III. Definitional Issues

Healthy life expectancy has been conceived as life without disability, functioning problems, dependency, and/or disease. Usually it has been defined in terms of long-term or chronic conditions rather than short-term or acute conditions but sometimes both have been included. In practice, most estimates of health expectancy for the total population have actually been estimates of disability-free life expectancy; while those estimated for the older population have usually been estimates of life without ADL or IADL impairment or difficulty. ADL (Activities of Daily Living) includes such activities as bathing, eating, dressing, toileting, walking etc. IADL (Instrumental Activities of Daily Living) includes shopping for personal items, preparing one's own meal, managing money, telephoning, etc. Many people have also estimated life without one or more specific diseases. Issues related to the use of the three dimensions of disability, functioning, and disease are discussed further in the following sections.

A. Disability

As noted above, disability-free life expectancy is the most commonly estimated indicator of health expectancy at birth because it is the indicator for which data are collected in most surveys that span the age range in most countries. In all applications of the method questions arise as to the comparability of the definition of disability across the age range and over time. Since disability is the inability to perform a social role (e.g. work, go to school, perform self-care), if expected social roles vary by age, it may be difficult to have one definition that is appropriate across ages.

Another issue that must be considered in use of this measure to monitor trends is that disability is affected not only by health and physical and mental functioning but also by the level of difficulty faced in performing social roles. If school and work are made more accessible to those with handicaps, people may

have less trouble performing their expected roles when there has been no physical change. Or, if attitudes toward ability to work with diseases and impairments change over time, a population could change its assessment of its ability to work. As jobs become less physically demanding, workers may be more able to work even though average physical condition stays the same. Disability defined in terms of ability to provide self care in terms of shopping, transportation, cooking, etc. may be highly affected by changes in technology and services (e.g. microwaves, delivery of groceries, transportation services). All of these are examples of how the disability level may change without a change in physical ability.

The point of this discussion is not that disability, or estimates of healthy life based on disability, are not correctly measured or represented by conventional methods of collecting disability information; but to indicate that one cannot assume that an increase in nondisabled life expectancy means that health has improved. It may mean that the ability to perform roles at a given level of impairment has become easier.

B. Functioning

Another approach to health expectancy is based on functioning ability. Functioning inability or difficulty is regarded as an outcome of diseases, impairments, and conditions that affect an individual's health. Functioning ability is usually defined so that it is not as affected by the outside environment as disability. For instance, questions about ADL activities can be asked in such a way that they are good indicators of innate level of physical functioning. Questions about IADL activity can also be asked this way. As currently asked, IADL questions are more influenced by environment and culture than ADL activities. Less basic functions - like the Nagi functions - can also be included as indicators of ability to function at levels appropriate for the community dwelling population. Functioning is clearly a basis for appropriate definitions of health expectancy in the community dwelling population and certainly a variety of types of functioning could be included in defining health states.

C. Diseases and Conditions

A third approach is to use diseases and conditions to define health expectancy. Depending on the issue, any reasonably prevalent condition could be used to categorize the population into health states. It would also be possible to combine disease and functioning or disability into composite definitions of health states (e.g. heart disease that does not prevent working, heart disease that does prevent working, no heart disease). One issue that needs consideration before using disease as the basis for health expectancy is that trends in life expectancy with and without disease can be influenced by the ability or opportunity to diagnose disease. Certainly over the past decades, life expectancy with hypertension or Alzheimer's would have increased due to improved diagnosis. Diagnosis of disease is also related to the usage of health care. Trends and differentials could thus be affected by changes in, or differential use of, health care. For instance, only those who receive medical care know that they have hypertension.

Much discussion has surrounded what dimensions of health are most appropriately used in estimates of health expectancy. In addition, there is substantial discussion as to how to use terminology to clarify what is being estimated. This discussion parallels other discussions of how and why to utilize concepts as defined in the ICIDH (International Classification of Impairment, Disability, and Handicap)(Mathers, Robine, and Wilkins, 1994).

A theoretical scheme that can be seen as organizing the different dimensions of health that might be used to define health expectancy has been provided by Lois Verbrugge and Alan Jette (Verbrugge, 1994; Verbrugge and Jette, 1994). Their "Disablement Process" presents a conceptual model of how the different components of health or health change are related. They conceptualize the process as proceeding from disease and impairment, to functioning problems and loss, to disability; that is, moving from disease to an inability to fulfill a social role. The value of this conceptual approach is that it clarifies how the different dimensions of health are related and perhaps more importantly, how external forces might affect

change or differences in levels of disability. This is an important insight that needs consideration in thinking about differences or change in health expectancy.

While theoretically, all of these dimensions of health could be included in indicators of health expectancy, some would be more appropriate than others depending on the policy issue at hand. Information about disease is more relevant to planning and policies directed at medical service usage and research. Disability and functioning loss may be more relevant to planning for social support and services. However, when one examines most existing studies of health expectancy, operational definitions have been chosen because the available data allowed the approach taken. For instance, in most countries an indicator of disability is collected for all ages; for this reason most country estimates are of disability-free life expectancy. Whether this includes both short and long-term disability, varies (short term is included in Wilkins, 1992; Crimmins et al., 1989; van Ginneken, Dissevelt, and Bonte, 1992) with the availability of data and the format of the question.

Similarly, for the older population, most estimates of healthy life have been life when one is not ADL and/or IADL impaired. The measurement of the ability to perform ADL and IADL functions has been included in virtually every survey of the older population in the world and thus provides some of the most readily available information on the health of the older population. This definition has also been used because ability to function represents an important indicator of the dependence or independence of this population and is regarded as a summary indicator of health in the older population.

In sum, there is no one concept that should be the basis of definitions of health expectancy. Different concepts provide answers to different questions and can be used to monitor different aspects of health. In practice, most analysts of health expectancy have been limited by available data to disability-free life expectancy but would have liked more options in their definitions underlying health expectancy.

IV. Methods

Almost all methodological approaches to estimating health expectancy can be described under two headings: the Sullivan Method or the multistate method. The double-decrement method has been used in a few situations but is not widely used or generally recommended. More recently, a microsimulation technique has been proposed to estimate health expectancy. This section will discuss each method.

1. Sullivan Method

Estimating health expectancy by the Sullivan method requires information on the age specific proportions of the population in the unhealthy or disability states, generally gathered in cross-sectional surveys. These proportions are prevalence measures of the actual-current health status of a real population; thus, for disability it would be a measure of the health composition of the observed population measured by disability status. This schedule of the health structure of the population is then used to proportion years lived in the life table population, implied by current mortality rates, into healthy and unhealthy years. If disability is the measure, it would be disabled and nondisabled years.

The Sullivan measure of health expectancy is clearly not a traditional life table measure because it rests on a combination of prevalence and incidence rates. The observed prevalence of health status in the population, the input to the Sullivan method, is determined by the complete history of health and mortality experienced over each age group's lifetime rather than just recent events.

The appropriate interpretation of the Sullivan approach is that it reflects the current health composition of a real population adjusted for mortality levels. The results of the Sullivan method are limited in that they indicate nothing about the expected life cycle events of individuals exposed to current mortality and morbidity conditions. In addition, the current forces that are at work to potentially change the population health structure are not represented by the Sullivan method.

The original approach designed by Sullivan can be adapted to include any number of unhealthy states: short term and long term disability, with and without disease, severe and less severe disability, institutionalization. All that is necessary is to divide the population into mutually exclusive health categories. Early articles using information on the U.S., Canada, and France have used the Sullivan method with a number of states reflecting short-term and both more-severe and less-severe long term disability and institutionalization (Crimmins, Saito, and Ingegneri, 1989; Colvez and Robine, 1986; Wilkins and Adams, 1983). These articles also provide good technical descriptions of the application of the Sullivan method using national data.

