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An Investigation on the Effects of Chamber Wall's Elasticity on Blood Flow in a LVAD Pump

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Abstract

Left Ventricular Assist Device (LVAD) is a pump that is designed to provide life support to patients with end stage heart failure. In an effort to ensure the safety of LVAD, the pumping mechanics must not exert excessive stress on the blood or hemolysis would occur. This study investigates the effects of chamber wall's elasticity (isotropic) from common materials on blood flow in a LVAD, especially the shear stress resulted therein. The materials considered are titanium, diamond-like carbon (DLC), 2-methacryloyloxyethyl phosphorylcholine (MPC) polymer, segmented polyurethane (SPU), polyurethane (PEU), and a material with properties corresponding to blood vessels, which is used as the reference. The study employs a Fluid Structure Interaction (FSI) simulation software suite to couple Computational Fluid Dynamics (CFD) with mechanical simulation (ANSYS). The test system is a centrifugal pump based on a 2012-Jarvik Patent. The flow through the pump is driven by an impeller rotating at set speed to achieve a pre-set blood flow-rate. The results show that there is no significant difference in turbulent dissipation rate among the different chamber-wall materials, with PEU giving closest figure to the blood vessels'. On the other hand, regarding wall shear stress which is an important factor in hemolysis, titanium, DLC and SPU result in similar maximum values, whereas MPC, PEU and blood vessel material give noticeably lower ones.

Introduction

End-stage (Stage D) Heart Failure is an incurable disease which plagues the population of developed worlds with an alarming estimated of 1 death every 12 minutes in Australia [1]. LVAD gives patients with end stage heart failure a second chance in the event that organ transplantation is not a viable option. Even though the device is designed to provide life support and improvement of lifestyle for the patient, there are risks present in the operation of these device. Blood flow within the human body is highly complex as the fluid is of non-Newtonian nature and due to the numerous types and number of particles present. An important component of the human blood includes haemoglobins which are essential in transporting oxygen to organs across the body. Haemolysis is the destruction of these haemoglobins which can compromises organs' function. It is a common fact all types of pumps exert some degree of stress on the fluid. In the case of human blood, the stress exerted by the pump could cause haemolysis, resulting in grave consequences to the patient and possibly heavy liability for the manufacturers of the particular LVAD system.

In an effort to ensure the safety of the LVAD, the pumping mechanism must not exert excess amount of stress on the blood for haemolysis to occur [2]. At the same time, it is impractical and potentially dangerous to perform medical trials for the LVAD without the proper calculations performed. Fluid Computation in the form of Computerised Fluid Dynamics is a proven method to ensure pump designs operate within safe perimeters. This is evident in studies conducted by Carswell [3], Lin [4] and Fraser [5] which utilised CFD software to optimise the design of pumps and developing blood damage models.

In this study, we will attempt to determine which surfacing material [6] can minimise the stress and turbulence within the LVAD chamber through its surface compliant properties [7]. The outcome of this project can help aid LVAD pump design and material selection.

Methodology

Computation method is used; and the commercial software package CFX of Ansys is employed. The nature of the simulation is to observe the elastic response of the chamber as blood flows through. This is accomplished via a computation method called Fluid Structure Interaction (FSI), which couples a solid structural solver with a CFD specialised counterpart. Ansys Workbench was the software suite used to perform these computations due to its simplicity in operation, robustness and popularity.

The model of the Pump Chamber and Impeller were constructed in SolidWorks and its design was based on the Jarvik patent [8]. The CAD model components can be seen in Figure 1. Note that the inlet and outlet caps are fluid domains constructed purely for the purpose of filling the inside of the pump with fluids in Design Modeller (DM).

