
A Multiscale Approach to Modeling Regional Coronary Perfusion and Myocardial Function

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Abstract

The disruption of regional coronary blood perfusion is a critical factor contributing to the pathophysiology of cardiac failure. Regional perfusion deficits compromise the oxygen and nutrient supply to cardiomyocytes, triggering ischemia and subsequent necrosis. The loss of viable myocardial tissue results in structural and functional deterioration of the heart, manifesting as irreversible myocardial damage and compromised cardiac output. Given the complex interplay between coronary perfusion and myocardial function, accurately modeling regional blood flow dynamics is paramount for advancing the understanding of cardiac pathologies and improving therapeutic strategies. To address this challenge, the incorporation of regional coronary perfusion as a dynamic parameter within finite element (FE) models of the human heart has become indispensable in cardiac computational simulations. FE models offer a powerful platform for simulating the mechanical behavior of the heart under various physiological and pathological conditions. However, their predictive accuracy is significantly enhanced when coupled with detailed representations of coronary perfusion, which directly influences myocardial contractility and viability. This study presents a comprehensive methodology for integrating regional coronary perfusion as a field variable into a patient-specific cardiac model. The approach begins with the reconstruction of the 3D coronary vascular geometry, derived from high-resolution medical imaging data. The vascular architecture is then stratified into subendocardial and subepicardial layers, reflecting the transmural heterogeneity in coronary blood flow. By averaging the vascular geometry within these layers, the conductances of distinct coronary compartments are quantified, accounting for variations in vessel diameter, length, and branching patterns. These conductance values are then embedded into a continuum coronary model, which serves to simulate regional perfusion by solving the governing equations of blood flow under varying hemodynamic conditions. This coupling of coronary perfusion with myocardial mechanics facilitates a fully integrated simulation environment, where the interplay between coronary flow dynamics and cardiac tissue deformation can be explored. The resulting virtual framework provides a robust and versatile tool for the preclinical evaluation of cardiac interventions. By simulating scenarios such as coronary artery occlusions, revascularization procedures, or pharmacological therapies, this model enables the prediction of treatment outcomes and the optimization of intervention strategies. Ultimately, this approach represents a significant advancement in the field of cardiac biomechanics, offering insights into the mechanistic underpinnings of coronary perfusion and its role in cardiac health and disease.

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