The estimation of the Sullivan method is more straightforward and involves many fewer issues of data quality. Often the population is the basis for the mortality estimates rather than a sample survey. These mortality schedules have often been smoothed statistically before publication.

The significance of the estimated proportions with a specified health state is also straightforward. The normal tests of significance can be applied to each relevant difference of proportions to determine significance. One can then make choices about whether or not to include insignificant differences in estimates. Of course, it may be desirable to smooth the estimates of the proportions with a given health state before using them in the life table.

Colin Mathers (1991) has derived a methodology for estimating standard errors of health expectancies for use with the Sullivan method.

A number of attempts have been made to use the Sullivan method along with weighting factors to estimate a global indicator of health expectancy where some states of life are not valued at a whole year but are weighted as to their value relative to a year of "perfect" health (Erickson, Wilson, and Shannon, 1995; Wilkins and Adams, 1983). While this approach has been used by some groups, it has not been generally adopted by those working within REVES. Members of REVES have discussed at some length the weighting systems used in the work of Torrance (Berthelot, Rokerge, and Wolfson, 1993) and in the Global Burden of

Disease project (World Bank, 1993; van Ginneken, 1994). These discussions have clarified that the weighting system is highly related to the estimates of healthy life and that the derivation of weights is a highly controversial topic. Questions arise not only as to how to derive weights methodologically; but also about whose views should be used to weight the value of life years - questions that have no agreed upon answers. General consensus among those who are interested in health differences and health change is that introducing this aspect into a healthy years of life index does not make the index better represent reality but makes what is represented harder to understand.

2. The Double Decrement Method

One of the first papers to use incident rates to estimate health expectancy was the paper by Katz et al. (1983). This analysis was novel in that it allowed people to drop out of the healthy population through death, ADL dependency, or institutionalization. Transitions from a healthy state to all of these states were used to estimate active life expectancy. This means that with this method, life table measures are based on incident measures of health change like traditional life tables. The problem with extending life table analysis to states other than death, is that not all states are absorbing states like death. An absorbing state is one from which there is no return. ADL disability and institutionalization are both states that one can exit as well as enter; therefore, they are not absorbing.

The use of the double-decrement method to obtain estimates of active life expectancy was quickly criticized because by treating all states as absorbing states it ignores the potential for returns to healthy life from unhealthy life. People can recover from ADL disability and be released from institutions. Thus, it clearly produces an estimate of active life expectancy that is biased downward. The double decrement method could be an appropriate approach to healthy life expectancy in the situation where unhealthy life is an absorbing state. For instance, one could potentially analyze life expectancy with and without dementia. Assuming that dementia is a state from which there is no return to non-dementia although not all

would agree that dementia could be considered an absorbing state, since a significant amount could be due to medication or anesthesia. A state from which there is no return, for instance, is "ever having had a disease" or "ever having been diagnosed with hypertension". Years of life after ever-having been diagnosed with hypertension could be estimated using incident indicators of this state and the double-decrement method.

The double decrement method, however, does not incorporate differential mortality for the different states of health into the model; a situation known to better reflect reality. Sicker people can be expected to have higher mortality than well people. For this reason current interest centers on the multistate life table rather than the multiple-decrement life table.

3. Multistate Methods

A. Introduction

The basic features of the multistate model that make it a valuable tool for analysis of active life expectancy are

1) It is based on incidence measures representing current health conditions.

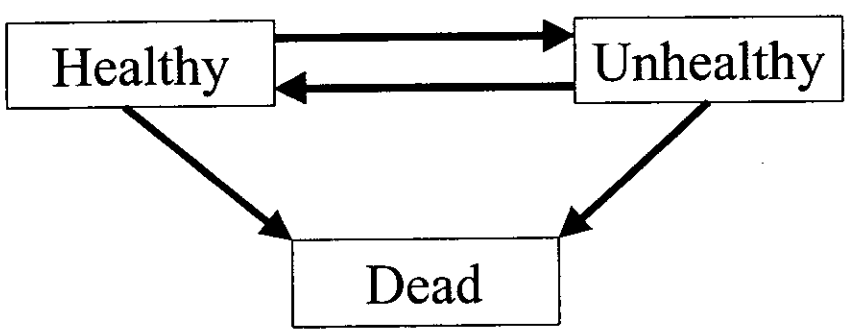
2) It allows movement in both directions between all nonabsorbing states.

3) It allows death rates to differ by state (A. Rogers et al., 1989, 1990; R. Rogers et al., 1989; Crimmins, Hayward, and Saito, 1994).

Multistate life tables were developed in response to a desire to model dynamic processes that involve multiple and recurrent events. A number of researchers have been instrumental in the development of multistate techniques (Schoen, 1975, 1988a, 1988b; Rogers, 1975, 1980; Hoem, 1977) and applications to these techniques have covered a number of topics in addition to health expectancy (e.g. marital status (Schoen, 1975), migration (Rogers, 1975), labor force participation (Willekens, 1980; Hayward et al., 1988)).

Multistate estimates of health expectancy are derived from a set of transitions to and from healthy and unhealthy states of life and to death. As an example, possible transitions among 2 health states and an absorbing state of death are depicted in Figure 1. As represented by each arrow, there are 4 transitions for each age group which is used in a study. These estimates are derived from panel studies. All of these rates are incident rates and, thus, all represent only recent or current population experience. The multistate approach is especially well suited to examining health expectancy since persons experience both declines and improvements in health status as they age. Moreover, it is sufficiently flexible to take into account the different mortality profiles by health status. Health expectancy computed by this measure is an indicator of the average length of healthy life for a member of a synthetic cohort who lives all of his or her remaining life exposed to current conditions of mortality and morbidity. As such, this measure provides an indicator of the implication of current rates for individual life cycles and population. Health expectancy measures based on multistate methods are analogous to conventional mortality-determined life expectancy; that is, we do not expect any cohort to actually live out life under unchanging conditions but this measure indicates the implications of this assumption for an average life cycle. On the other hand, health expectancy derived from multistate methods does not indicate the current population distribution of health status.

Figure 1. Depiction of Possible Transitions Among States



Multistate life tables can be either population-based, where we assume that the population enters the life table with the distribution over the healthy and unhealthy states observed at the radix age (Crimmins, Hayward, and Saito, 1994, 1996; Saito, Crimmins, and Hayward, 1995), or status-based, where we assume that everyone enters a life table in a given state (A. Rogers, R. Rogers, and Branch, 1989, 1990). Population-based tables describe the potential life cycle events for the whole population; while status-based tables can be used to compare the prospective life cycles of those who reach specified ages in different health states. Saito, Crimmins, and Hayward detail the differences between population-based and status-based life tables in a later paper in this NUPRI Research Paper Series.

B. Multistate Life Table

The application of multistate life table methods to health expectancy has two methodological components. One is the life table method itself and the other is the estimation of the transition rates (m_x's) which are used to calculate multistate life tables.

