Current recommendations on the estimation of transition probabilities in Markov cohort models for use in health care decision-making: a targeted literature review

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Objective: Although Markov cohort models represent one of the most common forms of decision-analytic models used in health care decision-making, correct implementation of such models requires reliable estimation of transition probabilities. This study sought to identify consensus statements or guidelines that detail how such transition probability matrices should be estimated.

Methods: A literature review was performed to identify relevant publications in the following databases: Medline, Embase, the Cochrane Library, and PubMed. Electronic searches were supplemented by manual-searches of health technology assessment (HTA) websites in Australia, Belgium, Canada, France, Germany, Ireland, Norway, Portugal, Sweden, and the UK. One reviewer assessed studies for eligibility.

Results: Of the 1,931 citations identified in the electronic searches, no studies met the inclusion criteria for full-text review, and no guidelines on transition probabilities in Markov models were identified. Manual-searching of the websites of HTA agencies identified ten guidelines on economic evaluations (Australia, Belgium, Canada, France, Germany, Ireland, Norway, Portugal, Sweden, and UK). All identified guidelines provided general guidance on how to develop economic models, but none provided guidance on the calculation of transition probabilities. One relevant publication was identified following review of the reference lists of HTA agency guidelines: the International Society for Pharmacoeconomics and Outcomes Research taskforce guidance. This provided limited guidance on the use of rates and probabilities.

Conclusions: There is limited formal guidance available on the estimation of transition probabilities for use in decision-analytic models. Given the increasing importance of cost-effectiveness analysis in the decision-making processes of HTA bodies and other medical decision-makers, there is a need for additional guidance to inform a more consistent approach to decision-analytic modeling. Further research should be done to develop more detailed guidelines on the estimation of transition probabilities.

Keywords: cost-effectiveness, decision models, probability, transitions

Introduction

Health technology assessment (HTA) and medical decision-making, more generally, rely on the use of decision-analytic models. Such models synthesize clinical, epidemiological, quality of life, resource use, and cost data in order to generate estimates of health effects and associated costs. Markov models are a popular form of decision-analytic models which characterize patient cohorts based on a finite number of mutually exclusive and exhaustive “health states”. Under the Markov property, membership...
of future health states depends only on the current health state, and not on the events that occurred before. Movement between health states is defined by “transition probabilities”, which determine the likelihood of a patient moving from one health state to another over a discrete period of time (the “cycle length”).

An illustrative example of a three-state Markov model with health states 1, 2, and 3 is presented in Figure 1; an example of health states for a model of a general condition may be asymptomatic disease, symptomatic disease, and death. Movements between health states are governed by a matrix \( P \) of transition probabilities \( p_{rs} \), which describes the risk of moving from state \( r \) to state \( s \neq r \) at time \( t \) over a model cycle of length \( u \), and \( p_{rr} \), which describes the probability of remaining in state \( r \) at time \( t \) over a model cycle of length \( u \). One health state (in this case health state 3, and usually the health state corresponding to death) will act as the “absorbing state”, for which the probability of moving to any other state is 0 and the probability of remaining in the state is 1.

Measures for cost and outcome can be associated with states and transitions to account for resource use during different stages of disease and the associated changes in health outcomes. These estimates of costs and outcomes may be accumulated over the course of the model and the cost-effectiveness of health technologies estimated.

The correct implementation of Markov models requires reliable and robust estimation of transition probability matrices (TPMs). In the simplest case, transition probabilities can be estimated in a straightforward manner using nonparametric methods based on observed counts for movements between health states in a data source. Briggs et al describe the methods for calculating probabilities in this scenario. However, calculating TPMs is challenging when the inputs to the economic evaluation cannot be derived directly and completely from a single dataset; for example:

- How should TPMs be constructed when not all transitions are observed within a dataset?

Briggs et al note that feasible transitions might not always be observed in all datasets, implying 0% probability of these transitions occurring. The authors advise not to exclude potential transitions because they were not observed in the data. Alternatively, a prior distribution may be specified; commonly, 1 is added to each cell count.

- How should subgroup analyses be performed in Markov cohort models?

