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Fluid—Structure Interaction Simulations of Aortic Dissection with Bench Validation

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Introduction: The blood flow and stresses in the flap in aortic dissections are not well understood. Validated fluid—structure interaction (FSI) simulations of the interactions between the blood flow and the flap will provide insight into the dynamics of aortic dissections and may lead to developments of novel therapeutic approaches.
Methods: A coupled, two-way blood flow and flap wall computational model was developed. The Arbitrary Lagrange—Eulerian method was used, which allowed the fluid mesh to deform. Inflow velocity waveforms from a pulse duplicator system were used in the simulations.
Results: The velocities for true lumen (TL) and false lumen (FL) were not significantly different between bench and simulation. The dynamics of the TL % cross-sectional area (CSA) during the cycle was similar between the bench and computational simulations, with the TL %CSA being most reduced near peak systole of the cycle. The experimental distal measurements had significantly lower velocities, likely due to the spatially heterogeneous flow distally. The conservation of mass and validity of simulations were confirmed. Additionally, regions of stress concentrations were found on the flap leading edge, towards the corners, and through the entire vessel wall. The pressure gradient across the FL results in a net force on the flap.
Conclusion: The FSI flow velocities in the TL and the FL as well as the dynamics of the CSA during the cardiac cycle were validated by bench experiments. The validated FSI model may provide insights into aortic dissection including the stresses on the dissection flap and related flow disturbance, which may be subdued by novel therapeutic approaches. Simulations of more realistic human aortic dissections and the effects of current therapeutic approaches such as stent-graft can be developed in the future using the validated computational platform provided in the present study.

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INTRODUCTION

Acute aortic dissection (AAD) is a potentially fatal condition where a tear occurs and propagates between the layers of the aortic wall, creating true and false aortic lumens separated by a dissection "flap." Severe complications associated with AAD include branch vessel and organ malperfusion, decreased end organ function, aortic rupture, and death.[1—4]

To date, studies of the blood flow and flap mechanics associated with aortic dissections have been limited. This is largely due to the complexities of AAD, which involves fluid (blood)—structure (flap) interactions (FSIs) of the dissected structures and associated fracture mechanics. The blood flow drives the flap dynamics, and the flap in turn affects the flow and creates flow disturbances and stagnations. The interaction of the dissection flap with the aortic flow may lead to dissection propagation and the associated complications. Hence, it is essential to develop FSI models to fully capture the dynamic mechanics of the disease process.

Previous computational simulations of AAD have considered computational fluid dynamics (CFD) only, however, and have not taken into account the dynamic interactions of the blood flow field and the dissection flap.[5,6] It has been shown that flow at the dissected region is highly disturbed and significant flow enters the false lumen (FL), which may further enlarge the dissection.[5,6] Additionally, the disturbed flow within the FL are likely factors in FL thrombosis during the initial, acute stage of the disease.[7,8]

The aim of the current study is to develop a bench-validated FSI computational model that will provide insights into the mechanics of AAD and may aid in future development of treatment strategies. To gain confidence in the model predictions, the three-dimensional (3D) FSI simulations will be validated against a in vitro testing of simulated aortic dissections.

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METHODS

Computational

A 3D FSI simulation with parallel computing was performed. The submerged dissection flap was within the fluid domain and not just at the fluid outer boundary as in regular arterial flow simulations without the dissection. The model was created in 3D CAD (Creo parametric, Pittsburgh, PA, USA) utilizing dimensions from the ex vivo geometries (length, diameters and wall thickness). The software platform was Abaqus (Providence, RI, USA) and the hardware was a Dell Xeon processor-based workstation. The co-simulations refer to combined fluid and solid simulations.

The cross-sectional area of the aortic true lumen (TL) measured in the in vitro testing was approximately 63% of total aortic cross-sectional area (CSA) and applied at the dissection inlet of the FSI model. The TL and FL covered approximately 60% and 40% of the aorta circumference, respectively. The frontal view of a porcine aorta used in the pulse duplicator is shown in Fig. 1A. In the model, the dissection flap is highlighted with green outline in Fig. 1C. The green outlines are the edges of the flap and the two vectors demonstrate the coordinate system used in the software. A transverse view of the ex vivo dissection from ultrasound is shown in Fig. 1B and a cross-sectional view of model geometry of the dissection flap is shown in Fig. 1D. A Young's modulus of 2 MPa based on experimental study of aorta and Poisson ratio of 0.45 were used to approximate incompressibility.[9]