To construct life tables, the matrix of transition rates ($\mathbf{M}_x$) is used to calculate a transition probability matrix, $\mathbf{P}_x$, by (Rogers and Ledent, 1976):

$$\mathbf{P}_x = (\mathbf{I} + \tfrac{1}{2} \cdot n \cdot \mathbf{M}_x)^{-1} (\mathbf{I} - \tfrac{1}{2} \cdot n \cdot \mathbf{M}_x). \qquad (1)$$

Elements of the transition probability matrix, ${}^{ij}P_x$, represent the probability that a person in state i at exact age x will be in state j at exact age x+n. The computed transition probability matrix allows the specification of the familiar life table relationship from which survivorship values for all ages can be calculated (Rogers, 1975; Schoen and Woodrow, 1980; Hayward and Grady, 1990):

$$\mathbf{l}_{x+n} = \mathbf{l}_x \cdot \mathbf{P}_x \qquad (2)$$

where,

$\mathbf{l}_{x+n}$ = a survivorship matrix whose elements ${}^{ij}l_{x+n}$ represent the number of persons in state i at exact age x who will be in state j at exact age x+n;

$\mathbf{l}_x$ = a survivorship matrix similar to $\mathbf{l}_{x+n}$ but whose elements, ${}^{ij}l_x$ represent the number of persons in both state i and j at exact age x (i.e., ${}^{ij}l_x=0$ where $i \neq j$) such that its diagonal elements represent the number of survivors in state i at exact age x.

Once the survivorship values are calculated, one can compute the expected magnitude of flows between states for all ages. For example, one can calculate the expected number of moves into and out of the state, healthy state, above a certain age or between ages. Calculation of transfers between states for each age, $\mathbf{D}_x$, is based on the matrix of occurrence/exposure transfer rates, $\mathbf{M}_x$, and a matrix of person-years lived, $\mathbf{L}_x$. In matrix notation,

$$\mathbf{D}_x = \mathbf{L}_x \cdot \mathbf{M}_x \tag{3}$$

where, assuming linearity in the gross flow functions,

$$\mathbf{L}_x = \tfrac{1}{2} \cdot n \cdot (\mathbf{l}_x + \mathbf{l}_{x+n}). \tag{4}$$

This allows the calculation of state-specific life expectancy estimates. Specifically, life expectancy in state i at age x is calculated as follows:

$${}^{i}e_x = {}^{i}T_x / l_x, \tag{5}$$

where,

${}^{i}T_x$ = number of person-years lived in state i beyond exact age x by the cohort who survived to age x; and

${}^{i}e_x$ = life expectancy in state i at exact age x (average number of years expected in that state).

Total life expectancy is the sum of life expectancy in each of the states.

C. Output from the Multistate Life Table

Expected years of life in each state is one value obtained from the multistate method, other output from the multistate model allows one to understand the processes of health change leading to the estimated years in specified states. This additional output is what makes the multistate method so valuable. The life table prevalence rates of health status, like the net migration rate, are a consequence of flows both into and out of the various health states within some specified period. Furthermore, the prevalence rates are a product not only of the incidence rates but also of the stock of persons in each status, which itself is a product of temporally prior behavior that has left its stamp on the composition of the population (Schoen, 1988b). This approach allows the depiction of the underlying processes that determine prevalence rates of health status.

The connections between prevalence rates and the incidence rates can be illustrated by adopting a simple life table model consisting of two "alive" states, healthy(o), unhealthy (i), and an absorbing state of death (δ). The prevalence rate can be expressed in terms of life-table notation as follows (Schoen and Woodrow, 1980):

$$\mathrm{PREV(i)}_x = \frac{{}^{i}L_x}{{}^{i}L_x + {}^{o}L_x} . \qquad (6)$$

In this expression, ${}^{i}L_x$ refers to the person-years lived in health state i during the interval x to x+n and is calculated according to equation 4. In scalar terms,

$$ {}^{i}L_x = \tfrac{1}{2} \cdot n \cdot ({}^{i}l_x + {}^{i}l_{x+n}). \qquad (7) $$

The flow equations that give rise to the person-year values and ultimately the health status prevalence rates can be expressed as follows:

$$ {}^{o}l_{x+1} = {}^{o}l_x + {}^{i}d_x^o - {}^{o}d_x^i - {}^{o}d_x^\delta \qquad (8) $$

and

$$ {}^{i}l_{x+1} = {}^{i}l_x + {}^{o}d_x^i - {}^{i}d_x^o - {}^{i}d_x^\delta \quad . \qquad (9) $$

The first flow equation says that the number of persons in healthy state at age x+n is equal to the number of persons in the same state at age x (i.e., a stock), plus the number of moves from unhealthy to healthy, minus the number of moves from healthy to unhealthy, minus those persons in the healthy state at age x and died during the interval. The interpretation of the second expression parallels that of the first. Since these two expressions ultimately define the numerator and denominator of the prevalence rate, the complexity of behavior underlying the seemingly simple prevalence measure of health status is readily apparent. One of the uses of the multistate life table is to clarify the demographic forces that underlie the prevalence measures of health status in the population.

D. Estimation of Transition Rates

The following discussion indicates a discrete-time hazard modeling approach to estimating the necessary health transitions for input to the multistate model. This

approach fits well with the usual panel data available for estimating such transitions. That is, movements between states are characterized by conditional hazard rates. The dependent variable in a hazard model is an unobservable quantity that refers to the instantaneous probability of experiencing an event at some instant of time $h_{ij}(t)$, given that the individual has not yet experienced the event. More formally, this can be expressed as follows:

$$h_{ij}(t \mid X(t)) = \lim_{\Delta t \downarrow 0} P_{ij}(t, t+\Delta t \mid T > t, X(T)) / \Delta t \qquad (10)$$

where T is a non-negative random variable representing the time the transition occurs, t is any fixed value of time and $P_{ij}(t, t+\Delta t)$ is the probability the event will occur in the infinitely small interval t, $t+\Delta t$. This expression also implies that the hazard rate is conditional on a set of random variables, X(t), hypothesized to influence the event. Note that the overall hazard rate is

$$h_i(t) = \sum_{j=1}^{J} h_{ij}(t)$$

where i is not equal to j. This corresponds to the central death rate in the more traditional life table framework. Thus, h_{ij}'s are analogous to the m_x's defined above. In the discrete-time approach, the h_{ij}'s are analogous to m_x's and not p_{ij}'s because

1) all transitions, including censoring, are assumed to occur in the middle of the interval and exposure is adjusted accordingly;

2) only one transition is assumed to occur in the interval, an assumption made necessary by the character of the data (Ledent, 1980; Rogers, Willekens, Ledent, 1983);

3) the h_{ij}'s are the appropriate input to the increment-decrement life table because each destination specific rate is independent of the other destination-specific

rates. The p_{ij} values are not independent and are a function of the total probability of moving to any destination.

E. The Introduction of Covariates

One of the values of the parameterized multistate approach is that transition schedules can be computed for a wide variety of covariates assumed to affect the transition outcomes. Some of these could be lifelong characteristics of individuals (e.g. race, sex) and others could be time-varying (e.g. marital status). Assuming that all individuals who share the same covariate values have identical hazard functions and that the hazard function for different covariate values are parallel over time, we can express the hazard rate as a product of two basic components (Namboodiri and Suchindran, 1987):

$$h_{ij}(t \mid X(t)) = h_{0ij}(t)\exp(\beta \cdot X(t)). \qquad (11)$$

In this equation, $h_{0ij}(t)$ is the baseline hazard function, and β is a vector of parameters corresponding to the covariates in X(t). This equation can be stated in log-linear form:

$$\ln h_{ij}(t \mid X(t)) = \ln h_{0ij}(t) + \beta \cdot X(t). \qquad (12)$$

Equation (12) indicates that there is a linear relationship between the log of the hazard and the predictor variables. Thus, the parameters in the hazard model can be interpreted much like OLS regression.

