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Numerical Study on the Effect of Miniaturized Impeller Diameter on Mechanical Performance in a Left Ventricular Assist Device

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ABSTRACT

Heart failure continues to be a major global health problem causing significant health issues and deaths. Left Ventricular Assist Device (LVAD) was developed as an alternative to heart transplant to support the patients with severe end stage heart failure. Despite the current advancement of LVAD, constant improvements are always being made in making it smaller LVADs tailored for patients with smaller physiology while still maintaining the flow ventricular pump capability to the body. This study evaluated the effect of using a smaller sized LVAD using Computation Fluid Dynamics (CFD) and compared with the initial pump size at their respective designed rotating speed. Two model variants were studied, the initial design with 44.8mm diameter impeller (2000 rpm rotating speed) and the smaller 37.0 mm diameter impeller (2500 rpm rotating speed). These designs were compared by their key criteria mechanical performances particularly the produced pressure difference along a range of flowrate and the efficiency curve. At the required flowrate of 5 L/min, the smaller sized 37.0 mm impeller was able to deliver the flowrate at a slightly higher pressure difference of 114.60 mmHg as compared to the 44.8 mm impeller at 106.01 mmHg. In overall, both model variant produced similar pressure-flowrate curve with the 37.0 mm impeller performing marginally better at higher flowrates. Efficiency was able to be maintained at 49-60 percent despite being a smaller impeller at a faster rotating speed. Miniaturizing the LVAD has been numerically demonstrated to be feasible to produce the needed flow output at the required pressure difference without affect efficiency significantly.

Keywords:
Computational Fluid Dynamics; Left Ventricular Assist Device; Miniaturized

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1. Introduction

Congestive heart failure is a cardiovascular disease that impairs ventricular functions and decreased cardiac output [1, 2]. One in five patients died within the first year and less than 60 percent survives to five years [3]. Heart failure continued to be a major global health problem causing a lot of

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number of death and is one of the leading causes of mortality in both developing and developed countries [4]. Heart failure (HF) is a progressive condition that affects the pumping abilities of the heart muscles. In Southeast Asia (SEA), it was reported that the risk factor for heart failure is higher compared to the West, with a prevalence of 6.7 percent of HF in the Malaysian population of 31 million, which accounts for 2.1 million people [5]. According to the data published in 2017 in the World Health Organization (WHO) official site, deaths caused by cardiovascular disease worldwide was around 17.9 million, which account for 31 percent of the global deaths. Heart transplantation and device implantation are the only possible treatment for patients in the end stages of heart failure.

Device implantation is an alternative treatment for end-stage heart failure patients who are ineligible for heart transplant [6]. For sever cases of heart failure, patients were implanted with Left Ventricular Assist Device (LVAD) at the left ventricular apex outflowing to the ascending aorta. The implanted LVAD would work in parallel to a weakened yet functional heart complimenting the pump load to maintain the flow of oxygenated blood to the body. The use of LVADs have affirmed in quality-of-life improvements for the patients for both short and long-term support [7].

Decades of development have aimed to make the LVADs even smaller and less cumbersome devices. Despite these advancements, the LVAD still proved a challenge for implantation in patients of small body size especially children [8], necessitating the need for even smaller LVADs. However, such an improvement results in some drawbacks; the reduction of impeller size would result in tighter gaps and higher rotational speed to maintain the required flow and pressure output. At higher operating speeds, blood damage and platelet activation will become a more apparent issue [9, 10].

This study assessed the comparison of two impeller diameters; the initial impeller size (44.8 mm) that was based on previous work [11,12] and a smaller miniature sized impeller (37.0 mm). The model used in this study is based on a conceptualized LVAD design that uses design practices from typical engineering pump design principles [13]. Computational Fluid Dynamics (CFD) simulations were used for simulating the pump models to characterize the mechanical output performance.

2. Methodology

In this section, the construction of the 3D model is presented, as well as the numerical simulation using computational fluid dynamics (CFD) software. Subsequently, the model variations and boundary conditions used in this study is also discussed.

2.1 Design Description

The components were modelled based on a proposed conceptual design of centrifugal type LVAD. Established design principles for centrifugal pump were adapted to scale with LVAD size for the design concept used in this study [14-16]. The geometries were constructed using SOLIDWORKS (Dassault Systemes Solid Works Corporation, Waltham, MA) and exported to ANSYS CFX (Canonsburg, PA, USA) for numerical simulation.