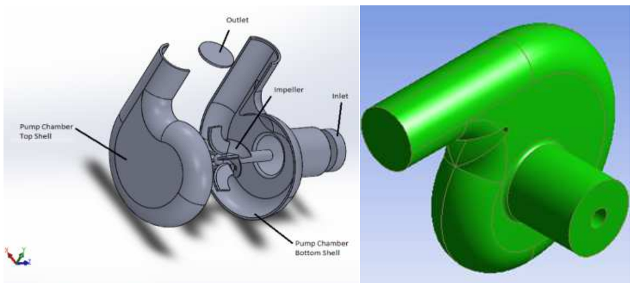

Figure 1. Exploded view of the pump chamber and impeller constructed in SolidWorks (right) Fluid body generated in Ansys DM (left)

Ansys Workbench provides a variety of ways to construct custom simulation systems, in this case of a 2-way FSI Simulation was used. The simulation for each chamber material is tested over a 5 second period with times steps of 0.1s. The final mesh of the fluid domain consist of around 23,000 nodes and 110,000 elements. While the mesh generated for the solid domain (impeller and pump chamber) has roughly 39,000 nodes and 20,000 elements. The most notable addition in the system were the insertion of the 'Fluid-Solid Interface' (not to be confused with FSI) which is the linking parameters for CFX to recognise which face (boundaries) of the solid is touched by the fluid domain. There are 2 such interfaces created: one for the pump chamber surfaces and the other for the impeller surfaces. The reason for the separation of the

2 interfaces are quite straight forward, the impeller is given an angular velocity (2500 rpm) and rotates relative to the frame of reference of pump chamber which remains stationary throughout the simulation.

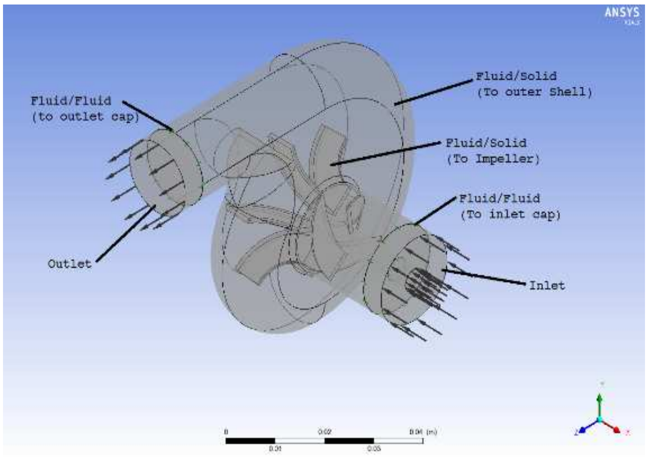

Figure 3. Boundaries defined in CFX

The main simulation is prepared in CFX, this includes the generation of the fluid mesh, CFX-pre setup. The parameters of Fluid Domain are defined within the CFX-pre which includes the initial conditions, boundaries locations (Figure 3), mesh deformation of the impeller FSI (set to match the same angular velocity of 2500rpm, which corresponds to the same speed the impeller is set to in the Ansys Solver), turbulence model and FSI coupling settings. Global initial conditions for velocity and relative pressure is set to 0 while the inlet boundary is given a 0.106kg/s flow rate (6L/min, assuming blood has almost the same density as water) to simulate nominal blood flow [9]. The turbulence model used for this simulation is Shear Stress Transport which is a combination of k-omega for close wall turbulence and k-epsilon for open space turbulence [10]. The model provides more flexibility and robustness than simply using k-epsilon or k-omega exclusively. FSI coupling is set to comply with Ansys Multi-field matches the appropriate FSI defined in the Ansys Solver which completes the coupling of the solver. For validation, a convergence criteria with residual target of 10^{-4} was applied to ensure the results are valid.

Choice of materials is based on Sin's review article [6], which presented a comprehensive list of popular VAD materials used in contemporary devices. The material data comes largely from academic sources, specifically journal articles which investigated the properties of the material or have used these data to performed CFD computations. Other data which are missing from academic sources are gathered from online source where possible. Due to the general lack of elastic data for materials like DLC, MPC and specific types of PEU, only isotropic elastic data are inputted into the simulation. For consistency, only the material composition for the pump chamber was interchanged, while the impeller remained titanium throughout the simulation. This is done because we are only interested in the effects of the different materials of the chamber wall and not the impeller. Additionally, certain materials such as the polymers may not be mechanically suitable for the role of the impeller. The material data used for this simulation are shown below.

