Analyzing Hemodynamic Markers of Thrombogenesis in the Berlin Heart EXCOR

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Introduction: Children in need of heart transplants have the highest waitlist mortality of all solid-organ transplant patients. The Berlin Heart EXCOR is an extracorporeal pulsatile ventricular assist device (VAD) for infants and children with severe heart failure. The device can provide left ventricular, right ventricular, or biventricular support. It has been proven as a successful therapy to bridge children to heart transplants. Pulsatile VADs are currently the only option for infants and young children who need mechanical support. However, high occurrence of clotting in the Berlin Heart puts patients at risk for thrombotic events, which can result in morbidity in extreme cases. Two characteristics of blood flow – particle residence time and shear stress – are hypothesized to contribute to clot formation. High particle residence time and low shear rates are both associated with flow stagnation and platelet aggregation. Understanding the causes of clot formation provides a starting point for discerning specific regions of the Berlin Heart that may be contributing the most to thrombosis. Our study investigates the effects of flow patterns and device geometry on hemodynamic markers linked with platelet activation and clot formation.

Materials and Methods: In this study, we use SimVascular, an open-source software for cardiovascular simulation, to model the Berlin Heart as a 25 mL blood chamber with rigid walls. We study two geometries of the device, an existing Berlin Heart with inlet/outlet arms angled at 20° and a modified geometry with arms angled at 45°. Each device is simulated over the course of the cardiac cycle. Blood flow is numerically imposed using a pediatric pulsatile waveform with no native heart contribution to replicate the pumping of the Berlin Heart. We analyze blood velocities and wall shear stress throughout the Berlin Heart model. Two additional simulations use the advection-diffusion (AD) equation and the Vascular Modelling Toolkit (vmtk) to trace particle movement. Comparisons are drawn between different Berlin Heart geometries to determine if the hemodynamics and regions at risk for clot formation differ (Figure 1).

Results and Discussion: Prior studies indicate that coagulation occurs at shear rates lower than 50 s⁻¹, forming erythrocyte-rich clots. We identified regions of low shear rate in both Berlin Heart models and found that the existing Berlin Heart design resulted in increased surface area of shear rates below 50 s⁻¹ compared to the modified design. We calculated the axial velocity of blood flow in the outlet arms and analyzed particle streamtraces throughout the device. We found that the modified Berlin Heart with arms at 45° produced higher blood velocities compared to the existing Berlin Heart, which indicates decreased propensity for clotting. Volume rendering of velocity and results from the AD simulation suggest that the modified Berlin Heart has less flow recirculation. We calculated the total particle concentration exiting the outlet of each Berlin Heart after a full cardiac cycle and found a higher proportion of particles exiting the modified Berlin Heart.

Translational Impact: Our results suggest that flow patterns within the Berlin Heart can indicate regions and parameters associated with thrombosis. This can aid in identifying and predicting regions at risk for clots in the current Berlin Heart. Continued study on the effect of different device geometries on blood flow features that correlate with clot formation can provide understanding and potentially guide improvements in redesigning the Berlin Heart or other pulsatile VADs for future patients. Future work will investigate the impact of valves and volume size on the parameters of interest to address clinically relevant concerns with the device.

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