INTRODUCTION

An estimated 150,000 patients in the Western World require heart transplantation every year, while only 4,000 (2.5%) of them actually receive a donor heart [1]. This lack of available donors for heart transplantation has led to a large effort since the 1960s to develop an artificial mechanical heart as an alternative to heart transplant. Most end stage cardiac failures result from cardiac disease or tissue damage of the left ventricle. After this failure, the ventricle is not strong enough to deliver an adequate supply of oxygen to critical organs. A left ventricular assist device (LVAD) is a mechanical pump that does not replace the native heart, but rather works in concert with it. An LVAD can effectively relieve some strain from a native heart, which has been weakened by disease or damage, and increase blood flow supplied to the body to maintain normal physiologic function. The inlet to the LVAD is attached to the native left ventricle, and the output of the assist pump rejoins the output of the native heart at the aorta, as shown in Figure 1. Blood flow from both the aortic valve and the assist pump combine and flow through the body. The clinical effectiveness of LVADs has been demonstrated; however, all of the currently available pumps have a limited life because of either the damage that they cause to blood or their limited mechanical design life.

OBJECTIVE

The overall goal of this research is to understand this type of mechanical blood pump and to develop a device that has sufficient long-term biocompatibility, performance, and reliability to be used as a permanent implant. A magnetically suspended rotary blood pump offers the potential to meet these requirements. There are numerous design considerations involved with this type of pump, including physiological effects, reliability of the magnetic suspension system, and biocompatibility issues involving damage to both the implant and to the native tissue. This research focuses on fluid dynamic effects within the UVa centrifugal LVAD, which has the same geometry as version CF4b of the HeartQuest™ LVAD. Besides determining the overall pump performance, the local flow field affects blood damage. Flow stagnation can lead to potentially fatal thrombosis [2] (clotting) and exposure to high shear stress can lead to hemolysis (red blood cell damage) [3]. Understanding the local fluid behavior inside the pump is, therefore, critical. The specific objective of this study is to fully characterize the flow within UVa LVAD using Particle Image Velocimetry (PIV) in order to 1) identify regions of potential blood damage due to high shear stress and or stagnation and 2) validate and refine computational models of the flow that are commonly used to design these devices in order to maximize performance while minimizing blood damage.

Figure 1: Location of LVAD in Human

Due to the way in which the pump is attached to the human circulatory system, the flow rate through the pump varies as the native heart pulses. This results from the fact that the pump inlet (suction) pressure is equal to the pressure within the left ventricle, which varies drastically during the pulse cycle. The outlet (discharge) pressure of the pump is attached to the aorta, whose pressure varies to a lesser extent. During systole, when the ventricle pressure is at its maximum, there is a very small pressure rise across the pump, which correlates to a very high flow rate. Likewise, low ventricular pressure during diastole leads to a large pressure rise and low flow rate. During a
typical heartbeat, the resulting flow rate through the pump varies drastically (between 2 to 10 l/min).

The fact that the flow through the pump (even while running at constant speed) is pulsed has some physiological advantages, but it also means that the pump is almost always operating at a flow rate and pressure rise different from the design conditions. This is termed an "off-design" operating condition. Nearly all reported numerical and computational studies of the flow through similar devices focuses only on the design condition, ignoring the off-design conditions. This study characterizes the flow over the entire range of on and off-design conditions seen by the pump in a physiological environment.

MEASUREMENT TECHNIQUE

Optical measurement techniques offer several advantages over physical probes for measurements in an LVAD. Traditional mechanical measurement probes may distort the flow that they are measuring. Second, optical techniques offer the advantage that light may be used to probe regions in which one could not easily locate a physical probe, such as the small clearance regions inside the heart pump. PIV is a technique that measures the instantaneous velocity field within an illuminated plane of the fluid field using light scattered from particles seeded into the fluid [4]. Using a laser as a light source, it is possible to very accurately locate and shape this illuminated plane so that one can make quantitative measurements within a very thin measurement volume.

In order to accomplish PIV measurements within the LVAD, a prototype pump that allows for optical access into nearly all interior regions of the pump has been designed and built. The internal flow paths (Figure 2) are identical to the clinical version of the pump that is currently in animal trials and has been modeled extensively using computational fluid dynamics (CFD). The pump housing is made of acrylic and has large flat exterior surfaces to eliminate optical distortion. Additionally, a novel working fluid with viscosity and density of blood and optical index of refraction that is equal to that of acrylic has been identified and characterized for these experiments. The pump is run within a mock circulatory loop that includes a pulsing diffuser. An example of an acquired image and the resulting instantaneous velocity field within the cut-water, diffuser, and a portion of the blade passage are shown in Figure 3. For each region and operating condition, a time series of instantaneous images has been processed to determine the time averaged velocity field and relevant turbulence statistics. By translating the light sheet to the entire three-dimensional volume of the flow field is characterized. Measured turbulence statistics include three components of the Reynolds stress tensor, turbulence intensity and estimates of turbulent length scales.

The paper presents a complete determination of the specific flow features that may contribute to pump inefficiency and blood damage in all regions of this representative centrifugal pump, including guidance to the design process as to ways to eliminate these. The study also includes identification of flow features that may contribute to thrombosis within the pump based on semi-quantitative analysis and a quantitative prediction of the extent of hemolysis. The work also provides a database that is being used to guide the quantitative assessment and refinement of CFD models, including turbulence models.

CONCLUSION

This paper presents a unique quantitative study of the velocity field within an entire rotary pump. Previously, no knowledge of the fluid behavior within the LVAD or similar devices during the usual, off-design, operating condition has been presented. Further, only limited quantitative data regarding the details of the mean and turbulent flow field internal to these devices exists even at the nominal, on-design, point. This study presents a first of its kind and comprehensive investigation of the flow field internal to a centrifugal LVAD at both design and off-design conditions. The work lends critical insight into the local fluid dynamics within an operating pump and their relation to pump performance and blood damage. Further, the measurements have been invaluable in guiding the validation and refinement of numerical (CFD) models of the pump.

REFERENCES