THE MULTISTATE LIFE TABLE METHOD: AN APPLICATION TO CONTRACEPTIVE SWITCHING BEHAVIOR*

TZY-MEY KUO, C. M. SUCHINDRAN, AND HELEN P. KOO

In many demographic behaviors (e.g., those relating to marriage, contraception, migration, and health), people change among multiple statuses through time, sometimes leaving and then returning to the same status. Data on such behaviors are often collected in surveys as censored event histories. The multistate life table (MSLT) can be used to properly describe, in a single analysis, these complex transitions among multiple states measured in such data, but MSLT is rarely applied in the demographic literature because practical guidance is lacking on how to compute MSLTs with such data. We provide methods for computing MSLT quantities using censored event-history data: namely, transition intensities and probabilities, "state occupancy" probabilities and standard errors, average time spent in specified states, and average number of visits to specified states. Applying these methods to contraceptive use, we find high levels of switching back and forth, particularly between barrier methods and non-use, resulting in high rates of unintended pregnancy.

In many demographic behaviors, people change among multiple statuses through time, sometimes leaving and then returning to the same status. Such behaviors include change in marital status among never-married, cohabiting, married, separated/divorced, and remarried states; contraceptive switching among different methods and use of no methods and pregnancy; migration to different places; and change between healthy and unhealthy states ending in death by different causes. Data on such behaviors are often collected in surveys as event histories with right-censored data. To properly describe the complex transitions back and forth among multiple states measured in such data, the multistate life table (MSLT) method is appropriate and useful. Despite its usefulness, this method has been rarely applied to event histories with censored data in the demographic literature, largely because practical guidance is lacking on how to compute MSLTs with such data (see Meira-Machado et al. 2006:5).

The purpose of this paper is to provide a step-by-step account of how to obtain from such data the transition probability matrix (the fundamental quantities on which the other life table measures depend), "state occupancy" probabilities (probabilities of being in a particular state at a particular time), average time spent in states, and average number of visits to specified states. In addition, we provide a practical formula for calculating the standard errors of the state occupancy probabilities, which has not hitherto been documented for individual-level data in the demographic literature.

We illustrate the MSLT method by applying it to contraceptive switching behavior among American women, describing changes among birth control methods, non-use, and

*Tzy-Mey Kuo, Health, Social, and Economic Research, RTI International. C. M. Suchindran, Department of Biostatistics, The University of North Carolina at Chapel Hill. Helen P. Koo, Health, Social, and Economic Research, RTI International. Direct correspondence to Tzy-Mey Kuo, RTI International, PO Box 12194, Research Triangle Park, NC 27709; E-mail: mkuo@rti.org. The research reported in this paper was funded by Grant RO1–HD34897 from the National Institute of Child Health and Human Development, Helen P. Koo as Principal Investigator. The authors gratefully acknowledge the roles of Drs. William L. Graves and Sherry Laurent as on-site investigators in Atlanta and Charlotte, the interviewers and respondents who participated in the survey, and the editors and anonymous reviewers who provided valuable suggestions to improve this paper.

intended and unintended pregnancy, measured in event histories with right-censoring. We also demonstrate that the method answers substantively interesting research questions. We formulate these illustrative research questions with respect to a synthetic cohort of women who enter the MSLT with an initial contraceptive method (including no method). Following are the research questions posed:

Research Question 1: What is the probability that a (synthetic) cohort of women who began with a specific method (at Month 1) will be using other methods (or no methods) at the end of 6, 12, or 24 months, or that they will be pregnant unintentionally at these time points?

Research Question 2: What is the expected length of time that women who began with a specific method will use it versus each of the other methods (or non-use), or be in the state of unintended pregnancy, during the first 24 months?

Research Question 3: What is the expected number of switches that women who began with a specific method will make to other contraceptive methods (or non-use) or to unintended pregnancy during the first 24 months?

The research questions and computational procedures provided in this paper have widespread applicability to various other demographic behaviors involving entry, exit, and reentry into multiple states.

BACKGROUND

An MSLT model is defined as a model for a stochastic process that allows individuals to move between a finite number of states over time, including exit and reentry into the same state (Chiang 1968; Fix and Neyman 1951; Hougaard 1999). Demographic applications of MSLT (also known as increment-decrement life tables) have appeared in the literature for several decades (e.g., Land and Rogers 1982; Namboodiri and Suchindran 1987; Palloni 2000; Schoen 1975, 1988). These earlier demographic applications were used mainly to describe and summarize demographic processes, using aggregate data drawn from census and registration data and aggregated tallies from large-scale survey data.

Using MSLT models for event-history data analysis is fairly new. What distinguishes the MSLT model applied to event-history data from the earlier works applied to aggregated data is the former's ability to handle incomplete observations caused mainly by right-censoring. Several authors have recently reviewed the statistical theory and estimation procedures that have been developed for MSLT models to handle censored data (Anderson and Keiding 2002; Commenges 1999; Meira-Machado et al. 2006; Putter, Fiocco, and Geskus 2007). The recent work builds upon the theoretical work for MSLT laid down some time ago, following the milestone work of Cox (1972) in the field of survival analysis (Anderson et al. 1993; Gill 1992; Hougaard 2000). However, practical guidance for applications is lacking in the demographic literature.

In the demographic literature, researchers have used individual event-history data to estimate models with covariates to determine the correlates of multistate transition probabilities; in some cases, they also derived some of the summary MSLT measures. For example, Islam (1994) extended the Cox proportional hazards modeling techniques to conduct covariate analysis of transition intensities in a MSLT, applying these techniques to analyze data on contraceptive use. Laditka and Wolfe (1998), Land, Guralnik, and Blazer (1994), and Lièvre, Brouard, and Heathcote (2003) used regression models of transition probabilities to determine covariate effects and average time spent in specified states. The objective of each of these papers was to obtain health expectancy from a simple three-state model that included two transient states (healthy, nonhealthy) and an absorbing state (death). This lower dimension of states made the model estimation relatively

easy to perform. Although valuable for investigating correlates of transition probabilities and for obtaining limited summary measures for cases in which no more than three states exist, this modeling approach does not fulfill the need to describe complex transitions back and forth among more than three states based on event-history data. This paper addresses this need.