2.2 Geometry Modeling

The 3D model of the LVAD was referenced from the geometric details from the previous study. The fluid domain was constructed from two main components; the pump volute housing and pump impeller which are illustrated in Figure 1. The volute housing was hollowed out with the impeller geometry. The resulting geometry formed the simulation domain and separated into 3 distinct domain region which are the impeller region (rotating domain) inflow region (stationary domain) and volute region (stationary domain).

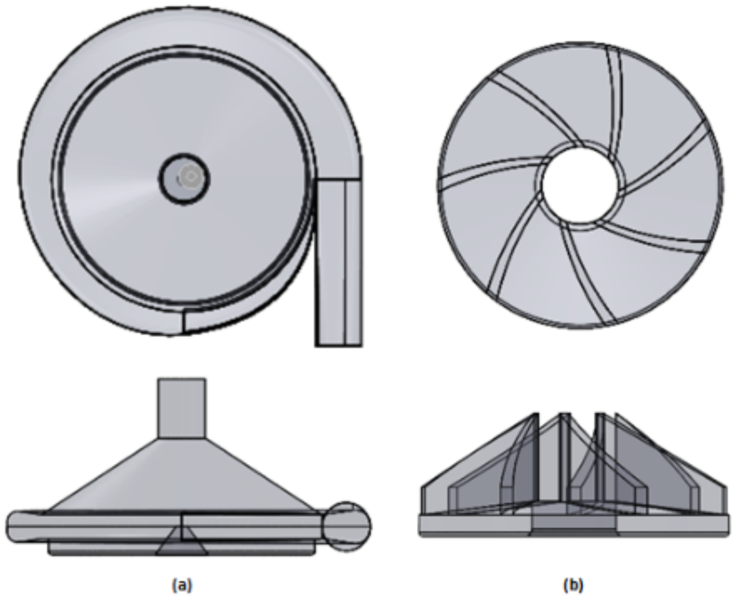

Fig. 1. 3D model of studied blood pump (a) Pump volute housing (b) Pump impeller

2.3 Model Variations

The geometric details of each LVAD model were based on a selected impeller speed. Essential geometry parameters were adjusted to the selected impeller speed while the flow requirement remained constant. The LVAD is required to deliver blood flow at a rate of 5 L/min at a pressure difference of 100 mmHg [17].

Two variants of impeller size were studied and had been designated throughout this study by the outer diameter of the impeller. The 44.8 mm diameter model which is the initial LVAD design was based on the rotating speed of 2000 rpm while the smaller 37.0 mm diameter model was for 2500 rpm rotational speed. Table 1 and Table 2 summarize the parameters for both the impeller and the volute of the LVAD respectively. The details of calculations involved have been further elaborated in detail from the works of the initial author [13].

Table 1
Impeller geometric parameters of LVAD model

Parameter (Unit)	Impeller Type	
	44.8 mm Diameter	37.0 mm Diameter
Outer diameter, D_2 (mm)	44.8	37.0
Inner diameter, D_1 (mm)	12.2	10.5
Rotating speed (rpm)	2000	2500
Vane Number	7	7
Vane Inlet angle, θ_1 (deg)	41.8	32.2
Vane Outlet angle, θ_2 (deg)	70	70
Vane Inlet thickness, t_1 (mm)	1	1
Vane Outlet thickness, t_2 (mm)	2	2

Table 2
Volute geometric parameters of LVAD model

Parameter (Unit)	Impeller Type	
	44.8 mm Diameter	37.0 mm Diameter
Base Circle Diameter, D_v (mm)	47.7	40.2
Throat Area, A_{th} (mm^2)	39.0	38.1
Volute Width, b_v (mm)	1.57	1.57
Volute Angle, α_v (deg)	9.15	9.15

2.4 Boundary Condition and blood properties

Newtonian fluid was used in this study with density of 1060 kg/m^3 and viscosity of 0.0035 Pa.s, similar to the characteristic of blood in a human body. Blood is a non-Newtonian compressible fluid but starts to behave as a Newtonian fluid incompressible when the shear rate is above threshold of 100 s-1, which in a LVAD is expected to operate above this value [10]. The inlet pressure was set to zero mmHg with five value of outlet flow rate offset from 5 L/min maximum and minimum to obtain performance output of the pump. Two model variations were studied with flow range of 3,4,5,6 and 7 L/min that resulted in a total of 10 flow configurations to simulate as illustrated in Figure 3. The shear stress turbulence (SST) model was used for this study as it performs well in estimating flow separation under adverse pressure gradient.