Subgroup analysis in Markov cohort models for economic evaluation is usually performed based on stratification of data, and estimation of transition probabilities at different values of \( t \) typically requires multiple partitions of the available data. This is often not an efficient use of data, and introduces many model parameters. An alternative approach is to allow covariate adjustment of the TPM. A growing body of literature has described these multi-state parametric models, which can be implemented in standard statistical software such as R, but have not yet been applied widely within economic evaluations for HTA submissions.

- How should treatment effects from clinical studies and meta-analyses be applied?

It is common to apply relative effects to TPMs to estimate the probability of events for an intervention. Such treatment effects may be drawn from clinical trials directly or from formal evidence synthesis. Relative risks and odds ratios (unlike hazard ratios) are specific to the time period for which the event probabilities are defined. If the length of the trial or study reporting the relative risk (or odds ratio) is not the same as cycle length \( u \), then applying this relative risk (or odds ratio) directly will be incorrect. Price et al present an adjustment to account for differences between the measured time point and the relative risk.

- How can we convert between alternative cycle lengths?

It is well known that in order to convert a probability from one cycle length to another (e.g., from annual to 6-months), it must be done by first converting to a rate. This is commonly achieved using the standard actuarial formula. However, conversion of a TPM from one cycle length to another is nontrivial; applying the actuarial formula to convert TPMs
in models with more than two states introduces bias, because this ignores competing risk among states. More appropriate conversion requires taking the root of the matrix, or alternatively, choosing a short cycle length such that the probability of multiple clinical events occurring during a cycle is very small, thereby minimizing the bias.

- How should missing data be handled?

A commonly recommended strategy for addressing missing data within economic evaluations is multiple imputation. Under multiple imputation, each missing value is replaced with multiple predicted values; a vector of possible values is created. M complete datasets are created, each with different imputations for the missing data. The datasets can then be analyzed together using standard statistical methods and uncertainty appropriately characterized using Rubin’s rules. In order to estimate transition probabilities nonparametrically following imputation, the analyst may, for example, assume that the observed value is represented by the mean of the values across the M datasets. However, this approach fails to recognize the uncertainty associated with the imputation process itself and as a consequence will underestimate uncertainty in the analysis. An obvious approach may be to estimate separate TPMs for each of the M datasets, and then sample between these alternative datasets in probabilistic sensitivity analysis. However, we are not aware of any studies assessing this.

Transparent and consistent decision-making relies on the availability of an accepted methodological approach to the calculation of TPMs; while individual researchers have contributed substantially to the discussion on these topics, the authors of the present study are not aware of any formal consensus statements or guidelines addressing questions such as those mentioned earlier. This targeted literature review therefore, sought to identify consensus statements or guidelines detailing how TPMs should be estimated for use in Markov models in the context of the economic evaluation of medical interventions.

**Methods**

A targeted literature review was performed to answer the following research question:

- What consensus statements or guidelines are available to inform the calculation of transition probabilities for use in Markov models for the economic evaluation of medical interventions?

Consensus statements were defined as “documents containing suggestions or recommendations based on the collective opinion of an expert panel” and guidelines as “systematically developed statements to assist researchers, HTA bodies, and other professionals in decisions about appropriate methodological approaches”.

**Search methods**

A base strategy was developed and refined to specifically target publications relevant to the research question.

**Electronic database search**

Search strategies specific to each database were designed to focus on retrieval of the published articles most likely to be relevant to the research question. The search strategies were designed and run by an experienced medical librarian.

The following electronic databases were searched:

- Medline (OvidSP)
- Medline In-Process Citations & Daily Update (OvidSP)
- Embase (OvidSP)
- PubMed
- The Cochrane Library, which includes six databases (Cochrane Database of Systematic Reviews, Cochrane Central Register of Controlled Trials, Cochrane Methodology Register, Database of Abstracts of Reviews of Effects, Health Technology Assessment Database, NHS Economic Evaluation Database)

Electronic searches were limited to English language publications. No country or time limits were applied. Details on the search strategy can be found in Figure S1.
HTA website search
The electronic search was supplemented by a literature search for relevant guidelines on HTA agency websites. The HTA agencies whose websites were searched are listed in Table 1. Reference lists of identified HTA guidelines were screened to identify additional relevant publications. No language limit was applied to searches of HTA websites.