Our discussion should make clear that the multistate model is a highly parameterized model that rests on estimating a series of transition rates between health states and to death. The number of transition schedules depends on the

number of states of health included in the model. In some analyses we have used four live states and death to estimate health expectancy for the older population; this requires 16 transition schedules as input to the multistate model (Crimmins, Hayward, and Saito, 1994, 1996). In others we have used two live states which only requires four schedules (Saito, Crimmins, and Hayward, 1995). Some of our experiences with estimating these transition schedules are worth describing.

In general, our studies show the fit of the mortality schedules to be better than the fit of the health transitions and some health transitions to be better described by our models than others (Saito, Crimmins, and Hayward, 1991). It is difficult to know how to incorporate poorly explained transitions into estimates of active life expectancy. In particular, the fit of the transitions from the poorest health states to good health was particularly poor - age was not significant in some cases. Of course, these transitions were based on extremely small N's. With a large number of health states, there are some types of transitions that occur so infrequently that no model will ever explain them. We tested the effects of using only significant coefficients, including the insignificant coefficients, assuming a small constant rate with age, and assuming that no transitions of this type were made. The results did not vary appreciably in the estimates of life expectancy in any state; however, we think this is a problem that needs further consideration in application of the multistate method.

As with all models of this type, there are issues that must be considered. For example, our approach in estimating multivariate, multistate health status life tables forces us to adopt the Markovian assumption that there are no effects of duration in a health state and prior history. Thus, we are interested only in the age-specific transition rates, regardless of a person's previous health experiences. Were the data reflective of the health experiences for an actual cohort, the multistate life table would accurately characterize the cohort's health history regardless of whether the underlying process was Markovian or semi-Markovian (Hayward and Grady, 1990; Schoen, 1988b).

4. Microsimulation Method

A. Introduction

Laditka and Wolf (1998) have recently applied a microsimulation technique to generate the data set for calculating health expectancy. "Microsimulation is a familiar tool used in policy analysis and forecasting" (Citro and Hanushel, 1991, cited in Laditka and Wolf, 1998), and "is also useful as a device for studying the sample paths of dynamic processes" (Laditka and Wolf, 1998). They simulate the lives of 100,000 seventy-year-old persons until everyone dies based on estimated health status transition schedules. Once a history of health status for each one of 100,000 persons is estimated, health expectancy after age 70 and other summary indices obtained from life tables can be estimated. In addition, indices only available with the microsimulation approach such as the length of expected spells in a given health state can be calculated. This is because the microsimulation method estimates an individual history of health status over one's life in contrast to the life table method which estimates the life outcomes of a group of people.

The three features of the multistate model also characterize the microsimulation method.

1) It is based on incidence measures representing current health conditions.

2) It allows movement in both directions between all nonabsorbing states.

3) It allows death rates to differ by state.

In order to undertake the microsimulation, health status transition schedules including mortality rates have to be estimated. Laditka and Wolf offered a new method of estimating these transition schedules and apply the method to the LSOA (Longitudinal Study of Aging), the same data set used by Crimmins, Hayward, and Saito (1994). They formulate the likelihood of an observed sequence of functional states in terms of monthly transition probabilities.

Laditka and Wolf developed their approach in order to overcome some problems posed in previous studies of health expectancy, which employed the multistate life table method and the LSOA data. In panel surveys such as the

LSOA, health status is only recoded at discrete times and often these times are separated by a couple of years. Because of this feature of the survey, previous research imposed restrictions and assumptions on the estimation of transition schedules. For instance, only one transition per interval is assumed and that transition is assumed to take place at the mid point of the interval. Also, if there is no transition during the interval, it is assumed that respondents stayed in the same health status between the two interviews.

Theoretically, the multistate life table method assumes an underlying Markovian process in which there is a positive probability of making a transition in any arbitrarily small time interval. Therefore, the assumption of no more than one transition between interviews is somewhat inconsistent with the assumption of the multistate life table method.

Laditka and Wolf also use their method to include baseline respondents for the LSOA who were interviewed only in the third and forth waves but not at the second wave. Previous studies were not able to utilize information on these respondents.

B. Estimating Transition Schedules

Laditka and Wolf use 3 functional states and an absorbing state, that is, death. The functional states are defined by number of impairments in ADLs including bathing, eating dressing, transferring, and using the toilet. If none of these activities are impaired, health status is classified as "unimpaired". The other two functional states are "moderately impaired", if one or two activities are impaired, and "severely impaired", if three to five activities are impaired. All the above mentioned problems are accommodated by "a maximum-likelihood approach that expresses the probability of an observed individual-level transition in terms of underlying model parameters" (Laditka and Wolf, 1998). The model is used to estimate monthly transition probabilities between states. A multinomial logistic

regression model with covariates representing age, race, and education by sex is used to estimate the parameters. The general form of the model is as follows:

$$\ln({}^{ij}p_x / {}^{IJ}P_x) = \beta_{ij0} + \beta_{ij1}*x + \beta_{ij2}*\text{race} + \beta_{ij3}*\text{education} \qquad (13)$$

where ${}^{ij}p_x$ is a transition probability from state i to state j at age x from month t to t+1, ${}^{IJ}P_x$ is a transition probability of the reference transition, i represents 3 initial functional states, and j represents the 4 destination states including death. By estimating monthly transition probabilities, they relax the assumption of only one transition among functional states between interviews.

C. Calculation of Active Life Expectancy

Once the transition schedules are estimated, the calculation of active life expectancy is straightforward. They simulate the lives of 100,000 males and females starting at age 70 every month based on the estimated transition schedules until all of them die out. The microsimulation procedure is done by assigning a computer generated random number from the uniform (0,1) distribution to each of the simulated lives each month. This number is compared with probabilities which are mapped into subsets of the 0,1 interval and assigned a health status according to the number. For example, those who are unimpaired at exact age 70 have 4 possible paths to reach the second month, i.e., stay unimpaired, move to moderately impaired, severely impaired, and dead. Let's assume each transition probability is 0.8, 0.1, 0.06, and 0.04, respectively (0.8+0.1+0.06+0.04=1.0). If the assigned number is less than 0.8, the health status assigned is unimpaired; between 0.8 and 0.9 (=0.8+0.1), moderately impaired; between 0.9 and 0.96 (=0.8+0.1+0.06), severely impaired; and between 0.96 and 1.0, dead. For each age, gender, racial and educational group, probabilities are mapped.

The 100,000 males or females can be regarded as a radix for life tables. To aid in understanding microsimulation, imagine a spread sheet with 100,000 rows and

480 columns representing each possible month of life assuming the last person dies just before reaching exact age 110 (40 years x 12 months). Each row represents a particular person with given characteristics such as gender, race, level of education, and functional status at age 70. Each column represents the functional status at each month for persons from age 70 to 110 or until death. The first column represents functional status at exact age 70 and the second column is for the beginning of the second month. Some may die before reaching the second month and for these persons, the second column indicates death as their status and the rest of the columns are empty. Some may die at age 80 and 6 months with no functional problems before they die. For those persons, the 127th column indicates death and up to the 126th column no functioning problem as functional status. The average column number which indicates death for each person is the total life expectancy in months for this population. If only males or females are used to compute the average, gender specific life expectancies are computed. The same thing applies for functional-status specific, or race-specific life expectancies.

Table 1 shows an example of the monthly history of simulated lives for a few people. "U" represents unimpaired life, "M" for moderately impaired, "S" for severely impaired, and "D" for dead. The first person shows no functional change in the first 6 months and the second shows functional change in the 3rd month from unimpaired to moderately impaired.

