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The Effect of Spiral Inducing Chamber to Left Ventricular Assist Device Outflow Cannula

Siti Aisyah Thomas[1], Ahmad Zahran Md. Khudzari[1,2*], Muhammad Rashidi Abdul Kadir[1], Kahar Osman[1,2], Jeswant Dillon[3], Ishkrizat Taib[4]

[1]School of Biomedical Engineering and Health Sciences, Faculty of Engineering, Universiti Teknologi Malaysia, Johor Bahru, Johor, MALAYSIA

[2]IJN-UTM Cardiovascular Engineering Centre, Institute of Human Centered Engineering, Universiti Teknologi Malaysia, Johor Bahru, Johor, MALAYSIA

[3]Institut Jantung Negara (IJN), Kuala Lumpur, MALAYSIA

[4]Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn, Parit Raja, Johor, MALAYSIA

*Corresponding Author

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Abstract: The rise of heart failure in the setting of shortage heart donor had brought to the emergence of development of left ventricular assist device (LVAD). However, patients are still encountering severe complications such as stroke and device thrombosis due to the hemodynamic changes. This study aimed to compare the hemodynamic characteristic between the standard and spiral LVAD outflow cannula. Two different anastomosis sites (2cm and 3cm) from sino-tubular junction are used and a spiral inducing chamber is attached to the cannula to promote spiral flow. The result showed that spiral LVAD cannula exhibit a lower output velocity with 37% percentage difference and lower region of low WSS value.

Keywords: Left ventricular assist device, cannula, computational fluid dynamic, spiral flow, pressure boundary condition

1. Introduction

Heart failure (HF) has been known to be the most alarming health problem in the present year. The heart muscle is said to be unable in pumping sufficient amount of blood to meet the body requirement. This predicament has affected up to 65 million people around the world, estimating 9.91 million years lived with disability (YLD) and approximately 345 billion US $ outlay [1]. For end stage HF patients, the most reliable treatment is heart transplantation. However, the scarcity of heart donors had brought upon the emergence of mechanical circulatory support (MCS) application. Left ventricle assist device (LVAD) is one of the MCS, functioned to augment or replace the ailing left ventricle [2] and to support the systemic circulation of the heart [3]. The advancement in LVAD technologies transformed its earliest function as bridge-to-transplantation (BTT) into a long-term support as destination therapy (DT) for the end stage HF patients. The amelioration of LVAD includes smaller sizes, enhanced pump performances and less invasive surgical techniques.

However, there are several drawbacks that unwantedly bring forth problems and adverse effects such as neurological complication due to thrombi formation can cause stroke events. Besides, the abnormal blood flow such as emerging jet flow can give rise to thrombogenesis, and platelet activation and development [4], [5]. A prolonged contact between the

*Corresponding author: zahran.kl@utm.my

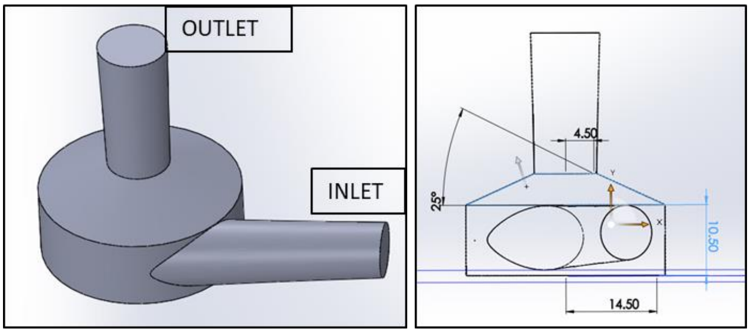
LVAD and the human organs will result in the hemodynamic changes too. Finally, high outflow velocity can cause outflow cannula malfunction in LVAD system [6]. Numerous studies have been conducted to amend the complications but most of them concentrated in altering the LVAD outflow cannula insertion site [5], [7] and adjusting the insertion angle on the aorta [7], [8].

