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A Parallel Numerical Method for Risk Assessment of Myocardial Infarction during Liver Transplantation: a Case Study

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Abstract. Coronary artery disease is a devastating complication of some patients undergoing liver transplantation. Anesthesia, anhepatic blood flow occlusion, and reperfusion of the liver can cause severe fluctuations in hemodynamics. However, the vast majority of liver transplant patients cannot undergo invasive coronary examinations due to their critical illness and abnormal coagulation function. In this paper, we present a retrospective case of acute myocardial infarction during surgery in order to demonstrate a noninvasive method to obtain coronary hemodynamic functional information based on scalable computational fluid dynamics technology. A P_1-P_1 stabilized finite element method and second-order backward differentiation formula are applied to discretize the time-dependent Navier-Stokes equations in the spatial and temporal directions, respectively. A Windkessel model constructed based on the measured clinic data is used to characterize the outlet blood flow. We then apply a parallel Newton-Krylov method with a restricted additive Schwarz preconditioner to accelerate the timeliness of the simulation. The simulated functional indicator successfully verifies the myocardial ischemia in the anhepatic phase of liver transplantation. We also present the parallel performance of the algorithm on a supercomputer, and the results show that the proposed solver achieves over 55% parallel efficiency with 3840 processor cores.

AMS subject classifications: 76D05, 76F65, 65M55, 65Y05

Key words: Numerical simulation, coronary artery disease, computational fluid dynamics, liver transplant, Newton-Krylov-Schwarz algorithm.

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1 Introduction

Coronary artery disease (CAD) is one of the most worrisome complications of liver transplantation (LT) surgery and carries high morbidity and mortality [1]. Studies have revealed that cardiovascular events remain a leading cause of early mortality (40%), followed by infection (28%) and graft failure (12%) [2]. LT is a high-risk surgery, and underlying CAD is considered a relative contraindication to the procedure [3]. LT is a significant cardiovascular stressor, as surgical operations such as intraoperative anesthesia, clamping of the hepatic vein and reperfusion can result in abnormal cardiovascular hemodynamic behavior. Myocardial ischemia or myocardial infarction (MI) will occur when the blood flow to the myocardium is affected and is insufficient during surgery. Accordingly, a thorough, accurate and rapid risk assessment of perioperative myocardial ischemia and further therapeutic intervention are essential for LT patients.

Currently, there is no consensus or standardized guideline regarding CAD risk assessment in the pretransplant period [4]. Each institution uses its own protocol, such as electrocardiography, ultrasonography, stress tests or nuclear myocardial perfusion imaging, for CAD risk assessment, and the final decision depends on the individual characteristics, with widespread variation in practice across LT centers [5]. Nevertheless, noninvasive coronary computed tomography angiography (CCTA) examination is recommended by some guidelines [6, 7] to evaluate the CAD risk. CCTA is an anatomic test and provides an expeditious and cost-effective method of assessing patients at intermediate risk for CAD, that is, anatomically obstructive CAD ($\leq 50\%$ luminal narrowing). However, perioperative myocardial infarction is also observed in LT patients with nonobstructive coronary artery stenosis [8]. Some studies have reported that anatomical stenosis does not directly result in functional ischemia [9, 10].

Since myocardial infarction is caused by an insufficient blood supply to the myocardium, that is, changes in coronary hemodynamics, cardiologists have developed an interventional technique, i.e., fractional flow reserve (FFR) [11], to assess the risk of CAD from the hemodynamic function perspective. FFR is defined as the ratio of maximum flow in the presence of stenosis to the normal maximum flow [12]. Clinically, FFR is a blood pressure ratio measured by a sensor on the tip of a guidewire during hyperemia by injecting adenosine or papaverine. The guidelines suggest that $\text{FFR} \leq 0.8$ indicates myocardial ischemia, and revascularization surgery (such as stenting) is needed to improve the patient's myocardial blood supply. However, in addition to the need for contrast and tolerating the radiation used to guide the operation, we need to put a pressure wire into the coronary arteries to measure their pressures. LT patients are usually in critical condition and have abnormal coagulation function, and most patients cannot undergo invasive coronary FFR examination. Therefore, although the invasive FFR has become the gold-standard method for risk assessment of myocardial ischemia, it is unrealistic to use it to preoperatively assess the risk of CAD for patients planning to undergo LT.

In the past few years, novel technologies that utilize computational fluid dynamics [13–17] and conventional medical imaging data have made significant progress in