Table 1. Example of the Monthly History of Simulated Lives Starting at Exact Age 70

Respondent's ID	Month 1	Month 2	Month 3	Month 4	Month 5	Month 6
1	U	U	U	U	U	U
2	U	U	U	M	M	S
3	S	S	S	D	--	--
4	M	M	M	M	U	S

The new technique also allows us to compute indices such as the frequency distribution of distinct spells of disability, and quantiles of the time spent in any given functional status. These indices are not available from conventional life tables and add depth to our understanding of the process of health change among individuals.

However, several difficulties must be overcome to use the microsimulation method. First, because this method requires longitudinal data it's use is limited. Second, there exits more than one possible solution. Third, the time and complexity of computation are enormous.

5. Grade of Membership (GoM) Method

A. Introduction

Manton and Stallard (1991) applied the concept of "fuzzy" states (Zadeh, 1965), a concept borrowed from the field of engineering, to the study of health expectancy. The Grade of Membership procedure (see Jackson, Woodbury, and Manton, 1988; Manton, Woodbury, and Liu, 1984; Woodbury and Clive, 1974) identifies dimensions or types of states to which a person belongs. A person can be characterized by one type of state for 100%. A person also could be characterized by more than one state. For example, a person could possess 50% of the traits of one type of state and 50% for another type of state. Manton and colleagues believe that it is not appropriate to use discrete measures to describe functional status because functional impairment is intrinsically multidimensional. While the elderly tend to have an increasing number of functional problems at advanced ages, most of them also retain some abilities to function at some degree. Therefore, Manton and colleagues believe that using a number of ADL difficulties to define disability threshold for active life expectancy is not meaningful.

B. GoM Procedure

In order to describe the GoM procedure several terms should be defined. The number of respondents is I, J variables are used to describe respondents' health status. Each of J variables has L response categories and L can vary from variable to variable. All L_j responses are coded into binary variables which are represented by x_{ijl} to determine K analytically suitable types which describe respondents' health status in the data. The building blocks of the GoM procedure are incidental parameters (g_{ik}) and structural parameters (λ_{kjl}) (Manton, Stallard, Woodbury, Tolley, and Yashin, 1987). The incidental parameters are scores for the i-th respondent and are estimated for each of K analytically determined dimensions. In concept the incidental parameters resemble factor scores. The conditions for the incidental parameters are:

$$\sum_k g_{ik} = 1.0 \quad \text{for each person} \quad \text{and} \quad 0.0 \geq g_{ik} \geq 1.0.$$

The structural parameters are "the probability that a person of the k-th pure type will have the l-th response to the j-th variable" (Manton et. al., 1987, p.313). An example of interpreting the structural parameters is shown in Table 2. Following the definition of the structural parameters, the probability that a person of the 1st pure type will have the 2nd response (which is 1) to the 1st variable (which is the number of dangerous illness conditions) is 0.207. Similarly, the probability that a person of 4th pure type will have arthritis is 1.0 and diabetes is 0.425. The basic structural equation and the multinomial likelihood for the GoM model are as follows:

$$\text{Prob}(x_{ijl}=1.0) = \sum_{k=1}^{K} g_{ik} \cdot \lambda_{kjl} = \lambda_{ijl} \qquad (14)$$

$$L = \prod_{i}\prod_{j}\prod_{l} \left(\sum_{k=1}^{K} g_{ik} \cdot \lambda_{kjl}\right)^{x_{ijl}} . \qquad (15)$$

Table 2. Example of Structural Parameters for 4 Types

Variables	Response	Type 1	Type 2	Type 3	Type 4
Number of dangerous illness conditions	0	0.0	65.2	0.0	0.0
	1	20.7	34.8	44.2	0.0
	2	37.7	0.0	55.8	23.9
	3	18.9	0.0	0.0	46.5
	4	22.8	0.0	0.0	29.5
Arthritis	1	87.2	0.0	100.0	100.0
Diabetes	1	18.4	0.0	10.7	42.5

Source: Manton, Stallard, Woodbury, Tolley, and Yashin, 1987, "Grade-of-Membership Techniques for Studying Complex Event History Processes with Unobserved Covariates," in Clifford Cloog (Ed.), Sociological Methodology 1987. San Francisco: Jossey-Bass.

C. Calculation of Life Tables

Manton and Stallard (1991) use the multidimensional disability measures generated by the Grade of Membership procedure based on survey data to stratify life table parameters. The mean of the incidental parameters ($\bar{g}_{kx}$) at age x are used to construct the life table. The basic formulas for constructing the life table are as follows:

$$l_x = \sum_k l_{kx} = l_x \sum_k \bar{g}_{kx} \tag{16}$$

$$T_x = \sum_k T_{kx} = \sum_k \int_x^\infty l_{kx}\, dt \tag{17}$$

$$e_x = \sum_k e_{kx} = \sum_k T_{kx} / l_x \tag{18}$$

where l_{kx} , T_{kx} , and e_{kx} , represent "duration-weighted measures of the population impact of the K types of disability" (Manton and Stallard, 1991). In a sense, they compute the distribution of the population by health status using the Grade of Membership procedure, then apply the Sullivan method to compute health expectancies for a cross-sectional population. Manton, Stallard, and Liu (1993) also applied the method to longitudinal data by computing transition probabilities based on the GoM procedure.

The work of Manton and colleagues differs from that of others in that active and inactive life are not discrete states into which an individual can be assigned. In their approach each person is characterized as being more or less in a set of functional states defined using GOM procedures. This contrasts with the work of

others in which each person is categorized in one discrete state defined as either healthy or unhealthy. This means the estimates of Manton's group are not directly comparable to those made using other methods. In practice, it was quite difficult for researchers not affiliated with Duke University to apply the GoM procedure because they could not access the special software for the procedure developed by researchers at Duke University. However, the Alpha version of the software is now available from the Center for Demographic Studies at Duke University. More information can be obtained from the following WWW address:

http://cds.duke.edu/page3.html.

V. Discussion of Methods Used in Existing Estimates of Health Expectancy

Estimates of health expectancy at more than one date have been made for the United States using prevalence-based measures or the "Sullivan method" by a number of researchers (U.S. Department of Health, Education, and Welfare, 1969; Sullivan, 1966, 1971a, 1971b; McKinlay and McKinlay, 1979; McKinlay et al., 1989; Colvez, 1980; Colvez and Blanchet, 1983; Crimmins et al., 1989, 1997; Erickson, Wilson, Shannon, 1995). Estimates for multiple dates using similar methods are also available for Great Britain (Bebbington, 1988, 1991), Canada (Wilkins and Adams, 1983; Wilkins et al., 1994), Australia (Mathers, 1990), and France (Robine and Mormiche, 1994). While the Sullivan approach used in these studies, which is at present our only alternative for tracking health expectancy at all ages on an annual basis, may present a realistic picture of the changing burden of actual disability in the population, it adds little to our understanding of the implications of current health conditions for the future distribution of health expectancy in the population. This is because the prevalence measures of health expectancy are based on the contemporary prevalence of unhealthy life at all ages in the population, a level which has built up over the lifetime of population members, rather than incidence rates representing only recent circumstances.