Besides, it has been proven that spiral flow exists in the aorta due to the curvy and twisted shape of the aortic arch. Studies by Stonebridge et al. [9] showed that spiral flow helps in minimizing turbulence in narrowing branch arterial tree, uniformly distributed the wall shear stress (WSS) and obliterate the vortex close the aorta wall [9], [10]. Furthermore, Zhang et al. [11] suggested that high jet flow velocity and low WSS zones can be reduced by increasing the spiral flow. Thus, aside from varying the insertion site of the cannula on the aorta, we also aimed to study the effects of spiral inducing chamber to the LVAD outflow cannula as it will passively promotes spiral flow from the LVAD into the aorta. It is believed that the presence of spiral inducing chamber in this study will promote a better hemodynamic environment for the LVAD outflow cannula compared to the standard cannula. Computational fluid dynamic (CFD) studies are carried out to determine the hemodynamic pattern produced by the LVAD outflow cannula.

2. Experimental

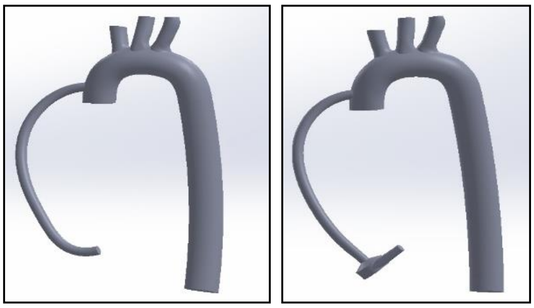
2.1 Geometrical Model

The geometries used in this study were created by using Solidwork (Dassault Systémes, USA). The aorta model was redrawn in reference to the Standard Tessellation Language or STereoLithography (.stl) file obtained from the online repository, Grabcade Community (https://grabcad.com). A 10 mm diameter cannula was designed, with the length of approximately 275 mm and is inserted 30° with respect to the axis of ascending aorta. There are two different anastomosis sites (2 cm and 3 cm) from the sino-tubular (ST) junction. As for the spiral inducing chamber, it was derived from Darlis et al. [12] which used the spiral flow aortic cannula (SPAC) for cardiopulmonary bypass (CPB) procedure. The geometrical details for the spiral inducing chamber is shown in Fig. 1 and the full model is shown in Fig. 2. Two different levels of flowrate for inlet flow were assigned, 5 lit/min and 6 lit/min. Full factorial design of experiment (DoE) method was employed to discover the relationship between all design factors (cannula type, anastomosis site, inlet flowrate). From the three design factors, and two level from each factor, it resulted 2^3 combination which yielded eight variations for the simulation as shown in Fig. 3.



(a) (b)

Fig. 1 - Spiral inducing chamber: (a) 3D view, (b) Geometrical dimension



(a) (b)

Fig. 2 - Full model of the cannula and aorta: (a) standard cannula, (b) spiral cannula

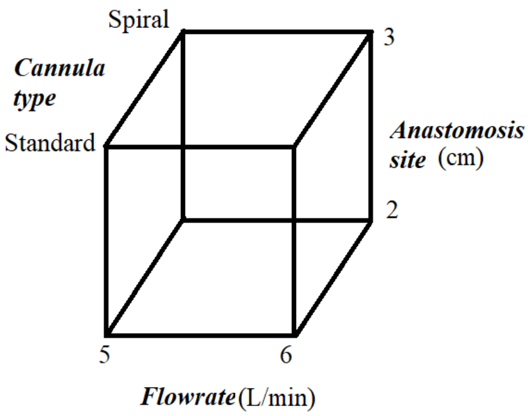


Fig. 3 - A two-level full factorial of three design factors (cannula type, flowrate, and anastomosis site) resulting in 8 variants