Study selection
Identified publications were screened by one reviewer, with any publication considered to be informative to the research question being included. Study selection occurred in three phases:

- Potentially relevant publications were identified based on their title; any title clearly irrelevant was discarded at this stage.
- Abstracts or keywords were used to screen the remaining articles in order to identify relevant publications for full-text review.
- The full text of each potentially relevant publication was reviewed.

Studies were included if they were guidelines or consensus statements on the calculation of transition probabilities from either clinical endpoints of clinical trials or from clinical parameters of indirect/multiple treatment comparisons in Markov models. Publications that were not produced on behalf of professional organizations, expert panels, or HTA bodies were excluded.

Results
Electronic database search
The electronic database search identified 3,636 publications; 1,931 unique publications were identified following deduplication (Table 2).

<table>
<thead>
<tr>
<th>Electronic database</th>
<th>Records identified</th>
<th>After deduplication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medline</td>
<td>1,057</td>
<td>1,043</td>
</tr>
<tr>
<td>Embase</td>
<td>1,422</td>
<td>775</td>
</tr>
<tr>
<td>PubMed</td>
<td>1,098</td>
<td>111</td>
</tr>
<tr>
<td>The Cochrane Library</td>
<td>59</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td>3,636</td>
<td>1,931</td>
</tr>
</tbody>
</table>

Of the 1,931 unique publications identified, 1,788 publications were excluded on the basis of title review and 143 publications were excluded on the basis of abstract review. No guidelines on the estimation of transition probabilities for use in Markov models were identified via the electronic database search (Figure 2). However, 56 studies were considered to be of broad relevance, typically reflecting the viewpoints of individual authors or independent research groups as opposed to formal guidelines or recommendations. A list of the 56 publications considered to be of broad relevance can be found in Table S1.

HTA website search
The HTA website search identified 10 guidelines on economic evaluation. However, no identified guidelines included

Table 1 HTA agency websites considered

<table>
<thead>
<tr>
<th>Country</th>
<th>HTA agency</th>
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<tbody>
<tr>
<td>Australia</td>
<td>Pharmaceutical Benefits Advisory Committee (PBAC)</td>
</tr>
<tr>
<td>Belgium</td>
<td>Belgian Health Care Knowledge Centre (KCE)</td>
</tr>
<tr>
<td>Canada</td>
<td>Canadian Agency for Drugs and Technologies in Health (CADTH)</td>
</tr>
<tr>
<td>France</td>
<td>The French National Authority for Health (HAS)</td>
</tr>
<tr>
<td>Germany</td>
<td>Institute for Quality and Efficiency in Health Care (IQWiG)</td>
</tr>
<tr>
<td>Ireland</td>
<td>National Centre for Pharmacoeconomics (NCPE)</td>
</tr>
<tr>
<td>Norway</td>
<td>The Norwegian Medicines Agency (NoMA)</td>
</tr>
<tr>
<td>Portugal</td>
<td>National Authority of Medicines and Health Products (INFARMED)</td>
</tr>
<tr>
<td>Sweden</td>
<td>Dental and Pharmaceutical Benefits Agency (TLV)</td>
</tr>
<tr>
<td>UK*</td>
<td>National Institute for Health and Care Excellence (NICE), Scottish Medicines Consortium (SMC), All Wales Medicines Strategy Group (AWMSG)</td>
</tr>
</tbody>
</table>

Note: *Including NICE Decision Support Unit reports.
Abbreviation: HTA, health technology assessment.
Discussion
The aim of the targeted review was to identify formal recommendations, such as consensus statements or guidelines, to inform the calculation of transition probabilities for use in Markov models for the economic evaluation of medical interventions. One relevant publication was identified, in which the ISPOR-SMDM Modeling Good Research Practices Task Force recommended that the conversion of transition probabilities from one cycle length to another should be done through rates. However, a substantial body of literature on this topic. An expert panel or working group should be convened to identify key circumstances in which the estimation of TPMs spanning all academic fields should be undertaken, and formal recommendations on the calculation of TPMs should be developed based on the basis of the review, and as part of an iterative process amongst the expert panel or working group.

In the absence of consensus statements or guidelines, currently developed Markov models may utilize approaches that reduce accuracy, introduce additional uncertainty, or underestimate the uncertainty that exists. The development of formal guidance on the estimation of TPMs for health care decision-making would allow a more consistent approach to decision-analytic modeling, and therefore to decision-making.