COMPUTATION OF MULTISTATE LIFE TABLES USING EVENT-HISTORY DATA

This section describes the construction of MSLTs using event-history data with right-censoring. To quantify the process of moving among multiple states, suppose there are a finite number of states with two or more transient states that individuals can move into and out of at various time points. Let $X(t)$ be a random variable that indicates the state (e.g., State 1 = oral contraceptives, 2 = condom, and 3 = female sterilization) occupied at time t by a randomly chosen individual. A major assumption that is common to all life tables is that the dependence among the random variables—$X(0)$, $X(1)$, …, $X(t)$, …, $X(w)$—is a Markov process (Namboodiri and Suchindran 1987; Rajulton 1992, 2001). That is, the probability distribution of $X(t)$ depends only on the value of the $X(t-1)$.

This multistate process is fully characterized through transition probabilities between states i and j expressed as

$$q_{ij}(s,t) = P[X(t) = j \mid X(s) = i] \text{ for } s \leq t.$$

The process can also be described by transition intensities defined as

$$r_{ij}(t) = \lim_{\delta t \to 0} \frac{q_{ij}(t, t+\delta t)}{\delta t}.$$

Estimation of transition intensities in MSLT models for censored data was first proposed by Aalen and Johansen (1978) as a generalization of the Kaplan-Meier estimate of the simple two-state model when the exact timing of each transition is known (Kaplan and Meier 1958). The basic tool for this estimation—namely, the matrix product integral—is difficult to implement. For general cases, explicit expressions of variance of the estimators are cumbersome. Because of these difficulties in implementation, only limited applications of MSLT models have appeared in the literature. To overcome these difficulties when using censored data, in this paper, we consider only situations in which the data were recorded in discrete intervals (as in abridged life tables) and assume that censoring is uniform within the indicated intervals. This approach of dividing time into discrete intervals is also used in ordinary survival analysis with two states; see SAS Procedure Lifetest (SAS 2006). Using discrete time intervals allows us to directly estimate the transition probabilities and express the variance formulas for state occupancy probabilities in an iterative form (which connects the estimate from one time point to the next), and to provide practical formulas for computing other summary measures, such as average length of stay and average visits in a particular state.

Transition Probability Estimate and the Variance

A transition probability, $q_{ij}(t, t+u)$, is the conditional probability that individuals transfer to state j at time $t+u$, given that they are in state i at time t, where $0 < t < t+u$. Assuming that censoring is uniform in the time interval between t and $t+u$, the transition probability can be estimated as

$$\hat{q}_{ij}(t,\ t+u) = d_{ij}(t,\ t+u) / [n_i(t) - 0.5c_i(t,\ t+u)], \tag{1}$$

where $d_{ij}(t, t+u)$ is the number of transitions from state i to state j between the time interval t and $t+u$; $n_i(t)$ is the number of individuals who remained in origin state i at time t; and $c_i(t, t+u)$ is the number of individuals in origin state i at time t who were censored between time interval t and $t+u$.

The transition probability for any successive time intervals (such as time units 0 to 1, 1 to 2) can be directly estimated following Eq. (1). By putting all transition probabilities in a matrix form, we form a matrix $\mathbf{Q}(t, t+u)$ with its (i,j)th element being $q_{ij}(t, t+u)$.

The variance of the estimated transition probability q_{ij} can be computed by using the multinomial formula of Eq. (2):

$$Var(\hat{q}_{ij}) = q_{ij}(1-q_{ij}) \big/ [n_i(t) - 0.5c_i(t,t+u)]. \tag{2}$$

The covariance between the transition probabilities q_{ij} and $q_{ij'}$ is Eq. (3):

$$Cov(\hat{q}_{ij}, \hat{q}_{ij'}) = -q_{ij}q_{ij'} \big/ [n_i(t) - 0.5c_i(t,t+u)]. \tag{3}$$

State Occupancy Probability Estimate and the Variance

After computing the successive transition probabilities for each time interval, we can also estimate the probability of being in a certain state at time points of interest, such as at Time 12, after having started in a specific state at Time 0. This estimate provides answers to Research Question 1. We name this the "state occupancy" probability: namely, the probability that an individual is in a particular state at a specified time. Specifically, it is the probability that an individual is in state j at time t, given that the individual occupies state i at time s. Assuming a partitioning of the interval (s, t) as $s = t_0 < t_1 < \ldots < t_i < \ldots < t_n = t$, the state occupancy probabilities are the elements of the matrix (following the Markovian assumption):

$$\mathbf{Q}(s,t) = \prod_{i=0}^{n-1} \mathbf{Q}(t_i, t_{i+1}). \tag{4}$$

Estimates of $\mathbf{Q}(s,t)$ are obtained by replacing $\mathbf{Q}(t_i, t_{i+1})$ by the corresponding estimates obtained through Eq. (1).

Computation of the variance of the matrix $\mathbf{Q}(s,t)$ given in Eq. (4) is complicated because it involves the product of many matrices. However, we developed a method for this computation. The Appendix provides the details of our method for obtaining the variance and covariance of the state occupancy probabilities.

Summary Measures

Following estimation of the transition probabilities and state occupancy probabilities, we need to compute transition intensities as an intermediate step to obtaining the summary measures.