The dynamic approach to the study of health expectancy has been demonstrated in the work of Andrei and Richard Rogers, Laurence Branch, Crimmins and colleagues, Manton and colleagues, Laditka and Wolf, and Land and Guralnik (Barendregt and Bonneux, 1994; Barendregt, Bonneux, and van dar Mass, 1994; Branch et al, 1991; A. Rogers et al., 1989, 1990; R. Rogers et al., 1989, 1992; Crimmins et al., 1994, 1996; Manton, Stallard, and Woodbury, 1991; Laditka and Wolf, 1998; Land et al., 1994; Guralnik at al., 1993). This work has demonstrated that the population consists of heterogeneous groups with respect to survival. In addition, because both the transitions to and from unhealthy life are explicitly modeled, flows in either direction are explicitly calculated. In fact, A.

Rogers et al. (1989) were the first to stress the importance of considering policies directed toward the rehabilitation of functioning in thinking about health expectancy.

In reviewing the studies of multistate estimates of life expectancy, it should be clear that authors pay less attention to the life expectancy numbers produced than to the differences or changes implied. Most of us who have used these methods, know that there are so many methodological choices that will affect the numbers, that we do not put too much emphasis on the point estimate of life expectancy. It is clear, however, that trends and differences are generally little affected by these choices so more emphasis is placed on interpretation of these findings.

While this approach has been valuable in demonstrating the usefulness of multistate models as a tool in understanding the age-dependent processes that underlie health expectancy, its application has often fallen short of demonstrating its potential for characterizing the process of health change in the older population. Branch et al. (1991) give point estimates for active and inactive life expectancy for men and women in three communities. Although the estimates differ across community and by sex, there is little insight into the source of the differences; and no inferences are drawn about the effect of these differences on population health structure. In addition, few details on the analytic techniques are presented; for instance, there is no indication of whether or how transition schedules were smoothed or whether attrition was taken into account.

Rogers and Rogers have concentrated on trying to answer questions about morbidity change over time using multistate methods and repeated waves of the LSOA. Their use of the multistate method has pushed the field to both understand and accept this tool but whether the estimates of active life expectancy obtained by the Rogers et al. should be viewed as reliable and valid is not clear. The definition of active life employed in these studies is less than ideal. In their analyses, active life is life when one does not receive assistance with any of seven activities of daily living. Unfortunately, receipt of assistance is both a function of need for assistance due to health and the availability of assistance; availability is largely determined by

living arrangements and socio-demographic factors. This becomes particularly problematic in their analysis of the return to health.

Even if the receipt of assistance aspect were removed from their definition of inactive life, the reliance of the work of both Rogers and Rogers and Branch et al. on ADL measures as the only scale differentiating active and inactive life results in little insight into much of the health change that occurs among the even the older population let alone the population at other ages. While ADL measures differentiate well among the institutionalized, the prevalence in the community of ADL impairment is so low that it is not a useful indicator of the range of health problems in the community. Incorporation of multiple health states better differentiating the community dwelling population is highly desirable.

Manton and Stallard (1990, 1991) go further in displaying the potential of using active life expectancy as a tool for understanding and summarizing the effects of health change on active life in the population. The point of their cross-sectional work on active life expectancy is to indicate the potential gain in active life expectancy achieved through the control of certain diseases. The usefulness of this approach is shown in that it clarifies that only relatively small proportional changes in total active and inactive life at age 65 are likely to occur even with complete elimination of diseases such as cancer and senile dementia. The effects at age 85 are shown to be much greater. In addition, it indicates how the elimination of different diseases would affect different states of active life expectancy. For instance, the elimination of senile dementia would affect institutionalized life expectancy while elimination of arthritis will affect inactive community life. In another paper (Manton, Stallard, and Woodbury; 1991), they have applied a dynamic model of active life expectancy. This work provides a greater understanding of the process by which sex differences in active life arise.

While we recognize the utility of Manton's arguments that health differences among the older population can best be characterized by "fuzzy" rather than discrete states, most research in active life expectancy has considered active life as non-disabled or independent and inactive life as dependent or disabled. Thus, the

concepts and measures employed including the use of discrete states follow common practices in disability or dependency research. Because this research has been geared to policies and programs for which individuals must be defined as either eligible or not, the treatment of people as whole individuals who either are, or are not, in a set of mutually exclusive discrete states has been traditional. This contrasts with Manton's use of a set of "fuzzy" states, a number of which may describe aspects of any one person.

Crimmins, Hayward, and Saito (1994) used the multistate life table model to illustrate the consequences for both active life expectancy and the prevalence of health status of differences in the incidence rates governing transitions into and out of various health states, differences in the force of mortality, and differences in a group's "predisposition" towards health. Our analysis shows that improving mortality but not changing onset or recovery rates implies increase in both the years of, and the proportion of, dependent life (Crimmins, Hayward, and Saito, 1994). We have also used the model to show how it is differential mortality rather than differences in the incidence of functioning problems that accounts for the difference in male/female functioning ability observed in the population (Crimmins, Hayward, and Saito, 1996). Our most recent paper has examined the effect of a changing cause of death structure on the length and proportion of active life (Hayward, Crimmins, and Saito, 1998).

Our work has been based on simulation as has the work of Barendregt et al. (1994) and Laditka and Wolf (1998). Barendregt et al. provide an important analysis that indicates the likely effect of recent changes in heart disease death rates on the health of the population. Laditka and Wolf simulate future life-cycle health events to portray differences by sex and race in life cycle functioning change.

VI. Summary

Many countries have an ongoing cross-sectional survey designed to provide regular estimates of population health composition. This is why the Sullivan method has been, and will continue to be, popular. It allows the production of reliable indicators of population health composition which are comparable across time and geographic area. In order to fully understand the health processes that reflect the outlook for individual lives and the implications of current conditions for future changes in population health structure, however, countries need to begin to collect the data that will allow them to compute multistate estimates of health expectancy; not just for the estimates of life expectancy, but also for an understanding of the processes that affect it.

When the REVES group was organized, one aim was to standardize procedures for estimating health expectancy. The group has had extensive discussions of standardizing methods of collecting and analyzing data used with the Sullivan method. As yet, they have had little discussion of standardizing approaches to estimating health expectancy using multistate methods because so few countries have appropriate data.

A comparison of the estimates of active life expectancy made using the LSOA and the multistate approach indicates that multistate estimates of active life expectancy are less stable and more influenced by survey design and analytic strategies than prevalence methods (Saito, Crimmins, Hayward, 1991). This is inherent in the use of incident rather than prevalent measures. Before we can begin to make comparisons of active life expectancy across countries and over time, we need to discuss the likely effect of such survey design issues as population coverage, sampling frame, sample size, interval length, and methods of finding and tracing respondents (Saito, Crimmins, and Hayward, 1991). In addition methods of dealing with missing data will be a major determinant of any estimate (Manton and Stallard, 1991). A large number of analytical choices also influence outcomes: including definitions of health states, the use of discrete or "fuzzy" states, method of

parameterization or nonparameterization of transition schedules, the choice of a transition approach or a movement approach (Ledent, 1980); the introduction of covariates, etc. In using the Sullivan method, the discussion on the measurement of health status centers on the validity of definitions of active and inactive life; in using multistate methods issues of reliability rise to the forefront.

References

Barendregt, J.J., and L. Bonneux (1994): "Changes in Incidence and Survival of Cardiovascular Disease and Their Impact on Disease Prevalence and Health Expectancy" in C.D. Mathers, J. McCallum, and J.M. Robine eds., Advances in Health Expectancies, (pp. 170-181), Canberra: Australian Institute of Health and Welfare.

Barendregt, J.J., L. Bonneux, and P.J. van der Mass (1994): "Health Expectancy: An Indicator for Change?" Journal of Epidemiology and Community Health, 48, pp. 482-487.