Acknowledgments
We would like to thank Richard Grieve for the critical review of this manuscript and Dave Fox for developing the search strategy. This study was sponsored by Takeda Pharmaceuticals International AG. The abstract of this article was presented as a poster at the International Society for Pharmacoeconomics and Outcomes Research 19th Annual European Congress in 2016. The poster's abstract has also been published.

Disclosure
HCS is a permanent employee of Takeda Pharmaceuticals International AG. EO, KKC, EH, and DT have received consulting fees from Takeda Pharmaceuticals International AG. The authors report no other conflicts of interest in this work.

References
Supplementary materials

Medline

**Searched 25/05/16 via OvidSP interface.**
Limited to English language.
Database: Epub Ahead of Print, In-Process & Other Non-Indexed Citations, Ovid MEDLINE(R) Daily and Ovid MEDLINE(R)<1946 to Present>
Search strategy:
1 (transition adj2 (probabilit$ or intensiti$)).ti,ab. (2,490)
2 markov$.ti,ab. (17,383)
3 (multi adj1 state) or (state adj1 transition) or cohort or decision or (decision adj1 analytic) adj1 model$.ti,ab. (3,477)
4 (matrix or matrices).ti,ab. (3,15,632)
5 or/2–4 (3,34,908)
6 1 and 5 (1,091)
7 limit 6 to english language (1,057)
1,057 results.

Embase

**Searched 25/05/16 via OvidSP interface.**
Limited to English language.
Database: Embase <1996 to 2016 Week 21>
Search strategy:
1 (transition adj2 (probabilit$ or intensiti$)).ti,ab. (2,832)
2 markov$.ti,ab. (20,059)
3 (multi adj1 state) or (state adj1 transition) or cohort or decision or (decision adj1 analytic) adj1 model$.ti,ab. (4,710)
4 (matrix or matrices).ti,ab. (3,60,188)
5 or/2–4 (3,82,938)
6 1 and 5 (1,731)
7 limit 6 to english language (1,682)
8 limit 7 to Embase (1,422)
1,422 results.

PubMed

**Searched 25/05/16 online at https://www.ncbi.nlm.nih.gov/pubmed/advanced**
Limited to English language.
Search strategy:
#8 (#6 and #7) (1,098)
#7 “english”[Language] (2,15,23,839)
#6 (#1 and #5) (1,129)
#5 (#2 or #3 or #4) (4,26,135)
#4 (matrix[Title/Abstract] OR matrices[Title/Abstract]) (3,14,406)
#3 (((multi-state[Title/Abstract] OR “multi state”[Title/Abstract] OR state-transition[Title/Abstract] OR “state transition”[Title/Abstract] OR cohort[Title/Abstract] OR decision[Title/Abstract] OR decision-analytic[Title/Abstract]) AND model*[Title/Abstract])) (99,167)
#2 markov*[Title/Abstract] (17,498)
#1 (transition probability*[Title/Abstract] OR “transition probabilities”[Title/Abstract] OR “transition intensity”[Title/Abstract] OR “transition intensities”[Title/Abstract]) (2,260)
1,098 results.

Figure S1 (Continued)
Cochrane Library
Includes Cochrane Database of Systematic Reviews (CDSR), Database of Abstracts of Reviews of Effects (DARE), Cochrane Central Register of Controlled Trials (CENTRAL), Health Technology Assessment Database (HTAD), NHS Economic Evaluations Database (NHSEED).

Searched 25/05/16 online at http://onlinelibrary.wiley.com/cochranelibrary/search/advanced
Search strategy:
#1 (transition near/2 (probabilit* or intensit*)):ti,ab (76)
#2 markov*:ti,ab (672)
#3 (((multi near/1 state) or (state near/1 transition) or cohort or decision or (decision near/1 analytic)) near/1 model*):ti,ab (358)
#4 (matrix or matrices):ti,ab (3,581)
#5 #2 or #3 or #4 (4,537)
#6 #1 and #5 (59)
59 total results all from CENTRAL. No results for CDSR, DARE, HTAD, or NHSEED.

Figure S1 Search strategy.