Transition intensities. A transition intensity can be loosely interpreted as a rate relating the number of transitions of a particular type to the person years of exposure to the risk of such a transition. Let $r_{ij}(t)$ denote the transition intensity from state i to state j at time t. Formally, $r_{ij}(t) = \lim_{u \to 0} q_{ij}(t, t+u)/u$ and $\sum_j r_{ij} = 0$. Let $\mathbf{R}(t)$ denote the matrix whose (i, j) element is $r_{ij}(t)$. This matrix can be partitioned according to transitions among transient states (i.e., $\mathbf{R}_{11}(t)$) and the transition from transient state to absorbing states (i.e., $\mathbf{R}_{12}(t)$) as

$$\mathbf{R}(t) = \begin{bmatrix} \mathbf{R}_{11}(t) & \mathbf{R}_{12}(t) \\ 0 & 0 \end{bmatrix}.$$

One also partitions the $\mathbf{Q}$ matrix, in the same manner, as

$$\begin{bmatrix} \mathbf{Q}_{11}(s,t) & \mathbf{Q}_{12}(s,t) \\ 0 & \mathbf{I} \end{bmatrix}.$$

Because we estimate the **Q** matrix directly from data, the **R** matrix can be obtained by using the computed **Q** matrix as follows. Assuming that transition intensities are constant in the interval (t_i, t_{i+1}), for $t_i < t < t_{i+1}$, then

$$\mathbf{R}_{11}(t) = -(1/h)[(\mathbf{I} - \mathbf{Q}_{11}(t_i,t_{i+1})) + (\mathbf{I} - \mathbf{Q}_{11}(t_i,t_{i+1}))^2/2 + \ldots] \tag{5}$$

and

$$\mathbf{R}_{12}(t) = \mathbf{R}_{11}(t)[\mathbf{Q}_{11}(t_i,t_{i+1}) - \mathbf{I}]^{-1}\mathbf{Q}_{12}(t_i,t_{i+1}), \tag{6}$$

where $h = t_{i+1} - t_i$. Although h can take any value, in our illustrative application, h is equal to 1 for all intervals. (For an alternative formula for converting transition probabilities to transition intensities, see Singer and Spilerman 1976.)

Expected length of time in a state. The summary measure—which is the expected length of sojourn time in state j between times s and t, given occupancy of state i at time s—addresses Research Question 2. It can be estimated by using the formula in Eq. (7) (see Namboodiri and Suchindran 1987):

$$\mathbf{E}(s,t) = \sum_{i=0}^{n-1} \mathbf{Q}(s,t_i)\mathbf{E}(t_i,t_{i+1}), \tag{7}$$

where the $\mathbf{E}(t_i,t_{i+1})$ can be obtained by partitioning the $\mathbf{E}(s,t)$ matrix so that the top n_1 rows and the first n_1 columns are for the transient states:

$$\mathbf{E}(t_i,t_{i+1}) = \begin{bmatrix} \mathbf{E}_{11}(t_i,t_{i+1}) & \mathbf{E}_{12}(t_i,t_{i+1}) \\ 0 & h*\mathbf{I} \end{bmatrix}.$$

Partitioning the $\mathbf{Q}(t_i,t_{i+1})$ matrix in the same manner, we obtain Eqs. (8) and (9):

$$\mathbf{E}_{11}(t_i,t_{i+1}) = (\mathbf{Q}_{11}(t_i,t_{i+1}) - \mathbf{I})(\mathbf{R}_{11}(t_i,t_{i+1}))^{-1} \tag{8}$$

$$\mathbf{E}_{12}(t_i,t_{i+1}) = (\mathbf{E}_{11}(t_i,t_{i+1}) - \mathbf{I})(\mathbf{R}_{11}(t_i,t_{i+1}))^{-1}(\mathbf{R}_{12}(t_i,t_{i+1})). \tag{9}$$

Alternatively, the computation of the **E** matrix can also be achieved as follows. In theory, $\mathbf{E}(s,t) = \int_s^t \mathbf{Q}(s,u)du$; and for a small interval (t_i, t_{i+1}), this integral can be approximated under the linearity assumption as Eq. (10):

$$\mathbf{E}(t_i,t_{i+1}) = \left(\frac{h}{2}\right)\left[\mathbf{I} + \mathbf{Q}(t_i,t_{i+1})\right], \tag{10}$$

where $h = t_{i+1} - t_i$. When $h = 1$, as is the case here, this approximation leads to the simplified formula of Eq. (11) (Lièvre et al. 2003):

$$\mathbf{E}(s,t) = \sum_{i=1}^{n} \mathbf{Q}(s,t_i). \tag{11}$$

Average number of visits to a particular state. Another summary measure that is often used in MSLTs, and that helps answer Research Question 3, is the expected number of visits made to a transient state j between the time interval s and t, given occupancy of state i at time s. Denote this as $\mathbf{M}(s,t)$. Partitioning $\mathbf{M}(s,t)$ so that the top n_1 rows and the first n_1 columns are for the transient states,

$$\mathbf{M}(s,t) = \begin{bmatrix} \mathbf{M}_{11}(s,t) & \mathbf{M}_{12}(s,t) \\ 0 & 0 \end{bmatrix}.$$

As shown by Namboodiri and Suchindran (1987), these partitioned matrixes can be computed as follows in Eqs. (12) and (13):

$$\mathbf{M}_{11}(s,t) = \sum_{i=0}^{n-1} \mathbf{Q}_{11}(s,t_i)\mathbf{E}_{11}(t_i,t_{i+1})\mathbf{B}_{11}(t_i,t_{i+1}) \tag{12}$$

$$\mathbf{M}_{12}(s,t) = \mathbf{Q}_{12}(s,t), \tag{13}$$

where $\mathbf{B}_{11}(t_i, t_{i+1})$ in Eq. (12) is obtained from the matrix $\mathbf{R}_{11}$ (i.e., Eq. (5)) by replacing the diagonal elements with 0 (zero).

APPLICATION

We use data from surveys conducted for the "Longitudinal Study of Contraceptive Choice and Use Dynamics" (Koo 1995). The baseline survey enrolled a probability sample of women choosing a "new" contraceptive method (one they had not used in the previous three months) at public family planning and postpartum clinics in Atlanta, Georgia, and in Charlotte, North Carolina. In the baseline and two follow-up surveys spanning from July 1993 to June 1997, respondents were asked to report their contraceptive use month by month.

We define eight transition states: (1) long-acting contraceptive methods (Norplant and IUDs); (2) the Depo-Provera injectable; (3) oral contraceptives (the Pill); (4) barrier and other methods (condoms, cervical cap, diaphragm, and sponge; withdrawal, calendar method, and spermicides used alone); (5) no use of any method (including no methods and abstinence for birth control);[1] (6) intended pregnancies; (7) unintended pregnancy[2]; and (8) female sterilization. Among these states, female sterilization is an absorbing state, and all the other states are transient states, which women can enter and exit repeatedly. Pregnancies are considered as a transient state because a pregnancy can end during any of the first nine months; and when a pregnancy occurs, a woman normally stops using any birth control methods but resumes use (or non-use) after her pregnancy ends.