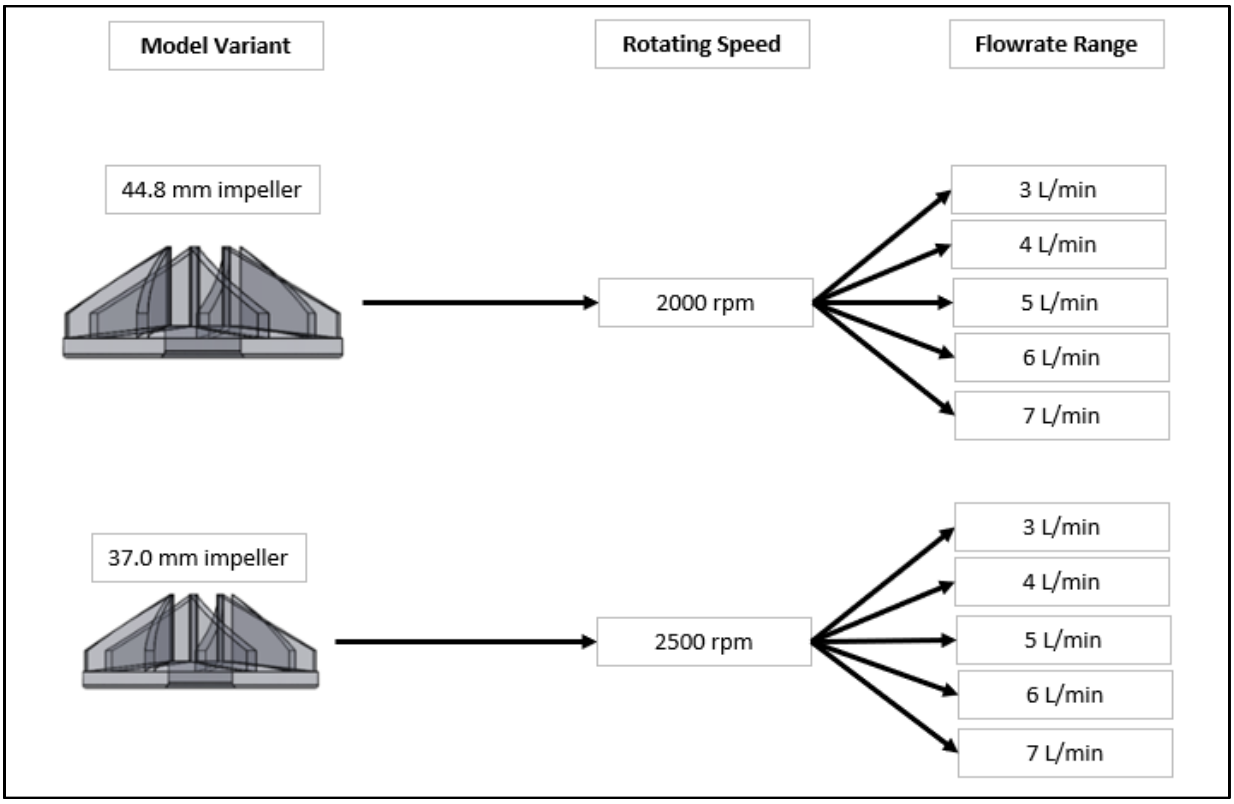

Fig. 3. Two impeller model variations with five flow conditions

The mesh model was separated into three-boundary domain: the inflow, the impeller, and the volute region. Non-slip boundary conditions were imposed on the walls of the model with tetrahedral mesh applied. The meshes generated had a total of 3.32 million nodes and 14.32 million elements with an average skewness of 0.231 and maximum value of 0.943. The wall function, y+

value was ensured to be close to 1 as possible for areas that are significant in the study with a value of 1.56±0.43.

Steady state conditions were implemented for this study. The rotating reference frame model is used to rotate the blood pump impeller. Stationary wall boundary was applied to inflow domain and volute domain. The impeller domain was specified as rotating reference frame or frozen rotor to simulate the impeller motion. Non-slip boundary conditions are imposed on the walls of the model, the impeller vanes, the volute casing, and the inflow walls.