Table S1 Potentially relevant publications identified via the electronic searches

<table>
<thead>
<tr>
<th>Reference</th>
<th>Title</th>
</tr>
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<tbody>
<tr>
<td>Aalen et al1</td>
<td>Covariate adjustment of event histories estimated from Markov chains: the additive approach</td>
</tr>
<tr>
<td>Alam et al2</td>
<td>Investigating the impact of structural changes in a nice single technology appraisal cost-effectiveness model</td>
</tr>
<tr>
<td>Alarid-Escudero et al3</td>
<td>Calibration of piecewise Markov models using a change-point analysis through an iterative convex optimization algorithm</td>
</tr>
<tr>
<td>Albert and Waclawiw4</td>
<td>A two-state Markov chain for heterogeneous transitional data: a quasi-likelihood approach</td>
</tr>
<tr>
<td>Allignol et al5</td>
<td>A competing risks approach for nonparametric estimation of transition probabilities in a non-Markov illness-death model</td>
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<tr>
<td>Andersen and Pohar Perme4</td>
<td>Inference for outcome probabilities in multi-state models</td>
</tr>
<tr>
<td>Black et al7</td>
<td>Determining transition probabilities from mortality rates and autopsy findings</td>
</tr>
<tr>
<td>Borgan7</td>
<td>Estimation of covariate-dependent Markov transition probabilities from nested case-control data. (Erratum is reference 9)</td>
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<tr>
<td>Borgen9</td>
<td>Erratum: Estimation of covariate-dependent Markov transition probabilities from nested case-control data (Original paper is reference 8)</td>
</tr>
<tr>
<td>Boruvka and Cook10</td>
<td>Sieve estimation in a Markov illness-death process under dual censoring</td>
</tr>
<tr>
<td>Cohen11</td>
<td>On estimating the equilibrium and transition probabilities of a finite-state Markov chain from the same data</td>
</tr>
<tr>
<td>Cooper et al12</td>
<td>Comprehensive decision analytical modelling in economic evaluation: a Bayesian approach</td>
</tr>
<tr>
<td>Craig and Sendi13</td>
<td>Estimation of the transition matrix of a discrete-time Markov chain</td>
</tr>
<tr>
<td>Dabrowska and Ho14</td>
<td>Confidence bands for comparison of transition probabilities in a Markov chain model</td>
</tr>
<tr>
<td>Debosscher15</td>
<td>Unifying stochastic Markov process and its transition probability density function</td>
</tr>
<tr>
<td>Denton and Spencer16</td>
<td>Modeling the age dynamics of chronic health conditions: life-table-consistent transition probabilities and their application</td>
</tr>
<tr>
<td>Diaby et al17</td>
<td>Survival modeling for the estimation of transition probabilities in model-based economic evaluations in the absence of individual patient data: a tutorial</td>
</tr>
<tr>
<td>Gaveau and Schulman18</td>
<td>Multiple phases in stochastic dynamics: geometry and probabilities</td>
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<tr>
<td>Gupta et al19</td>
<td>Transition probability estimation using repeated sampling from a fitted mixed model</td>
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<tr>
<td>Gupta et al20</td>
<td>Generalized implementation of EM algorithm for estimation of transition probability matrix</td>
</tr>
<tr>
<td>Hawkins and Han21</td>
<td>Estimating transition probabilities from aggregate samples plus partial transition data</td>
</tr>
<tr>
<td>Healy and Engler22</td>
<td>Modeling disease-state transition heterogeneity through Bayesian variable selection</td>
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<tr>
<td>Huang23</td>
<td>Integrated analysis of incidence, progression, regression and disappearance probabilities</td>
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<tr>
<td>Iacobelli and Carstensen24</td>
<td>Multiple time scales in multi-state models</td>
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<tr>
<td>Kassteine et al25</td>
<td>Estimating net transition probabilities from cross-sectional data with application to risk factors in chronic disease modeling</td>
</tr>
<tr>
<td>Kaushik et al26</td>
<td>A methodology to monitor the changing trends in health status of an elderly person by developing a Markov model</td>
</tr>
<tr>
<td>Li and Pack27</td>
<td>An application of Markov models in estimating transition probabilities for postmenopausal women with osteoporosis</td>
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Table S1 (Continued)