The two long-acting methods, Norplant and IUDs, were considered as a transient state because women could decide to have these contraceptives removed at any time. The Pill, barrier/other methods, and non-use are also transient states from which women could exit at any month.

Depo-Provera needed to be treated differently because it is a hormonal injection that is effective for four months on average. In the survey, we determined the month of the first injection and asked whether the respondent obtained any subsequent injections; and if so, when. Although women typically would not obtain another injection until three or four months later, after probing to ascertain correct understanding, we recorded whatever month they reported for each injection. To meet the Markovian assumption, we create four intermediate states for Depo-Provera, corresponding to the four successive months of coverage by the injection—namely Depo1 (the month of injection); and Depo2, Depo3, and Depo4 (for each of the three subsequent months, respectively). We compute the monthly transition probabilities between these four Depo-Provera states. Most women moved successively from Depo1 through Depo4 to complete a cycle of Depo-Provera use before

1. At enrollment, all women were choosing a method to use, but the interviews determined what method they actually used in that month. This actual method was considered the starting method. Sixty-one women were found not to have used any method in the enrollment month, and nine women used abstinence.

2. Questions like those used in the National Survey of Family Growth (NSFG) were asked about each pregnancy. Following NSFG practice, unintended pregnancies were defined as those occurring earlier than the woman wanted (mistimed) or occurring when she wanted no pregnancies (Abma et al. 1997).

obtaining another injection. However, some women obtained their injections early; that is, they moved from Depo2 or Depo3 into Depo1. Some received their injections late—after more than four months; they moved from Depo4 into non-use for the number of months they were late (and did not use another method) before returning to Depo1.

Counting the four Depo-Provera states, our analyses include 11 origin and destination states. However, in presenting results, we summarize measures for the four Depo-Provera states to present a single summary result for Depo-Provera to focus on entry and exit from this contraceptive method as a whole.

For illustrative purposes, this paper analyzes transitions among methods only within the first 24 months after enrollment in the study. The contraceptive method that women chose and actually used when enrolled into the study was considered the initial origin method. The first time interval started at the month of enrollment. Women entered the life table at the beginning of the time interval (0 to 1)—that is, in Month 1—and the timing of all subsequent events is recorded as time elapsed since that first interval. However, five women who were pregnant at enrollment were entered into the life table analysis only after their pregnancies ended; their initial time interval was the first month after pregnancy termination and their initial method was whatever method (or non-use) they started then. Data of respondents who were lost to follow-up in the survey are treated as censored.

RESULTS

A total of 1,840 women were included in the analysis after excluding women who chose female sterilization at enrollment (n = 355) and those who were lost to follow-up after the baseline interview (n = 282). The majority of women were young (60% were 21 or younger), were African American (85%), were unmarried (90%), and had relatively many pregnancies (53% with two or more).

Most women's initial methods were coitus-independent methods: Norplant (14.8%), Depo-Provera (37.9%), IUD (only one woman), or oral contraceptives (the Pill; 36.5%). Only 6.6% chose barrier methods or other methods, and 3.8% did not use any method at all in the month of enrollment.

Transition Probabilities

The first step in constructing MSLTs is to compute transition probabilities, using Eq. (1). We use data from the monthly contraceptive histories to compute transition probabilities for each of the 24 consecutive months following Time 0. These transition probabilities are presented in a matrix form, in which the rows represent the origin states and the columns represent the destination states. To illustrate the tables produced for each time interval, Table 1 displays the transition probabilities for the first interval, Month 0–1, for each origin method. The sixth row shows, for example, that 93.3% of women who began with the Pill continued using it during the first interval, while 0.2% switched to long-acting methods, 1.9% switched to barrier methods, 1.8% switched to non-use, 0.9% had become pregnant intentionally, 1.2% had become pregnant unintentionally, and 0.3% were sterilized.

Research Question 1: State Occupancy Probabilities

To answer Research Question 1, we use Eq. (4) to compute the state occupancy probabilities at months 6, 12, and 24. We also compute standard errors by using the algorithm documented in the Appendix. Table 2 presents the state occupancy probabilities of using each destination method or being pregnant or sterilized at Months 6, 12, and 24 for women beginning at Time 0 with each of the four contraceptive methods or with non-use.

By the end of 6, 12, and 24 months, women beginning with long-acting methods had the highest state occupancy probabilities of using their origin method (.933, .836, .636, respectively), followed in decreasing order by women who began with Depo-Provera, the Pill, barrier/other methods, and non-use. Furthermore, women beginning with the most

Table 1. Transition Probabilities in Interval (0, 1)

	Destination State										
Initial State	Long-Acting	Depo1	Depo2	Depo3	Depo4	The Pill	Barrier/Other	Non-use	Intended Pregnancy	Unintended Pregnancy	Female Sterilization
Long-Acting	0.996	0	0	0	0	0	0.004	0	0	0	0
Depo1	0	0	1.000	0	0	0	0	0	0	0	0
Depo2	0	0	0	1.000	0	0	0	0	0	0	
Depo3	0	0	0	0	1.000	0	0	0	0	0	0
Depo4	0	0.912	0	0	0	0	0.029	0.059	0	0	0
The Pill	0.002	0.005	0	0	0	0.933	0.019	0.018	0.009	0.012	0.003
Barrier/Other	0.008	0.033	0	0	0	0.123	0.721	0.074	0.008	0.025	0.008
Non-use	0.014	0.043	0	0	0	0.271	0.057	0.557	0.014	0.029	0.014

Table 2. State Occupancy Probabilities (and standard errors) for Each Destination State, by Initial State