The fluid was modeled with a $\rho = 1050$ kg/m^3, and dynamic viscosity, $\mu = 4$ cP or 0.004 Pa-s. A Newtonian fluid property was used because of the high flow and large diameter aorta. A non-Newtonian fluid can be simulated in future models as the FL may have regions of low flow when there is no re-entry. The inlet velocity waveforms utilized for the ex vivo set-up were applied at the inlet of the model as

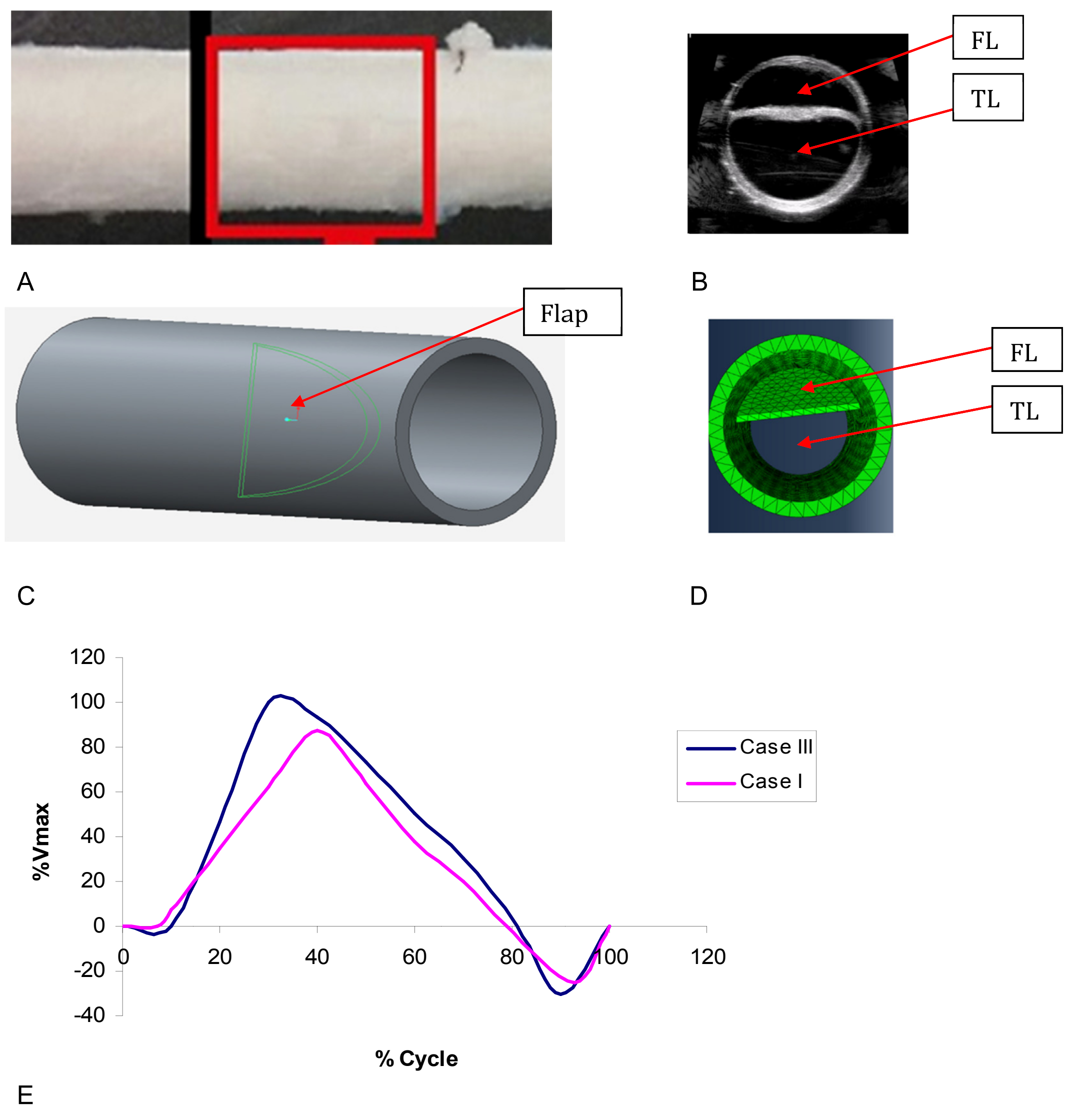

Figure 1. (A) The vessel in the pulse duplicator. (B) Transverse view of the vessel with dissection flap. (C) 3D Creo CAD model geometry of the dissection flap and aortic wall. The flap is highlighted in green outline. (D) Transverse view of the model vessel with dissection flap. (E) Inflow velocity waveforms for the simulations. Cases I and III are shown. Case II waveform is similar to Case I, therefore Cases I and III are shown for clarity. FL = false lumen; TL = true lumen.

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