Bebbington, A.C. (1988): "The Expectation of Life Without Disability in England and Wales," Social Science and Medicine, 27, pp. 321-326.

Bebbington, A.C. (1991): "The Expectation of Life Without Disability in England and Wales: 1976-88," Population Trends, 66, pp. 26-29.

Berthelot, J.M., R. Roberge, M.C. Wolfson (1993): The Calculation of Health-Adjusted Life Expectancy for a Canadian Province Using a Multi-Attribute Utility Function: A First Attempt" in J.M. Robine, M.R. Bone, and I. Romieu eds., Calculation of Health Expectancies: Harmonization, Consensus Achieved and Future Perspectives, (pp. 161-174), Montrouge, France: John Libbey Eurotext.

Bone, M.R., A.C. Bebbington, C. Jagger, K. Morgan, and G. Nicolaas (1995): Health Expectancy and Its Uses, London: HMSO.

Branch, L.G., J.M. Guralnik, D.J. Foley, F.J. Kohout, T.T. Wetle, A. Ostfeld, and S. Katz (1991): "Active Life Expectancy for 10,000 Caucasian Men and

Women in Three Communities," Journal of Gerontology, 46 (3), pp. 145-150.

Citro, C.F. and E.A. Hanushek (1991): Improving Information for Social Policy Decisions: The Uses of Microsimulation Modeling, Vol. I: Review and Recommendations, Washington, DC: National Academy Press.

Colvez, A. (1980): Evolution de l'Etat de Santé au Cours de la Dernière Décennie: Peut-on Continuer a Parler d'Amélioration? Québec: Ministère des Affaires Sociales, 10 (Services des Etudes Epidémiologiques).

Colvez, A., and M. Blanchet (1983): "Potential Gains in Life Expectancy Free of Disability: A Tool for Health Planning," International Journal of Epidemiology, 12, pp. 224-229.

Colvez, A., and J.M. Robine (1986): "L'Esperance de Vie Sans Incapacite en France en 1982," Population, 41 (6): pp. 1025-1042.

Crimmins, E.M., M.D. Hayward, and Y. Saito (1994): "Changing Mortality and Morbidity Rates and the Health Status and Life Expectancy of the Older Population," Demography, 31, pp. 159-175.

Crimmins, E.M., M.D. Hayward, and Y. Saito (1996): "Differentials in Active Life Expectancy in the Older Population of the United States," Journal of Gerontology: Social Sciences, 51B (3), pp. S111-S120.

Crimmins, E.M., Y. Saito, and D. Ingegneri (1989): "Changes in Life Expectancy and Disability-Free Life Expectancy in the United States." Population and Development Review, 15 (2): pp. 235-267.

Crimmins, E.M., Y. Saito, and D. Ingegneri (1997): "Trends in Disability-Free Life Expectancy in the United States, 1970-1990," Population and Development Review, 23 (3), pp. 555-572.

Erickson, P., R. Wilson, and I. Shannon (1995): "Years of Healthy Life," Healthy People 2000: Statistical Notes, 7, pp. 1-15.

Fries, J. (1981): "Aging, Natural Health, and the Compression of Morbidity," New England Journal of Medicine, 303, pp. 130-135.

Gruenberg, E.M., (1977): "The failures of success," Milbank Memorial Fund Quarterly, 55, pp. 3-24.

Guralnik, J.M., K.C. Land, D. Blazer, G.G. Fillenbaum, and L.G. Branch (1993): "Educational Status and Active Life Expectancy Among Older Blacks and Whites," The New England Journal of Medicine, 329 (2), pp. 110-116.

Hayward, M.D., E.M. Crimmins, and Y. Saito (1998): "Cause of Death and Active Life Expectancy in the Older Population of the United Status," Journal of Aging and Health, 10 (2), 192-213.

Hayward, M.D., and W.R. Grady (1990): "Work and Retirement Among a Cohort of Older Men in the United States, 1966-1983," Demography, 27 (3), pp. 337-356.

Hayward, M.D., W.R. Grady, and S.D. McLaughlin (1988): "Changes in the Retirement Process Among Women in the United States: Changes in the 1970s," Research on Aging, 10, pp. 358-382.

Hoem, I. (1977): "A Markov Chain Model of Working Life Tables," Scandinavian Actuarial Journal, pp. 1-20.

Jackson, D.J., M.A. Woodbury, and K.G. Manton (1988): "An Introduction to the Grade of Membership Classification Model," Bulletin de Methodologie Sociologique, July (19), pp. 22-52.

Katz, S., L.G. Branch, M.N. Branson, J.A. Papsidero, J.C. Beck, and D.S. Greer (1983): "Active Life Expectancy," New England Journal of Medicine, 309 (2), pp. 1218-1224.

Katz, S., D.S. Greer, J.C. Beck, L.G. Branch, and W.D. Spector (1985): "Active Life Expectancy: Societal Implications" in American's Aging: Health in an Older Society, (pp. 57-72), Washington, DC: National Academy Press.

Kramer, M., (1980): "The rising pandemic of mental disorders and associated chronic diseases and disorder," in Epidemiologic Research as Basic for the Organization of Extramural Psychiatry, Acta Psychiatrica Scandinavica, 62 (Supplement 285).

Laditka, S. B., and D.A. Wolf (1998): "New Methods for Modeling and Calculation Active Life Expectancy," Journal of Aging and Health, 10 (2), pp. 214-241.

Land, K., J. Guralnik, and D. Blazer (1994): "Estimating Increment-Decrement Life Tables with Multiple Covariates from Panel Data: The Case of Active Life Expectancy," Demography, 31, pp. 297-319.

Ledent, J. (1980): "Multistate Life Tables: Movement Versus Transition Perspectives," Environment and Planning, A12, pp. 533-562.

Liu, X., L. Liang, N. Muramatsu, and H. Sugisawa (1995): "Transitions in Functional Status and Active Life Expectancy Among Older People in Japan," Journal of Gerontology: Social Sciences, 50B (6), S383-S394.

Manton, K.G., and E. Stallard (1990): "Changes in Health Functioning and Mortality" in S. Stahl ed., The Legacy of Longevity, (pp. 140-162), Newbury Park, CA: Sage Publications.

Manton, K.G., and E. Stallard (1991): "Cross-Sectional Estimates of Active Life Expectancy for the U.S. Elderly and Oldest-Old Populations," Journal of Gerontology, 46 (3), pp. S170-S182.

Manton, K.G., E. Stallard, and K. Liu (1993): "Forecasts of Active Life Expectancy: Policy and Fiscal Implications," The Journal of Gerontology, 48, pp. 11-26.

Manton, K.G., E. Stallard, and M. A. Woodbury (1991): "A Multivariate Event History Model Based Upon Fuzzy States: Estimation From Longitudinal Surveys with Informative Nonresponse," Journal of Official Statistics, 7 (3): pp. 261-293.

Manton, K.G., E. Stallard, M.A. Woodbury, H.D. Tolley, and A.I. Yashin (1987): "Grade of Membership Techniques for Studying Complex Event History Processes With Unobserved Covariates," in C. Clogg ed., Sociological Methodology, 1987, San Francisco: Jessey-Bass.

Manton, K.G., M.A. Woodbury, and K. Liu (1984): "Life Table Methods for Assessing the Dynamics of Nursing Home Utilization: 1976-1977," Journal of Gerontology, 39, pp. 79-87.