Initial State and Time Point	Destination State							
	Long-Acting	Depo-Provera[a]	Pill	Barrier/Other	Non-use	Intended Pregnancy	Unintended Pregnancy	Female Sterilization
Long-Acting Method								
6 months	.933 (.005)	.015 (.007)	.016 (.017)	.019 (.011)	.015 (.001)	.004 (.004)	.006 (.008)	.000 (.002)
12 months	.836 (.005)	.037 (.008)	.045 (.016)	.041 (.011)	.019 (.009)	.004 (.005)	.018 (.009)	.001 (.003)
24 months	.636 (.004)	.065 (.010)	.093 (.013)	.086 (.011)	.064 (.010)	.014 (.006)	.034 (.008)	.007 (.005)
Depo-Provera[a]								
6 months	.009 (.003)	.779 (.007)	.037 (.017)	.090 (.011)	.059 (.010)	.006 (.004)	.017 (.008)	.003 (.002)
12 months	.009 (.004)	.488 (.008)	.127 (.016)	.155 (.011)	.125 (.009)	.018 (.005)	.062 (.009)	.016 (.003)
24 months	.013 (.004)	.335 (.010)	.157 (.013)	.201 (.011)	.140 (.010)	.040 (.006)	.080 (.008)	.035 (.005)
The Pill								
6 months	.010 (.004)	.050 (.007)	.586 (.018)	.148 (.012)	.110 (.010)	.024 (.005)	.067 (.008)	.005 (.003)
12 months	.016 (.004)	.081 (.008)	.424 (.017)	.195 (.011)	.126 (.009)	.033 (.005)	.113 (.009)	.012 (.003)
24 months	.020 (.004)	.161 (.010)	.266 (.013)	.214 (.011)	.165 (.010)	.044 (.006)	.094 (.008)	.037 (.005)
Barrier/Other								
6 months	.023 (.008)	.090 (.016)	.133 (.024)	.386 (.018)	.181 (.012)	.052 (.007)	.122 (.012)	.013 (.008)
12 months	.026 (.007)	.117 (.013)	.165 (.019)	.284 (.013)	.169 (.010)	.053 (.006)	.166 (.011)	.021 (.009)
24 months	.029 (.006)	.184 (.011)	.187 (.014)	.225 (.011)	.172 (.010)	.051 (.006)	.103 (.008)	.050 (.009)
Non-use								
6 months	.028 (.014)	.098 (.022)	.220 (.034)	.213 (.017)	.264 (.021)	.036 (.011)	.118 (.016)	.025 (.014)
12 months	.030 (.012)	.118 (.017)	.215 (.024)	.231 (.014)	.173 (.012)	.044 (.008)	.156 (.013)	.033 (.014)
24 months	.032 (.010)	.179 (.011)	.200 (.014)	.216 (.012)	.167 (.011)	.047 (.006)	.099 (.008)	.060 (.015)

[a]State occupancy probabilities for Depo-Provera were obtained by summing the state occupancy probabilities of Depo1 through Depo 4. The standard errors for Depo-Provera were computed by taking the squared root of the sum of the variances.

effective methods had the lowest probabilities of being pregnant unintentionally at each time point.

Table 2 also shows that if women did not remain in their origin method, they were most likely to have switched to barrier/other methods at most time points.

Note that the estimated state occupancy probabilities do not imply continuous use of the origin method—for example, the Pill—from the beginning to Months 6, 12, and 24 because women could have switched from the Pill to other methods and returned to the Pill by these time points. However, we do capture all methods that women used during the 24 months. We summarize this information as expected durations of use and expected number of transitions among all methods.

Research Question 2: Average Length of Stay

To answer Research Question 2, we compute the expected length of use of each method conditional on the method used at the beginning of the life table, using Eq. (11).

Table 3 shows that within 24 months, women who began with long-acting or Depo-Provera methods spent the longest times using their origin methods (19.80 months and 13.80 months, respectively) and had shortest expected lengths of stay in the unintended pregnancy state (0.41 months and 1.18 months, respectively). Women who began with the Pill were next: they used their origin method for 11.22 months and were in an unintended pregnancy state for 2.13 months. Women who started with barrier/other methods and non-use used their origin methods for much shorter periods (7.74 and 5.55 months, respectively) and spent considerably more time in the unintended pregnancy state (3.02 and 2.90 months, respectively) than those who began with the more effective methods.

Research Question 3: Average Number of Visits

To answer Research Question 3, we use Eq. (12) to compute the expected number of visits to all destination states within 24 months. Table 4 indicates that compared with women with other origin methods, women who started with long-acting methods made the fewest visits (changes) to other methods. During the 24 months, 1,000 women who began with long-acting methods made a total of 1,404 visits to other methods (i.e., 1.4 changes per woman), with the most to Depo-Provera and barrier/other methods, and had the fewest unintended pregnancies (85). During the 24 months, 1,000 women who began with a Depo-Provera injection made 3,069 visits to Depo1 (i.e., on average, women obtained 3.1 injections), switched most frequently to barrier/other methods, and had 225 unintended pregnancies.

During the 24 months, 1,000 women who began with the Pill made a total of 3,116 visits, including more than 614 visits each to Depo-Provera, barrier/other methods, and non-use. They stopped using the Pill and later went back to the Pill 230 times. They had 340 unintended pregnancies.

Women beginning with barrier/other methods made the most switches to non-use (867), made many changes back to barrier/other methods (628), and had many unintended pregnancies (439). Similarly, women beginning with non-use made many visits to barrier/other methods (879), returns to non-use (604), and to unintended pregnancy (419). These results suggest that women frequently switched back and forth between barrier methods and non-use. Table 3 indicated that the women who started with these methods also used them for considerable durations. For these reasons, they experienced the most unintended pregnancies.

DISCUSSION AND CONCLUSION

In this paper, we document how to compute various quantities in MSLTs using event-history data involving censoring—procedures that are lacking in the existing demographic literature. To illustrate the method, we apply it to contraceptive switching behavior. Earlier studies of the dynamics of contraceptive use used single-decrement life tables (e.g.,

Table 3. Expected Months of Stay in Each Destination State During the First 24 Months, by Initial Method

	Destination State							
Initial State	Long-Acting	Depo1[a]	The Pill	Barrier/Other	Non-use	Intended Pregnancy	Unintended Pregnancy	Female Sterilization
Long-Acting	19.80	0.76	1.12	1.00	0.70	0.16	0.41	0.05
Depo-Provera[a]	0.21	13.80	2.52	3.16	2.24	0.48	1.18	0.38
The Pill	0.34	2.10	11.22	3.96	3.08	0.79	2.13	0.36
Barrier/Other	0.59	2.90	3.85	7.74	4.08	1.21	3.02	0.59
Non-use	0.69	2.91	5.26	4.82	5.55	0.98	2.90	0.87

[a]The expected months of Depo-Provera use were obtained by summing the expected months of use of Depo1 through Depo4.