3. Results

3.1 Model Validation

The numerical models were validated from the comparison of the published work by Day *et al.*, [18] due to the closest similarity in impeller size of 5-blade 46 mm diameter. This contrasts with the currently studied models that featured a 7-blade 44.8 mm diameter impeller for the initial design and 7-blade 37.0 mm diameter impeller for the miniaturized LVAD. The pressure-flow curve for the comparison was illustrated in Figure 4.

Both model variants follow closer to the 2500 rpm curve of the experimental data with an average difference of 2.27 percent for the 37.0 mm model and 10.93 percent for the 44.8 mm model. Additionally, the trend of the studied models has a flow profile of a typical centrifugal flow pump where the pressure difference decreases with increasing in flow rate. At the studied flowrate range of 3-7 L/min, the pressure difference of the numerical models was in relatively good agreement with the experimental data, although minor disparities were expected due to the referenced work having a different design.

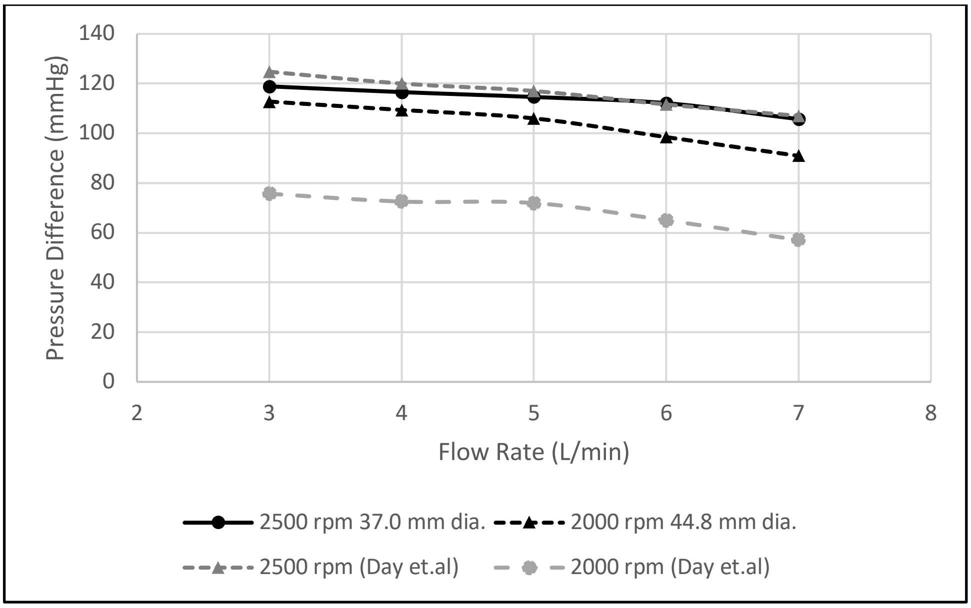

Fig. 4. Pressure – Flow curve comparison between studied models and Day *et al.,* experimental data [18]

3.2 Pressure Difference vs. Flow Rate

At 5 L/min both variants were capable of meeting 100 mmHg requirement, 44.8 mm model produce pressure difference at 106.01 mmHg while the 37mm model has a slightly higher pressure output by 8.59 percent at 114.60 mmHg.

The 37 mm impeller has higher pressure difference curve in overall by an average of 10.04 percent but differing along the flow rate range. The largest improvement in pressure difference for the smaller impeller were at high flow rates by value of 13.87 percent for the 6 L/min and 16.25 percent for 7 L/min. The lower range of flow rate however exhibit a lower value of pressure difference in comparison which are 5.42, 6.57 and 8.10 percent respectively for 3 L/min, 4 L/min, and 5 L/min.

3.3 Efficiency vs. Flow Rate

Figure 5 illustrates the pump efficiency against flow rate for both model variants. For both models the efficiency increases as the flowrate increases until it reaches the peak efficiency value at the intended flow rate of 5 L/min but begins to drop afterwards. At 5 L/min, the efficiency peaked at a value of 58.45 percent for the 44.8 model and for the 37.0 mm model had a value of 61.43 percent. Operating at higher than 5 L/min, efficiency drops with increasing flow rate.

In general, the 37mm model has slightly higher efficiency curve. At lower flow rates of 3 and 4 L/min the difference the two models were a mere 0.73 percent. However, at higher flow rates of 5, 6 and 7 L/min the difference was larger with an average of 2.84 percent. The efficiency range expected of the LVAD to operate at a range of 48.2-58.5 percent for the 44.8 mm model while similarly the 37.0 mm model has a range of 49.1-61.4 percent.