Property	Value	Unit
Density	4.506	g/cm^3
Young's Modulus	1.16E+05	MPa
Poisson's Ratio	0.32	n/a

Table 1. Elastic properties of titanium used for simulation [11]

Property	Value	Unit
Density	2.6	g/cm^3
Young's Modulus	7.59E+05	MPa
Poisson's Ratio	0.17	n/a

Table 2. Elastic properties of DLC used for simulation [12, 13]

Property	Value	Unit
Density	1.2	g/cm^3
Young's Modulus	125	MPa
Poisson's Ratio	0.48	n/a

Table 3. Elastic properties of MPC used for simulation [14]

Property	Value	Unit
Density	1.2252	g/cm^3
Young's Modulus	3.17	MPa
Poisson's Ratio	0.49	n/a

Table 4. Elastic properties of PEU used for simulation [15]

Property	Value	Unit
Density	1.2252	g/cm^3
Young's Modulus	50	MPa
Poisson's Ratio	0.49	n/a

Table 5. Elastic properties of SPU used for simulation [16]

Property	Value	Unit
Density	1.05	g/cm^3
Young's Modulus	0.4	MPa
Poisson's Ratio	0.49	n/a

Table 6. Elastic properties of blood vessels used for simulation [9]

Turbulence Eddy Dissipation Rate

Eddy Dissipation is a measure of the rate whereby turbulent kinetic energy is reduced and transferred into other bodies (such as the chamber material) or dissipated into heat in non-isothermal flow as the fluid flows through the pump. This particular measurement can imply how well a material is at absorbing this turbulent energy, returning the fluid flow to a less turbulent state. Therefore the higher the dissipation rate, the better the material is for reducing turbulence, creating a more steady flow.

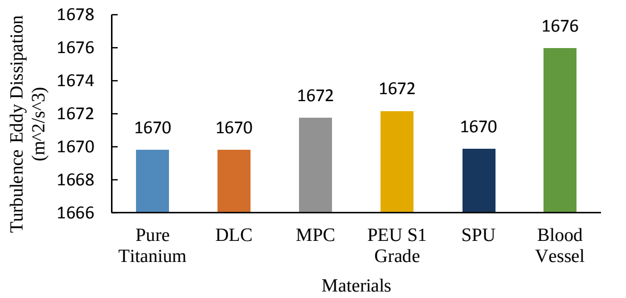

Figure 4. Maximum turbulence Eddy dissipation of various materials (higher the better)

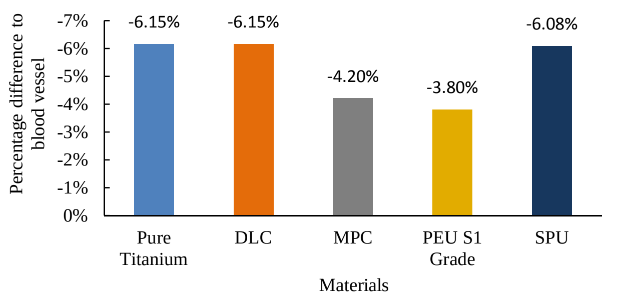

Figure 5. The Eddy Dissipation percentage difference to blood vessel (lower means behaving closer to a blood vessel)

To allow for a better level of comparison, the materials were compared to the human blood vessel where the percentage difference is calculated. From the results of the simulation, we can see that there is not a huge difference between the dissipation rates of the various materials (figure 5). Unsurprisingly, blood vessel exhibited the higher rate of dissipation (figure 4). In this simulation we also see that all the materials come fairly close to exhibiting the same quality as the blood vessel, particularly PEU tends to be the closest to blood vessels at dissipating turbulence with a difference of 3.8%.