Table 4. Expected Number of Visits to Each Destination State During the First 24 Months for 1,000 Women Beginning With Each Initial Method

	Destination State								
Initial State	Long-Acting	Depo1[a]	The Pill	Barrier/Other	Non-use	Intended Pregnancy	Unintended Pregnancy	Female Sterilization	Total Visits
Long-Acting	3	230	170	216	172	28	85	500	1,404
Depo1[a]	17	3,069	334	620	510	85	225	380	5,240
The Pill	26	615	230	750	676	119	340	360	3,116
Barrier/Other	40	827	473	628	867	163	439	590	4,027
Non-use	45	862	604	879	604	139	419	870	4,422

[a]The expected number of visits for Depo-Provera is presented only for Depo1, the month of injection.

Hammerslough 1984; Trussell and Vaughan 1999) or multiple-decrement life tables (e.g., Grady et al. 1989; Grady, Billy, and Klepinger 2002). Unlike these methods, the MSLT method includes the history of all contraceptive methods used in a single analysis and allows for both exit and reentry into reversible contraceptive methods. It thus yields a more accurate account of the complexity and level of contraceptive switching (e.g., duration of use as well as the number of changes back and forth among all methods) and the associated unintended pregnancy rates.

As we mentioned earlier, the MSLT method can be applied to the study of a variety of multistate processes, not only contraceptive switching. In multistate processes, individuals occupy one of a set of discrete states at any time; the model identifies the states and specifies between which states transitions are possible. In general, MSLTs would be the method of choice for describing behaviors that involve transitions into and out of nonabsorbing states (and into absorbing states). For example, MSLTs have been used to describe being in healthy, diseased, and dead states, as well as to determine measures, such as the average number of years in the healthy and diseased states and average number of occurrence of illnesses (e.g., Laditka and Wolf 1998 and Lièvre et al. 2003). The model allows returning to the healthy state after illness; furthermore, it would be possible to add a state of being recuperated after illness and thus examine the recurrences of illness after recuperation. The nuptiality process (marriage, divorce, separation, and death) and labor force dynamics (employment, unemployment, and death) have been studied extensively with MSLTs using aggregated data (see Namboodiri and Suchindran 1987; Schoen 1988). With the procedures that we present in this paper, one can also examine these processes using event-history data. In addition, MSLTs could be used to study recurrent event processes. In these processes, individuals experience the same event several times, and the order of the event is of interest. (The states are defined as the order in which the event occurs.) For example, MSLTs could be used advantageously to study births of different order and obtain summary measures, such as parity progression ratios and average birth intervals by birth order.

It should be noted that we illustrate the construction of MSLTs using data in which observation began when women chose a contraceptive method. Therefore, there is no left-censoring of these data (although there is right-censoring). In other event-history data, an individual may have already entered a state (e.g., already using a contraceptive method, or was already ill) when observation began, so that the data are left-censored. If the state that the individual was in and the time when she or he entered that state are known, such left-censored data can also be easily used in the calculation of the transition probabilities (Guo 1993). These left-censored observations will enter into the denominator of Eq. (1) with the appropriate duration of stay in the state at the beginning of observation. For situations in which it is not known when the left-censored spell of a state began, Guo (1993) suggested other ways to deal with this problem.

The MSLT method has a few limitations. First, the state occupancy probabilities provide the probabilities of being in a destination state at the beginning of a given time interval. It is a "prevalence rate" at the given time and does not include all the previous transitions to other states before arriving at the destination state. Thus, in our illustrative application, the state occupancy probability for a destination method that is the same as the origin method does not indicate the probability of continuous use of that method. For example, the state occupancy probability at Month 12 for use of the Pill, given that the origin state is the Pill, may not equal the probability of using the Pill for the entire 12 months. It should be noted, however, that although the state occupancy probabilities do not reveal the interim methods that women may use between the origin and destination methods, the expected durations of use and the expected number of changes of methods do provide comprehensive information on all methods used during a given period.

The MSLT method described in this paper depends on the Markov assumption. Traditionally, this assumption has been accepted in demographic analysis of nuptiality,

migration, contraceptive use dynamics, and health status models. Such an assumption may not work well in all situations. For example, in health status models, a recent entry into the nonhealthy status is more likely to die than individuals who entered that state a long time ago. One way to overcome this limitation is to use semi-Markov models (Commenges 1999). More recently, non-Markov MSLTs have appeared in the literature (Datta and Satten 2001; Meira-Machado, De Una-Alvarez, and Cadarso-Suarez 2006). These models have not had widespread applications in the literature, however.

This paper fills a gap in the demographic literature by providing detailed methods for the computation of MSLTs using censored event-history data. We also illustrate the method's usefulness in analyzing dynamics of contraceptive use. We show that a very large amount of switching back and forth among contraceptive methods occurred in the sample studied, particularly between barrier/other methods and non-use, resulting in high rates of unintended pregnancy—and that these dynamics changed over time. These insights are not possible with the methods previously used to study contraceptive switching. Application of the MSLT method to other demographic behaviors may similarly yield more comprehensive insights.

APPENDIX

Calculation of Standard Errors of State Occupancy Probabilities

Let $\mathbf{N}_t$ denote the vector with k elements showing the state occupancy probabilities at time t. The initial vector $\mathbf{N}_0$ is assumed to be known. In theory

$$\mathbf{N}_t = \mathbf{N}_0 \prod_{i=1}^{n} \mathbf{Q}(t_{i-1}, t_i),$$

where t_0 is the starting time and $t_n = t$. The corresponding estimate of $\mathbf{N}_t$ is

$$\hat{\mathbf{N}}_t = \mathbf{N}_0 \prod_{i=1}^{n} \hat{\mathbf{Q}}(t_{i-1,}\ t_i) = \hat{\mathbf{N}}_{t-1} \hat{\mathbf{Q}}(t-1, t).$$

The problem is to find the variance of $\hat{\mathbf{N}}_t$ assuming that $\mathbf{N}_0$ is known. We derive the required formula for the computation of variance of $\hat{\mathbf{N}}_t$ by using an iterative equation as shown below.

