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Design of a Miniature Pump for Chronic Mechanical Circulatory Support using Computational Fluid Dynamics and Flow Visualization

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1 Background

Ventricular assist devices (VADs) have become an accepted method of treating end-stage heart failure over the last few decades. In recent years, the use of rotary blood pumps (RBPs) as continuous flow VADs has surged ahead, and virtually eliminated the use of pulsatile-flow or volume-displacement pumps for implantable, chronic mechanical circulatory support (MCS). As the use of RBPs has become commonplace for the treatment of end-stage heart failure, the need for an implantable right-side MCS device for adults [1] and implantable MCS for the pediatric population has increased. Development of an implantable device specific to these populations includes unique challenges of anatomic placement and fixation.

Computational Fluid Dynamics (CFD) is the use of numerical methods and algorithms to solve and analyze problems involving fluid flow. CFD has become a standard tool when designing RBPs, as it can calculate pressure-flow characteristics for a given rotary impeller speed. Additionally, through calculation of shear forces, CFD can also predict hemocompatibility by means of constitutive equations derived from empirical data. Particle image velocimetry (PIV), also known as flow visualization, is an optical measurement technique used to obtain velocity in fluids, which can be employed experimentally to verify CFD-based predictions of flow field. PIV also permits more rapid investigation of the RBP operativing range and transient conditions than can be achieved with CFD due to computational requirements.

We have developed a RBP platform for chronic use with CFD to optimize hemodynamic performance. The miniaturized device includes unique inlet geometry with a rotating impeller and a vaned-diffuser in a 7mm axial hydraulic diameter. The design scheme separates the bearing and motor region from the primary flow path to further improve hemocompatibility and reduce the pump size without compromising the hydraulic capacity.

Here we report CFD and PIV results of our device geometry optimized for right-sided MCS.

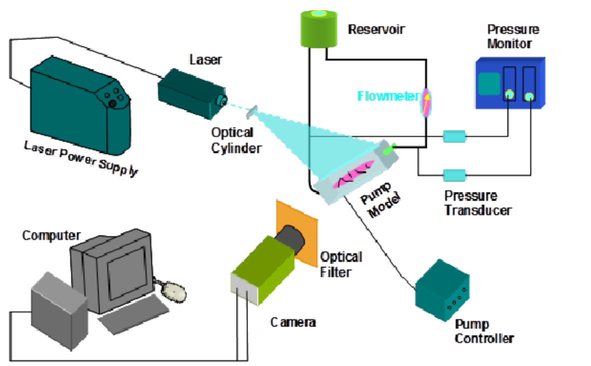

Fig 1. Schematic of PIV set-up, including: high-speed camera, computer, laser, fluid reservoir, blood pump, and flow meter.

2 Methods

2.1 Computational Analysis. CFD-based design optimization techniques were used to optimize the blade geometries and the flow path to maximize the hydrodynamic performance while minimizing the hemolysis. The CFD-based design optimization system integrated the custom developed 3D inverse design methods , parameterized models of the geometry, automatic mesh generator, target functions, and mathematical models of hemolysis with a commercial CFD software package (ANSYS, Canonsburg, PA). Hemolysis index (NIH) is calculated using Fraser's version of the power law model [2] with evaluation by Eulerian approach. For this study we primarily use the two-equation Shear Stress Transport (SST) eddy-viscosity turbulence model, employing the k-ω model in the inner region with the k-ε model in the free shear flow region.

2.2 In Vitro Analysis. CFD predictions were verified by particle image velocimetry (PIV). The particle exposure history was computationally analyzed by Lagrangian method in MATLAB (MathWorks, Natick, MA) [3]. Flow visualization set-up, illustrated in Figure 1, employs a high-speed camera and viewer software (Fastcam SA3 and PFV; Photron, San Diego, CA), and a 532 nm wavelength Nd:YAG laser (Optotronics, Mead, CO). Images are captured at 20000 frames per second. Fluid through the flow path is a water-glycerin solution maintained at 2.8 cP and 21 °C containing 30 µm red fluorescent polymer microspheres (polystyrene, polystyrene divinylbenzene, or polymethyl methacrylate; Thermo Fisher Scientific, Waltham, MA). Volumetric flow rate is measured with an ultrasonic flow probe and meter (9XL and T110; Transonic Systems, Ithaca, NY).

