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Sensitivity Analysis of Intraoperative Pressure-Derived Boundary Conditions in Acute Type B Aortic Dissection CFD Simulations

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Abstract

Acute Type B Aortic Dissections (ATBAD) are life-threatening conditions involving a tear in the intimal layer of the descending thoracic aorta, creating a false lumen alongside the true lumen. While uncomplicated ATBAD (uATBAD) is typically managed with optimal medical therapy, up to 80% of cases progress to aneurysmal degeneration of the false lumen. This progression is driven by hemodynamic changes in the aorta, including abnormal pressure distributions and shear stress, which contribute to false lumen expansion, true lumen compression, and ischemic complications. Despite growing evidence supporting the role of hemodynamics in aneurysmal degeneration using computational fluid dynamics (CFD), limitations remain in the reliability of boundary conditions used for CFD modeling, particularly regarding patient-specific inlet and outlet parameters in the computational domain. To address this limitation, this study evaluates the impact of modifying boundary conditions on CFD simulations of ATBAD and explores potential standardized scenarios for future modeling. A 55-year-old male with a history of uATBAD who recently underwent a catheter-based intervention was selected for analysis. During surgery, pressure waveforms were recorded intraoperatively at the ascending aorta (inlet) and at Zone 5 and Zone 9 of the true and false lumens (outlets), providing a unique dataset for patient-specific CFD modeling. A contrast-enhanced computed tomography scan was used for segmentation and reconstruction of the aortic geometry, followed by meshing and preparation for simulation in COMSOL. The study was designed to compare multiple boundary condition scenarios. In the first scenario, a patient-specific pressure-based inlet condition was tested against different outlet conditions, including intraoperative pressure recordings at both Zone 5 and Zone 9, a three-element Windkessel model applied to both outlets, and a geometrically modified single-outlet three-element Windkessel model. In the second scenario, a constant outlet boundary condition derived from intraoperative pressure data was maintained while varying inlet conditions, including non-patient-specific ideal velocity profiles taken from literature and modified velocity profiles adjusted to match patient-specific cardiac output. Additionally, CFD simulations were conducted with varying aortic lengths to examine differences between Zone 5 and Zone 9 geometries and the impact of single vs. double lumen outlets. Through this analysis, we illustrate the impact of modifying inlet and outlet boundary conditions on hemodynamic simulations and demonstrate a potential modified non-patient-specific model that can be applied in future ATBAD CFD studies. By evaluating these scenarios, this study aims to improve CFD modeling accuracy and provides a more reliable risk assessment of aneurysmal degeneration in ATBAD patients.