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EVALUATING MDP-DERIVED PERSONALIZED STRATEGIES AGAINST GUIDELINE-BASED CARE FOR THE MANAGEMENT OF SMALL RENAL MASSES

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ABSTRACT

Management of small renal masses (SRMs) requires balancing cancer control with preservation of kidney function, while accounting for competing causes of mortality. We developed a patient-level microsimulation model to evaluate health outcomes under alternative treatment strategies, including published guidelines and MDP-derived personalized policies. Patients were simulated with heterogeneous attributes—age, sex, tumor size, subtype, and chronic kidney disease (CKD) stage—followed in 6-month cycles starting from age 65, evolving probabilistically across health states. The model incorporated tumor growth, CKD progression, recurrence, metastasis, and mortality from cancer, CKD-related cardiovascular disease, and other causes. Outcomes included life expectancy, quality-adjusted life years (QALYs), and cause-specific mortality, highlighting trade-offs between cancer control and renal function preservation. Results showed that MDP-derived policies improved survival and QALYs compared with guideline-based care. This work demonstrates the value of microsimulation in supporting treatment planning for SRM patients under competing risks.

1 INTRODUCTION

Small renal masses (SRMs) are increasingly detected due to widespread cross-sectional imaging, yet optimal treatment strategies remain uncertain. Clinical management requires balancing long-term cancer control with preservation of kidney function, which is especially critical for patients with chronic kidney disease (CKD). This challenge is compounded by uncertainty in tumor progression, risk of renal function decline, and heterogeneity in patient demographics, tumor subtype, and anatomical complexity. Outcomes are further influenced by competing causes of mortality, including deaths from cancer, CKD-related cardiovascular disease, and other causes. Current guidelines provide general recommendations but do not adapt to individual risk profiles, leading to potential over- or undertreatment.

Microsimulation has been widely applied in cancer decision-analytic modeling, most prominently by the CISNET consortium (2025), where it has informed national screening guidelines. In SRMs, prior microsimulation studies have evaluated treatment strategies but largely at the population level. For example, Kang et al. (2019) incorporated tumor anatomic scoring to guide nephron-sparing treatment, yet their model compared fixed strategies rather than optimizing sequential decisions over time. Such sequential decision optimization can be formalized using Markov decision process (MDP) models, which have been applied in other cancer settings but not to SRM management. To our knowledge, no study has combined MDP modeling with patient-level microsimulation to generate and evaluate personalized SRM strategies.

Our study addresses this gap by integrating CKD progression, post-treatment states, and competing risks alongside tumor dynamics, with outcomes validated against multiple external benchmarks. Our framework uniquely combines formal model checking with patient-level microsimulation, allowing verification of state transitions and reward structures before policy evaluation. Building on our finite-horizon MDP, which computes optimal policies to maximize quality-adjusted life years (QALYs), we now evaluate these policies in practice. Our objectives are (i) to simulate long-term patient trajectories while accounting for heterogeneity in clinical and demographic characteristics, and (ii) to compare health outcomes of guideline-based strategies versus MDP-derived treatment policies.

2 METHODOLOGY

We developed a state-transition microsimulation model to project health outcomes in patients with clinical stage T1a ($\leq$4 cm) renal masses. Patients entered the model at age 65 and were characterized by fixed attributes (sex and tumor subtype) and time-dependent variables (age, tumor size, and CKD stage). Each patient was simulated in 6-month cycles until death or age 100. Treatment decisions were only applied up to age 85, after which no active treatment was provided.

At each cycle, a strategy-specific rule selected a treatment: (i) NCCN guideline-based care, or (ii) MDP-derived personalized policy. Actions included active surveillance (AS), ablation (ABL), partial nephrectomy (PN), and radical nephrectomy (RN). Transitions for tumor growth, CKD progression, recurrence, metastasis, and mortality were based on cohort data and published literature. Secondary treatment following recurrence or incomplete removal was permitted.

Patients were simulated under each strategy, and outcomes included life expectancy, quality-adjusted life years (QALYs), and cause-specific mortality. We generated 1,000 patient trajectories to approximate the size of the source cohort from which input parameters were derived. Model outputs were validated against external benchmarks, including SEER survival (2025) (e.g., 93% 5-year overall survival) and DISSRM registry outcomes (e.g., 100% 5-year cancer-specific survival).

3 RESULTS

Compared with NCCN guideline–based rules, personalized MDP-derived policies achieved higher life expectancy and QALYs. Benefits were greatest for patients with CKD at baseline or aggressive tumor subtypes, where individualized decisions reduced cancer deaths without accelerating CKD-related mortality. Cause-specific analyses showed that guideline-based rules increased cancer mortality from undertreatment in some high-risk patients and CKD-related deaths from overtreatment with RN, whereas personalized strategies better balanced these risks.

Model validation confirmed that simulated survival trajectories were consistent with published benchmarks and within reported 95% confidence intervals, supporting external validity. In addition, CKD transition probabilities were estimated using an expectation–maximization (EM) algorithm to account for sparse and unevenly observed cohort data, and the resulting transitions were validated by comparing simulated CKD progression against observed patterns in the source cohort.

4 CONCLUSIONS

This study shows that guideline-based approaches may overlook important factors such as tumor heterogeneity, pre-existing CKD, and competing causes of mortality, leading to mistreatment. By integrating personalized policies within a microsimulation framework, we found improvements in survival and QALYs, particularly among high-risk patients, while reducing unnecessary treatments. These results highlight the potential of simulation models to support individualized, evidence-based treatment planning in oncology.

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