<table>
<thead>
<tr>
<th>Reference</th>
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<tbody>
<tr>
<td>Limwattananon and Limwattananon28</td>
<td>Constructing a state-transition model for an economic evaluation of cancer treatments</td>
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<tr>
<td>McCombs29</td>
<td>Pharmacoeconomics: what is it and where is it going?</td>
</tr>
<tr>
<td>Meidan and Ghanem10</td>
<td>Uncertainty quantification for Markov chain models</td>
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<tr>
<td>Meira-Machado et al11</td>
<td>Nonparametric estimation of transition probabilities in a non-Markov illness-death model</td>
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<tr>
<td>Meira-Machado et al12</td>
<td>Multi-state models for the analysis of time-to-event data</td>
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<tr>
<td>Miller and Homan13</td>
<td>Determining transition probabilities: confusion and suggestions</td>
</tr>
<tr>
<td>Milne14</td>
<td>Pharmacoeconomic models in disease management. A guide for the novice or the perplexed</td>
</tr>
<tr>
<td>Moussa et al15</td>
<td>Measuring the change in contingency tables using Markov models application to the effect of preceding conception on the next one</td>
</tr>
<tr>
<td>Muenz and Rubinstein16</td>
<td>Markov models for covariate dependence of binary sequences</td>
</tr>
<tr>
<td>Nagyliki27</td>
<td>The distribution of sojourn times in finite absorbing Markov chains</td>
</tr>
<tr>
<td>Neine et al18</td>
<td>Bayesian calibration method to estimate transition probabilities for a Markov model based on a continuous outcome measure: application in Parkinson’s disease</td>
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<tr>
<td>Ng and Cook29</td>
<td>Modeling two-state disease processes with random effects</td>
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<td>O’Mahony et al40</td>
<td>Dealing with time in health economic evaluation: methodological issues and recommendations for practice</td>
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<td>Oppe et al41</td>
<td>Comparing methods of data synthesis: re-estimating parameters of an existing probabilistic cost-effectiveness model</td>
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<tr>
<td>Paes and Lima42</td>
<td>A SAS macro for estimating transition probabilities in semiparametric models for recurrent events</td>
</tr>
<tr>
<td>Putter et al13</td>
<td>Tutorial in biostatistics: competing risk and multi-state models</td>
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<tr>
<td>Regnier and Shechter44</td>
<td>State-space size considerations for disease-progression models</td>
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<tr>
<td>Rodriguez-Girondo and Una-Alvarez43</td>
<td>A nonparametric test for Markovianity in the illness-death model</td>
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<tr>
<td>Rodriguez-Girondo and Una-Alvarez44</td>
<td>Testing Markovianity in the three-state progressive model via future-past association</td>
</tr>
<tr>
<td>Rosychuk et al48</td>
<td>Methods for testing the Markov condition in the illness-death model: a comparative study</td>
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<tr>
<td>Rosychuk and Thompson48</td>
<td>Comparison of variance estimation approaches in a two-state Markov model for longitudinal data with misclassification</td>
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<tr>
<td>Saint-Pierre et al49</td>
<td>Bias correction of two-state latent Markov process parameter estimates under misclassification</td>
</tr>
<tr>
<td>Spitoni et al51</td>
<td>The analysis of asthma control under a Markov assumption with use of covariates</td>
</tr>
<tr>
<td>Tattar and Vaman12</td>
<td>Estimation and asymptotic theory for transition probabilities in Markov renewal multi-state models</td>
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<tr>
<td>Tattar and Vaman13</td>
<td>Testing transition probability matrix of a multi-state model with censored data</td>
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<tr>
<td>Titman48</td>
<td>The k-sample problem in a multi-state model and testing transition probability matrices</td>
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<tr>
<td>Tsang et al15</td>
<td>Transition probability estimates for non-Markov multi-state models</td>
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<tr>
<td>Welton and Ades16</td>
<td>Estimation of Markov chain transition matrices in limited data samples: Monte Carlo experiment</td>
</tr>
<tr>
<td></td>
<td>Estimation of Markov chain transition probabilities and rates from fully and partially observed data: uncertainty propagation, evidence synthesis, and model calibration</td>
</tr>
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References