Mathers, C.D. (1990): "Disability-Free and Handicap-Free Life Expectancy in Australia," Australia Institute of Health: Health Differentials Series No.1.

Mathers, C.D. (1991): Health Expectancies in Australia 1981 and 1988. Australian Institute of Health: Canberra: Australian Government Publishing Service.

Mathers, C.D., J. McCallum, and J.M. Robine (1994): Advances in Heath Expectancies, Canberra: Australian Institute of Health and Welfare.

Mathers, C.D., J.M. Robine, and R. Wilkins (1994): "Health Expectancy Indicators: Recommendations for Terminology" in C.D. Mathers, J. McCallum, and J.M. Robine eds., Advances in Health Expectancies, (pp. 18-33), Canberra: Australian Institute of Health and Welfare.

McKinlay, S.M., J.B. McKinlay (1979): "Examining Trends in the Nation's Health," American Public Health Association Annual Meeting, New York.

McKinlay, J.B., S.M. McKinlay, and R. Beaglehold (1989): "A Review of the Evidence Concerning the Impact of Medical Measures on Recent Mortality and Morbidity in the United States," International Journal of Health Services, 19 (2), pp. 181-208.

Namboodiri, K. and C.M. Suchindran (1987): Life Table Techniques and Their Applications. New York: Academic Press.

Nusselder, W.J., (1998): Compression or Expansion of Morbidity? A Life-Table Approach. Thesis Publishers, Amsterdam.

Robine, J.M. (1986): Disability-Free Life Expectancy (DFLE) Indicators: General Indicators of the Health of Population, Québec: Conseil des Affaires Sociales et de la Famille (Scientific Report).

Robine, J.M., M. Blanchet, and E.D. Dowd (1992): Health Expectancy, OPCS, London: HMSO.

Robine, J.M., C.D. Mathers, M.R. Bone, and I. Romieu (1993): Calculation of Health Expectancies: Harmonization, Consensus Achieved and Future Perspectives, Montrouge, France: John Libbey Eurotext.

Robine, J.M., and P. Mormiche (1994): "Estimation de la Valeur de l'Espérance de Vie Sans Incapacité en France en 1991," Les Français et Leur Santé, 1, pp. 17-36.

Robine, J.M., and K. Ritchie (1991): "Healthy Life Expectancy: Evaluation of a New Global Indicator for Change in Population Health," British Medical Journal, 302, pp. 457-460.

Rogers, A. (1975): Introduction to Multi-regional Mathematical Demography, New York: Wiley.

Rogers, A. (1980): "Introduction to Multistate Mathematical Demography," Environment and Planning, A11, pp. 489-498.

Rogers, A., and J. Ledent (1976): "Increment-Decrement Life Tables: A Comment," Demography, 13, pp. 287-290.

Rogers, A., R. Rogers, and L.G. Branch (1989): "A Multistate Analysis of Active Life Expectancy," Public Health Reports, 104, pp. 222-226.

Rogers, A., R. Rogers, and L.G. Branch (1990): "Longer life but worse health? Measurement and Dynamics," The Gerontologist, 30, pp. 640-649.

Rogers, A., F. Willekens, and J. Ledent (1983): "Migration and Settlement: A Multiregional Comparative Study," Environment and Planning, A15, pp. 1585-1612.

Rogers, R.G., A. Belanger, and A. Rogers (1992): "Active, Dependent, and Institutionalized Life Among the Elderly in the United States," Cashiers Québécoes, 20 (2), pp. 269-288.

Rogers, R.G., A. Rogers, and A. Belanger (1989): "Active Life Among the Elderly in the United States: Multistate Life Table Estimates and Population Projections," The Milbank Memorial Fund Quarterly, 67 (3-4), pp. 370-411.

Saito, Y., E.M. Crimmins, and M.D. Hayward (1991): "Stabilité des Estimations de l'Espérance de Vie Sans Perte d'Autonomie Calculées au Moyen de Deux Méthodes de Construction de Tables de Survie," Cahiers Québécois de Démographie, 20, pp. pp. 291-327.

Saito, Y., E.M. Crimmins, and M.D. Hayward (1995): "Approaches to Measuring Active Life Expectancy: Prevalence vs. Incidence, Population vs. Status-based Life Tables," Paper presented at REVES 8.

Sanders, B. (1964): "Measuring Community Health Level," American Journal of Public Health, 54:1063-1970.

Schoen, R. (1975): "Constructing Increment-Decrement Life Tables," Demography, 12, pp. 313-324.

Schoen, R. (1988a): "Practical Uses of Multistate Population Models," Annual Review of Sociology, 14, pp. 341-361.

Schoen, R. (1988b): Modeling Multigroup Population. New York: Plenum Press.

Schoen, R., and K. Woodrow (1980): "Labor Force Status Life Tables for the United States, 1972," Demography, 17, pp. 297-322.

Sullivan, D.F. (1966): Conceptual Problems in Developing an Index of Health. Vital and Health Statistics, Series 2 (17), Washington, DC: National Center for Health Statistics.

Sullivan, D.F. (1971a) "A Single Index of Mortality and Morbidity," HSMHA Health Reports, 86, pp. 347-354.

Sullivan, D.F. (1971b) Disability Components for an Index of Health. Vital and Health Statistics, Series 2 (42), Rockville, MD: National Center for Health Statistics.

TNO Health Research (1994): TNO Report: An International Comparison of Health Expectancies, Netherlands: TNO Institute of Preventive Health Care.

U.S. Department of Health, Education and Welfare (1969): Toward a Social Report. Washington, DC: U.S. Department of Health, Education, and Welfare.

van Ginneken, J.K. (1994): "Potential of the Global Burden of Disease Project for Determining Health Expectancy" in C.D. Mathers, J. McCallum, and J.M. Robine eds., Advances in Heath Expectancies, (pp. 170-181), Canberra: Australian Institute of Health and Welfare.

van Ginneken, J.K., A.G. Dissevelt, J.T. Bonte (1992): "Summary of Results of Calculation of Life Expectancy Free of Disability in the Netherlands in 1981-1985," Health Expectancy, London: OPCS.

Verbrugge, L.M. (1994): "Disability in Late Life" in R. Abeles, H. Gift, and M. Ory eds., Aging and Quality of Life, (pp.79-98), New York: Springer.

Verbrugge, L. M., and A.M. Jette (1994): "The Disablement Process," Social Science and Medicine, 38 (1), pp. 1-14.

Wilkins, R. (1992): "Health Expectancy in Québec, 1987," Health Expectancy, London: OPCS.

Wilkins, R., and O.B. Adams (1983): "Health Expectancy in Canada, Late 1970s: Demographic, Regional, and Social Dimensions," American Journal of Public Health, 73, pp. 1073-1080.

Wilkins, R., J. Chen, and E. Ng (1994): "Changes in Health Expectancy in Canada from 1986-1991" in C.D. Mathers, J. McCallum, and J.M. Robine eds., Advances in Health Expectancies, (pp. 115-132), Canberra: Australian Institute of Health and Welfare.

Willekens, F. (1980): "Multistate Analysis: Tables of Working Life," Environment and Planning, A12, pp. 563-588.

Woodbury, M.A., and J. Clive (1974): "Clinical Pure Types as a Fuzzy Partition," Journal of Cybernetics, 4, pp. 111-121.

World Bank (1993): World Development Report 1993: Investing in Health, New York: Oxford University Press.

World Health Organization (1995): World Health Report (WHR95), Geneva : World Health Organization.

Zadeh, L.A. (1965): "Fuzzy Sets," Information Control, 8, pp. 338-353.