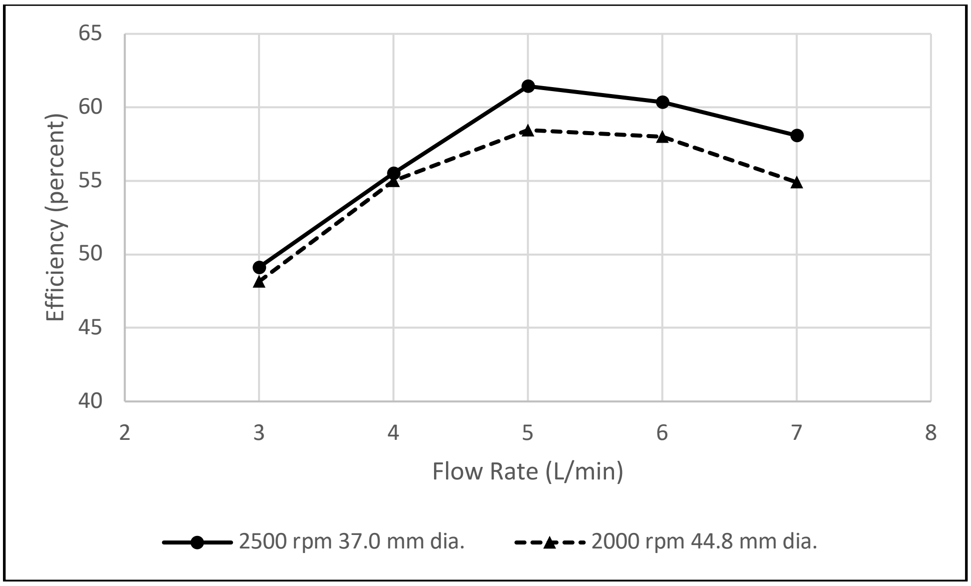

Fig. 5. Efficiency – Flow curve for studied model variants

4. Discussion

Numerical models of LVAD were simulated to characterize the mechanical performance output. This study assessed the effect of using a smaller faster rotating impeller on produced pressure output and efficiency. At the target flowrate of 5 L/min, the 37.0 mm model was able to generate the difference in pressure at 114.60 mmHg, well above the required 100 mmHg due to the higher rotational speed of 2500 rpm to compensate for the smaller sized impeller. In overall, both model variants produced similar pressure-flowrate curve with the 37.0 mm impeller having a higher pressure difference by an average of 10.04 percent compared to the 44.8 mm impeller. Additionally, the difference in efficiency at comparable flow rate between the two models was at an average of 2.84 percent at most in high flow rate conditions maintaining similar efficiency range to the initial

44.8 mm model. Thus, from the mechanical performance perspective, using a miniaturized LVAD could be feasible to make LVAD to fit patients with smaller body.

There are several limitations to this study to take into consideration. One limitation is the assumption that the impeller rotation was stable for the entire simulation. Using a smaller impeller could affect the stabilization of the 3-axis magnetic levitation expected from this design. However, such speculation could not be assessed at the present time as this design had only been in the conceptual phase.

Another limitation that was present was lack of the bio-compatibility aspect in the study. The higher rotational speed of the miniaturized LVAD would affect the localized shear of the blood flowing through the device. Given that the LVAD are expected to operate over long durations to support the heart of a patient, serious complications could occur well before the device could fail mechanically, if aspect of bio-compatibility is not considered particularly on the potential of blood damage (haemolysis) and blood clot (thrombosis). Further work would likely address these aspects and the potential severity to the patients that are to be implanted with this LVAD design similar to those working on other implantable cardiovascular devices such as mechanical heart valve [19,20] and stents or even on fundamental aspect with regards to properties that affect blood haemodynamic [20,21].

4. Conclusions

Numerical models of LVAD were simulated to assess the effect of using miniaturized impeller on the mechanical performance. At the required flowrate, the smaller sized impeller was able to deliver the flowrate at a slightly higher pressure of 114.60 mmHg as compared to initial impeller design at 106.01 mmHg. Both model variants produced similar pressure-flowrate curve with the smaller impeller performing marginally better at higher flowrates. At a faster rotating speed, efficiency was able to be maintained at 49-60 percent. Further works are needed to address the potential severity from bio-compatibility aspect.

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