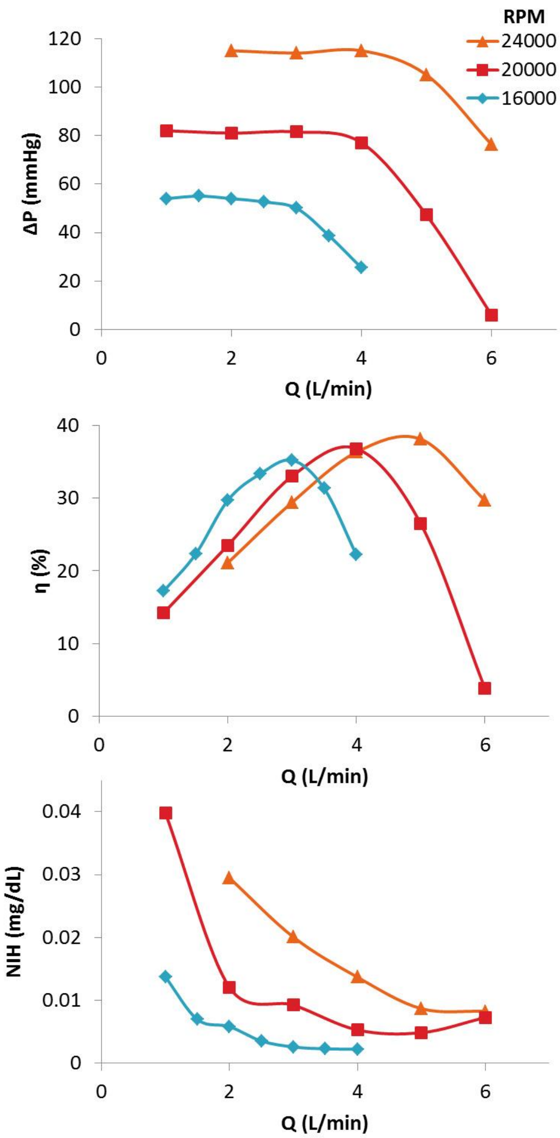

Fig. 2. CFD-predicted hemodynamic performance for pressure differential (ΔP), hydraulic efficiency (η), and normalized index of hemolysis (NIH) for rotor speeds of 16k, 20k, and 24k RPM against flow rate (Q).

3 Results

Operating conditions of 20000 RPM and 4 L/min yield a differential pressure of 77 mmHg between the outlet and inlet of the blood flow path with calculated normalized index of hemolysis (NIH) at .005 g/100L by Eulerian method in CFD analysis. An average dwell time of 115 ms can be observed by way of PIV at the previously mentioned operating conditions. For the same speed and a volume flow rate of 1 L/min, a differential pressure of 82 mmHg and NIH of .04 g/100L are calculated by CFD. A maximum dwell time of 367 ms is observed in PIV analysis.

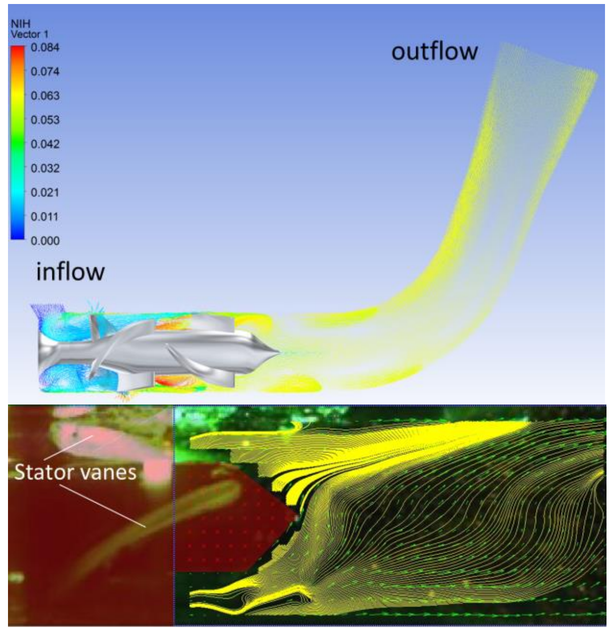

Fig. 3. CFD plot of velocity vectors colored with normalized index of hemolysis (NIH) at 20k RPM and 1 L/min. Corresponding PIV streamline analysis of outlet flow field at 20k RPM and 1 L/min.

4 Interpretation

Predictions made by CFD are in agreement with in vitro experimental data. Flow field predictions given by CFD are closely matched by PIV results. It should be noted that location and intensity of some flow field characteristics observed in PIV vary slightly from CFD predictions. This is, in part, due to out of plane velocity components captured by the PIV system. The agreement between these results has led to further optimization of the hydraulic performance and decreased NIH values as non-desirable (recirculation, stagnation, excessive shearing, and others) flow field features can be avoided.

Acknowledgement

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