Relationship between Bulk Modulus of Elasticity and Turbulent Dissipation Rate

Using the relationship the between the Young Modulus, Poisson's ratio and Bulk Modulus of Elasticity:

$$E = 3K(1 - 2v) \qquad (1)$$

Where E is Young's Modulus, v is Poisson Ratio and K stands for the Bulk Modulus. We can express the various materials' elastic behaviour as Bulk Modulus, which represents the materials resistance to compression which is expressed by equation 2.

$$K = -V\frac{dP}{dV} \qquad (2)$$

Where P is pressure and V is volume. The compressibility of the material means that external pressure or forces are absorbed by the material which may affect the turbulence dissipation rate. Through the conversion to bulk modulus and graphing it against the turbulent dissipation of various materials, we are able to examine the trend the modulus has on the turbulence dissipation rate.

Materials	Young's Modulus (E, MPa)	Poisson Ratio (v)	Bulk Modulus (K, MPa)
Pure titanium	116000	0.32	107407.41
DLC	759000	0.17	383333.03
MPC	125	0.48	1041.67
PEU S1 grade	3.17	0.49	52.83
SPU	50	0.49	833.33
Blood vessel	0.4	0.49	6.67

Table 7. The Bulk modulus of each material

According to the graph in Figure 6, we see that there is a general trend where the lower the bulk modulus, the higher dissipation rate was experienced by the pump chamber. However the difference between the highest and lowest dissipation rate is of the order of roughly 0.4% which could be below the computational errors. This could indicate that there are hardly any differences regarding the effects of the bulk modulus of elasticity on the dissipation rate of turbulence (and if there are any, they would be very small).

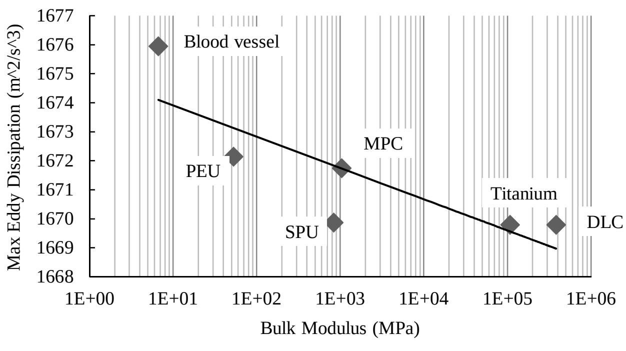

Figure 6. Comparing Bulk modulus to the max eddy dissipation rate

Wall Shear Stress

Wall Shear Stress is an indication of how much shear stress (expressed in Pascals) is developed as the fluid travels along the wall of the impeller chamber. Higher stresses are developed when fluid flows at an angle to the chamber wall rather than travelling in parallel path. Although there are many factors which can lead to Wall Shear being developed, in this simulation we are only concerned if the elasticity of the material can help reduce this stress due to its ability to reduce turbulent flow.

