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EVALUATING LIVER GRAFT ACCEPTANCE POLICIES USING A CONTINUOUS-TIME MARKOV CHAIN SIMULATION FRAMEWORK

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ABSTRACT

Liver transplantation is the only curative treatment for patients with end-stage liver disease. The United Network for Organ Sharing operates the national liver transplant waiting list and allocates organs under a complex priority system based on medical urgency, geography, and waiting time. However, the limited availability of high-quality organs and variability in acceptance decisions continue to challenge the system. I develop a continuous-time Markov reward process simulation framework to evaluate liver offer acceptance practices in the United States. This simulation framework models organ arrivals and patients' health progression as continuous-time processes and mimics how decisions are made in practice using a randomized policy. Results highlight the trade-offs between waiting for higher-quality organs and accepting earlier offers of lower quality. This framework provides insights and identifies areas for enhancing patient management and liver offer acceptance.

1 INTRODUCTION

End-stage liver disease is one of the leading causes of death in the United States. Liver transplantation is the only curative treatment, but the persistent shortage of donor organs remains a critical challenge, and ongoing population growth is expected to exacerbate this scarcity, further straining the liver transplantation system (Parikh et al. 2015). The United Network for Organ Sharing manages allocation based on urgency, geography, and waiting time. When an organ becomes available, it is sequentially offered to suitable candidates on the waiting list, and the final decision to accept or refuse a liver offer mainly relies on individual transplant centers and clinicians, who consider clinical and organ quality factors. Current acceptance practices result in low utilization rates and variable outcomes across centers, motivating the need for systematic evaluation. However, the complexity inherent in acceptance decisions makes analytical solutions difficult. In such settings, simulation provides a practical approach for evaluating outcomes (Ross 2022). Most existing simulation models in liver transplantation assess waiting list dynamics, patient survival rates, and organ utilization through discrete-event simulations. In this work, I extend these approaches by developing a continuous-time framework.

2 MODELING FRAMEWORK

I develop a simulation environment to evaluate liver offer acceptance practices using a continuous-time framework. Candidate health is modeled using the Model for End-Stage Liver Disease (MELD) score (Kamath et al. 2001), while liver quality is represented by the Donor Risk Index (DRI) (Feng et al. 2006). To reflect patient-level variation more precisely, the MELD score is grouped into individual categories — $< 15, 15, 16, ..., 39, 40, > 40$ — forming a finite set of health states through which candidates transition over time. Higher MELD scores correspond to more severe liver dysfunction and greater urgency for transplantation. Similarly, higher DRI values indicate increased relative risk of graft failure after and thus reflect lower-quality organs. I discretize the DRI into 10 intervals — $(0, 1.1]$, $(1.1, 1.2]$, $(1.2, 1.3]$, $(1.3, 1.4]$, $(1.4, 1.5]$, $(1.5, 1.6]$, $(1.6, 1.7]$, $(1.7, 1.8]$, $(1.8, 2]$, $(2, \infty)$ — which enables the model to capture heterogeneity in organ quality and its influence on post-transplant outcomes. Health progression and organ arrivals are parameterized using exponential transition rates estimated from the Organ Procurement and Transplantation Network database from 2010 to 2023. At each offer arrival, a transplant clinician may choose to accept or decline the offer, based on the health condition of a candidate and the quality of the liver, according to the current acceptance practices. If the offer is rejected, the simulation proceeds to the next potential offer. If the offer is accepted, the simulation replicate terminates, and the candidate's 1-year post-transplant survival probability, conditional on MELD and DRI, is calculated and recorded. The full simulation concludes once each candidate's health progression has been replicated N times. This structure allows replication of candidate trajectories under observed practices and the evaluation of policies.

In particular, I model the decision-making process of accepting or refusing liver offers for candidates on the waiting list as a continuous-time, finite-horizon Markov reward process. The planning horizon is calculated as the time until the candidate's expected removal from the waiting list. The state space consists of health states defined by MELD categories and an absorbing unsuitable state, as well as liver quality states defined by DRI intervals. At each offer arrival, the action space includes accepting or waiting, with rewards quantified as the probability of 1-year post-transplant survival for acceptance and no reward for waiting. Transitions occur through health progression rates and liver offer arrival rates.

3 RESULTS AND DISCUSSION

I evaluate patient outcomes across every combination of health state and organ quality under the current liver acceptance practices. The findings show that candidates with lower MELD scores have the highest 1-year survival proportion and average survival time after a transplant for any DRI score while experiencing the longest waiting list time. In addition, candidates transplanted with high-quality organs have higher 1-year survival proportion and survival time. The 1-year post-transplant survival probability exceeds 92% for candidates with low MELD scores receiving low-DRI livers but falls to about 88% for those with MELD scores above 33 and high-DRI offers. Average post-transplant survival time follows a similar pattern, with healthier candidates receiving higher-quality livers experiencing the longest survival. Waiting list times decrease as MELD scores rise, reflecting prioritization of sicker candidates: those with MELD < 23 typically wait more than 100 days, whereas candidates with MELD > 33 wait only about 6 days.

These results also highlight the trade-off between waiting for better-quality organs while having risks for health deterioration versus accepting earlier offers of lower quality. Candidates with higher MELD scores have shorter waiting times but face reduced post-transplant outcomes. To assess the robustness of those findings, I conduct a sensitivity analysis by varying organ acceptance behavior and organ arrival rates.

4 CONCLUSIONS

I introduce a continuous-time Markov simulation framework to evaluate liver acceptance policies in the U.S., which are highly selective and favor only the high-quality grafts, thereby limiting overall system efficiency. Simulation and sensitivity analyses show that broader acceptance of clinically appropriate organs and improved availability can enhance patient survival and reduce waiting times. This study also provides a data-driven foundation for informing policy interventions and optimizing clinical decision-making in liver transplantation.

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