Because elements of $\hat{\mathbf{Q}}(t-1,t)$ are unbiased estimates of the elements of $\mathbf{Q}(t-1,t)$, we have

$$E\left[\hat{\mathbf{N}}_t \middle| \hat{\mathbf{N}}_{t-1}\right] = \hat{\mathbf{N}}_{t-1} \mathbf{Q}(t-1,t). \tag{A1}$$

Taking expectation one more time, we get

$$EE\left[\hat{\mathbf{N}}_t \middle| \hat{\mathbf{N}}_{t-1}\right] = E\left\{\hat{\mathbf{N}}_{t-1} \mathbf{Q}(t-1,t)\right\} = \mathbf{N}_{t-1} \mathbf{Q}(t-1,t) = \mathbf{N}_t. \tag{A2}$$

Variance of $\hat{\mathbf{N}}_t$ can then be expressed as

$$\mathrm{Var}\left(\hat{\mathbf{N}}_t\right) = E\left[\mathrm{Var}\left(\hat{\mathbf{N}}_t \middle| \hat{\mathbf{N}}_{t-1}\right)\right] + \mathrm{Var}\left\{E\left[\hat{\mathbf{N}}_t \middle| \hat{\mathbf{N}}_{t-1}\right]\right\}. \tag{A3}$$

The conditional variance of $\hat{\mathbf{N}}_t$ is given by

$$\mathrm{Var}\left(\hat{\mathbf{N}}_t \middle| \hat{\mathbf{N}}_{t-1}\right) = E\left[\hat{\mathbf{N}}_t' \hat{\mathbf{N}}_t \middle| \hat{\mathbf{N}}_{t-1}\right] - \mathbf{Q}'\left(t-1,t\right) \hat{\mathbf{N}}_{t-1}' \hat{\mathbf{N}}_{t-1} \mathbf{Q}\left(t-1,t\right). \tag{A4}$$

For simplicity in presentation, ignore the time indicator $(t-1,t)$.

The (ij)th element of the matrix $E\left[\hat{\mathbf{N}}_t' \hat{\mathbf{N}}_t \middle| \hat{\mathbf{N}}_{t-1}\right]$ can be written as

$$\sum_{\alpha=1}^{k}\sum_{\beta=1}^{k}\hat{N}_{\alpha t-1}\hat{N}_{\beta t-1}E\left[\hat{q}_{\alpha i}\hat{q}_{\beta j}\right]=\sum_{\alpha=1}^{k}\sum_{\beta=1}^{k}\hat{N}_{\alpha t-1}\hat{N}_{\beta t-1}\left\{\operatorname{cov}\left[\hat{q}_{\alpha i}\hat{q}_{\beta j}\right]+q_{\alpha i}q_{\beta j}\right\}, \tag{A5}$$

where $\hat{N}_{xt}$ denotes the xth element of vector $\mathbf{N}_t$.

In Eq. (A5), the covariance terms are zero unless $\alpha = \beta$. Eq. (A5) can be rewritten as Eq. (A6):

$$\sum_{\alpha=1}^{k}\hat{N}^2_{\alpha t-1}\operatorname{cov}\left[\hat{q}_{\alpha i}\hat{q}_{\alpha j}\right]=\sum_{\alpha=1}^{k}\sum_{\beta=1}^{k}\hat{N}_{\alpha t-1}\hat{N}_{\beta t-1}q_{\alpha i}q_{\beta j}. \tag{A6}$$

The second part of Eq. (A6) is the (ij)th element of the matrix $\mathbf{Q}'(t-1,t)\hat{\mathbf{N}}'_{t-1}\hat{\mathbf{N}}_{t-1}\mathbf{Q}(t-1,t)$. Substituting in Eq. (A4) and taking the expectation, we get the (ij)th element of the matrix $E\operatorname{Var}\left(\hat{\mathbf{N}}_t\middle|\hat{\mathbf{N}}_{t-1}\right)$ as

$$\sum_{\alpha=1}^{k}E\left[\hat{N}^2_{\alpha t-1}\right]\operatorname{cov}\left[\hat{q}_{\alpha i}\hat{q}_{\alpha j}\right]=\sum_{\alpha=1}^{k}\left\{\operatorname{Var}\left(\hat{N}_{\alpha t-1}\right)+N^2{}_{\alpha t-1}\right\}\operatorname{cov}\left[\hat{q}_{\alpha i}\hat{q}_{\alpha j}\right]. \tag{A7}$$

Denote this matrix as $\mathbf{C}_{t-1}$. Also denote the matrix $\operatorname{Var}\left(\hat{\mathbf{N}}_t\right)$ as $\mathbf{V}_t$. Then, from Eq. (A3), we can write

$$\mathbf{V}_t=\mathbf{C}_{t-1}+\mathbf{Q}'(t-1,t)\mathbf{V}_{t-1}\mathbf{Q}(t-1,t), \tag{A8}$$

and $\mathbf{V}_0$ is a null matrix. This recurrence equation can be directly used to compute the necessary variance.

The computation of the $\mathbf{C}$ matrix can be performed as follows. First, form a row vector, stacking the elements of variance covariance matrix of $\hat{\mathbf{Q}}(t-1,t)$ in numerical order by row and column. Denote this row vector as $\mathbf{L}_{t-1}$ and it will have $k^2(k + 1) / 2$ elements.

Second, form a row vector $\mathbf{N}^*_t$ with elements $E\left[\hat{N}^2_{xt-1}\right]=\operatorname{Var}\left(\hat{N}_{xt-1}\right)+N^2_{xt-1}$. This vector has k elements. Form an identity matrix $\mathbf{I}$ of size $k(k + 1) / 2$. Form the Kronecker product $\mathbf{N}^*_t\otimes\mathbf{I}_{k(k+1)/2}$. Denote this matrix as $\mathbf{A}_{t-1,}$ and this matrix will be of the order $\left[k(k+1)/2\right]\times k^2(k+1)/2$. The stacked $\mathbf{C}_{t-1}$ vector is calculated as $\mathbf{L}_{t-1}\mathbf{A}_{t-1}$.