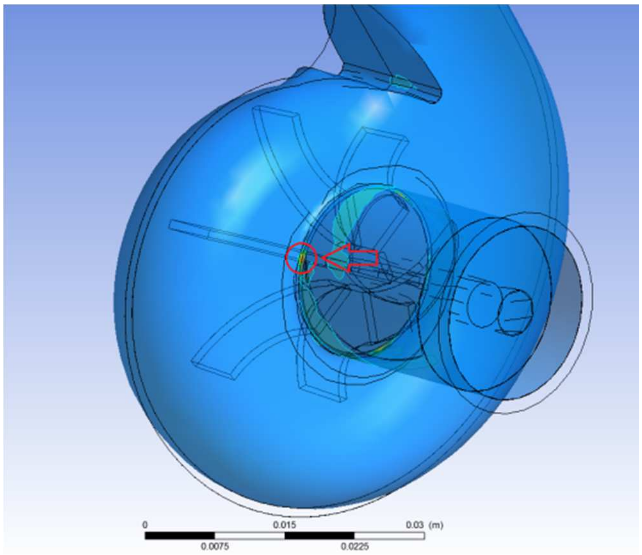

Figure 7. Area of highest wall shear stress

Wall Shear Stress is an important factor associated with haemolysis. As blood cells travels inside the pump, shear stress which is too high can cause the blood cells to rupture resulting in the destruction of the cells and lowering the capacity at which oxygen can be transported and distributed across the body. According to the contour render from the results of the simulation, the concentration of wall shear stress appears on the wall nearest to the impeller blade (indicated in Figure 7), which is an expected result as shear stress should be highest in the most confined spaces between the impeller blade and the wall. Using the rendering results we were able to record and compare the maximum wall shear stresses (Figure 8) of the various chamber materials and display them as graphs. Based on the data comparison for Maximum Wall Shear Stresses, Titanium, DLC and SPU all exhibited similar stress levels, while MPC, PEU and Blood Vessel are noticeably lower at 61.96, 61.89 and 61.69 Pa respectively. Again, this demonstrates that there is a general trend where wall shear stress decreases in response to a lower bulk modulus (excluding SPU), however it should be noted that their influence is rather small. It should be taken into account that these figures are based solely on the Chamber Wall (where the coating material usually lies) and excludes the wall shear stress on the impeller surfaces, which is considerably higher at roughly 462 Pa across all simulations.

The data generated in the FSI simulation, which took into account of the effects of elasticity shows that all materials are well above the threshold cell damage of 30 Pa [17] but well below the occurrence of haemolysis at roughly 150 - 400 Pa [17]. However if you take into account of the shear stress produced by the impeller, it will most definitely cause haemolysis on the long run.

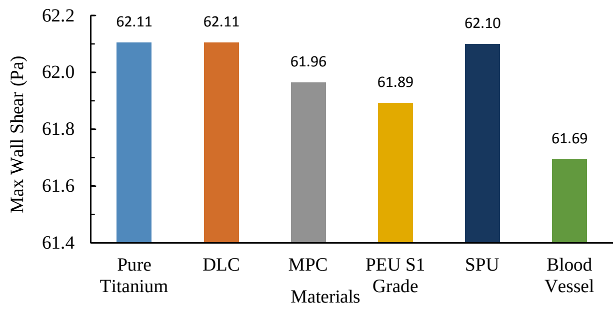

Figure 8. Maximum wall shear in pump chamber (lower the better)

In comparison to a study done by Day [18], who produced stresses near the impeller to be around 300 Pa and elsewhere in the pump to be roughly 30 Pa. Our results were higher but within the same significant figures. This could be attributed to the different blade design and a lower impeller's rotation speed in their work (2100RPM versus our 2500RPM).

Conclusions

This investigation demonstrates that the elastic properties of wall materials have only a small effect on the turbulence and shear stresses in the flow through an LVAD. Across the simulations, there are indications that as the blood travel along the walls of the centrifugal pump, no substantial damage occurs. However the results do not take into account of wall shear stress on the surface of the impeller; impeller-induced shear stress is large and would cause haemolysis. The high impeller-induced shear stress is most likely caused by the design of the impeller and there seems very little the elasticity of a material can alter that.

The investigation indicates that turbulent dissipation rate increases with lower bulk modulus of elasticity of wall material; however the changes are small. It has also been found that generally a lower bulk modulus also results in a lower wall shear stress. Again, overall changes are marginal and may not cause a significant difference in reducing damage to blood cells.

The findings in this study can hopefully point future research in the right direction; showing that as elasticity has only a small effect on dissipation rate and wall shear stress, other properties such as viscoelasticity should be considered. That is, future studies should concentrate more on the effects of materials' viscoelastic properties, especially with more recent materials such as DLC and MPC. However, a potential issue would be the general lack of relevant data on such materials.

Acknowledgments

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Nomenclature

CAD	Computer Aided Drawings
CFD	Computational Fluid Dynamics
DLC	Diamond-Like Carbon
DM	Design Modeller (of Ansys)
FSI	Fluid–Structure interaction
LVAD	Left Ventricular Assist Device
MPC	2-Methacryloyloxyethyl Phosphorylcholine Polymer
PEU	Polyurethane

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