REFERENCES

Aalen, O. and S. Johansen. 1978. "An Empirical Transition Matrix for Non-homogeneous Markov Chains Based on Censored Observations." *Scandinavian Journal of Statistics* 5:141–50.

Abma, J., A. Chandra, W. Mosher, L. Peterson, and L. Piccinino. 1997. "Fertility, Family Planning, and Women's Health: New Data From the 1995 National Survey of Family Growth." *Vital Health Statistics.* Series 23, Number 19. Hyattsville, MD: National Center for Health Statistics.

Anderson, P.K., O. Borgan, R.D. Gill, and N. Keiding. 1993. *Statistical Models Based on Counting Processes*. New York: Springer.

Anderson, P.K. and N. Keiding. 2002. "Multistate Models for Event History Analysis." *Statistical Methods in Medical Research* 11:91–115.

Chiang, C.L. 1968. *Introduction to Stochastic Processes in Biostatistics*. New York: John Wiley & Sons, Inc.

Commenges, D. 1999. "Multistate Models in Epidemiology." *Lifetime Data Analysis* 5:315–27.

Cox, D.R. 1972. "Regression Models and Life Tables (With Discussion)." *Journal of the Royal Statistical Society*, Series B 34:187–220.

Datta, S. and G.A. Satten. 2001. "Validity of the Aalen-Johnson Estimators of Stage Occupation Probabilities and Nelson Aalen Integrated Transition Hazards for Non-Markov Models." *Statistics and Probability Letters* 55:403–11.

Fix, E. and J. Neyman. 1951. "A Simple Stochastic Model of Recovery, Death, and Loss of Patients." *Human Biology* 23:205–41.

Gill, R.D. 1992. "Multistate Life-tables and Regression Models." *Mathematical Population Studies* 3:259–76.

Grady, W.R., J.O.G. Billy, and D.H. Klepinger. 2002. "Contraceptive Method Switching in the United States." *Perspectives on Sexual and Reproductive Health* 34(3):135–45.

Grady, W.R., M.D. Hayward, J.O.G. Billy, and F.A. Florey. 1989. "Contraceptive Switching Among Currently Married Women in the United States." *Journal of Biosocial Science* (Suppl.) 11: 117–32.

Guo, G. 1993. "Event-History Analysis of Left-Truncated Data." *Sociological Methodology* 23: 217–43.

Hammerslough, C.R. 1984. "Characteristics of Women Who Stop Using Contraceptives." *Family Planning Perspectives* 16(1):14–18.

Hougaard, P. 1999. "Multi-state Models: A Review." *Lifetime Data Analysis* 5:239–64.

———. 2000. *Analysis of Multivariate Survival Data. Statistics for Biology and Health*. Springer: New York.

Islam, M.A. 1994. "Multistate Survival Models for Transitions and Reverse Transitions: An Application to Contraceptive Use Data." *Journal of the Royal Statistical Society,* Series A 157:441–55.

Kaplan, E.L. and P. Meier. 1958. "Nonparametric Estimation From Incomplete Observations." *Journal of the American Statistical Association* 53:457–81.

Koo, H.P. 1995. "Who Chooses Norplant and Why?" Paper presented at the annual meeting of the Population Association of America, April 6–8, San Francisco.

Laditka, S.B. and D.A. Wolf. 1998. "New Methods for Analyzing Active Life Expectancy." *Journal of Aging and Health* 10:214–41.

Land, K.C., J.M. Guralnik, and D.G. Blazer. 1994. "Estimating Increment-Decrement Life Tables With Multiple Covariates From Panel Data: The Case of Active Life Expectancy." *Demography* 31:297–319.

Land, K.C. and A. Rogers. 1982. *Multidimensional Mathematical Demography*. New York: Academic Press.

Lièvre, A., N. Brouard, and C. Heathcote. 2003. "The Estimation of Health Expectancies From Cross-Longitudinal Surveys." *Mathematical Population Studies* 10:211–48

Meira-Machado, L., J. De Una-Alvarez, and C. Cadarso-Suarez. 2006. Non-Parametric Estimation of Transition Probabilities in a Non-Markov Illness-Death Model." *Lifetime Data Analysis* 12:325–44.

Meira-Machado, L., J. De Una-Alvarez, C. Cardarso-Suarez, and P.K. Anderson. 2006. "Multistate Models for the Analysis of Time to Event Data. Research Report." Department of Biostatistics, University of Copenhagen, Denmark.

Namboodiri, K. and C.M. Suchindran. 1987. *Life Table Techniques and Their Applications. Studies in Population,* edited by H.H. Winsborough. Orlando, FL: Academic Press.

Palloni, A. 2000. "Increment-Decrement Life Tables." Pp. 256–72 in *Demography: Measuring and Modeling Population Processes,* edited by S.H. Preston, P. Heuveline, and M. Guillot. Oxford, England: Blackwell.

Putter, H., M. Fiocco, and R.B. Geskus. 2007. "Tutorial in Biostatistics: Competing Risks and Multistate Models." *Statistics in Medicine* 26:2389–430.

Rajulton, F. 1992. "Life History Analysis in Demography: Implications for Teaching and Research." *Canadian Studies in Population* 19(1):1–16.

———. 2001. "Analysis of Life Histories—A State Space Approach." *Special Issue on Longitudinal Methodology—Canadian Studies in Population* 28:341–59.

SAS Institute Inc. 2006. SAS OnlineDoc 9.1.3. Cary, NC: SAS Institute Inc.

Schoen, R. 1975. "Constructing Increment-Decrement Life Tables." *Demography* 12:313–24.

———. 1988. *Modeling Multigroup Populations.* New York: Plenum.

Singer, B. and S. Spilerman. 1976. "The Representation of Social Processes by Markov Models." *American Journal of Sociology* 82(1):1–54.

Trussell, J. and B. Vaughan. 1999. "Contraceptive Failure, Method-Related Discontinuation and Resumption of Use: Results From the 1995 National Survey of Family Growth." *Family Planning Perspectives* 31(2):64–72, 93.