2.2 Computational Fluid Dynamic

The computational fluid dynamic (CFD) analyses in this study were carried out by using ANSYS CFX 14 (ANSYS INC., USA) to discretize the Navier-Stokes equations using finite volume method. Mesh structure were generated independently for both standard and spiral outflow cannula. Tetrahedral meshing was used, due to the complex geometry of the aorta. Mesh independence was achieved with 5.3 million elements for standard cannula and 4.4 million elements for spiral cannula. Furthermore, the wall function (y+) value for both cannula were ensured to be close to 1 [13]. For the simulation, the flow filed were set as steady flow with the inlet flow rate of 5 liter/min and 6 liter/min. The aortic valve is considered to be fully clamped. The wall of aorta and the cannula were considered to be rigid. Instead of applying free flowing option for the outlet pressure, a much more realistic method, a pressure boundary condition, was employed on each aortic arteries and can be expressed as the following expression (Eq. 1):

$$P_n = P_0 + RQ \qquad (1)$$

where P_n is the pressure boundary condition in vessel n, P_0 is the physiological aortic outlet pressure (80 mmHg), Q is the instantaneous flow rate in each vessel and R is the resistance. The value of R depends on the considered outlet: 2.9×108 Pa.s/m^3 for the brachiocephalic artery, 6.0×108 Pa.s/m^3 for left carotid and left subclavian arteries and 0.6×108 Pa.s/m^3 for the descending thoracic aorta [5]. Blood is modelled as a Newtonian fluid, with density of 1060kg/m^3 and dynamic viscosity of 0.0035 Pa.s [5]. With the inlet flow rate as stated above, the calculated Reynolds number are in between 3000-3600 which fall in the transitional zone. Thus, this study used k-ω shear stress transport (SST) turbulence model.

3. Results and Discussion

There are two parameters that were used to determine the cannula performance such as 1) outlet velocity, 2) wall shear stress (WSS) distribution. These parameters were chosen due to its relevance to the hypothesis of this study, which stated that the presence of spiral inducing chamber would provide a better hemodynamic environment to the LVAD outflow cannula as compared to the standard cannula.

3.1 Outlet Velocity

The maximum outlet velocity measured along the Line 1, created from the cannula outlet up to the aorta wall, for both standard and spiral cannula, in two anastomosis site and different mass flow rates are shown in Table 1. It can be seen that for both anastomosis site, spiral flow cannula exhibits lower maximum outlet velocity compared to standard cannula, with the highest percentage difference of 37%. Besides, the outlet velocity also increases with increasing mass flow rate for both cannula. Fig. 4 shows the velocity distribution graph in comparing the standard and spiral cannula with the highest percentage difference of 37% (3 cm anastomosis site, 5 liter/min). The velocity was taken along the line created from the cannula outlet up to the aorta wall.

3.2 Wall Shear Stress (WSS) Distribution

The WSS distribution in this study was analyzed by using contour plots and percentage histograms. The value of WSS brings an insight of the blood flow in the aorta especially near the wall. Low WSS value (< 0.5 Pa) is prone to atherosclerosis while high WSS value (1-2 Pa) can provide a conducive environment for an acute formation of athero-protective substances [7]. The average value of WSS is tabulated in Table 2 and the contour plots for all variants are shown in Fig. 5. The table shows that the average WSS values portrayed by all variants ranged between 1.4 Pa (0.011 mmHg) to 3.18 Pa (0.024 mmHg). Besides, there are no low WSS (<0.5 Pa or 0.004 mmHg) value recorded. From the contour plots, it can be seen that high WSS values present around the aorta arch and until the epiaortic branches.

Table 1 – Maximum velocity at cannula outlet

Anastomosis site	LVAD outflow cannula	Maximum Velocity at cannula outlet (m/s) Inlet mass flow rate	
		5 litre/min	**6 litre/min**
2cm from ST-junction	Standard	1.14	1.37
	Spiral	0.95	1.32
	Percentage difference (%)	17	3.6
3cm from ST-junction	Standard	1.39	1.66
	Spiral	0.88	1.13
	Percentage difference (%)	37	32

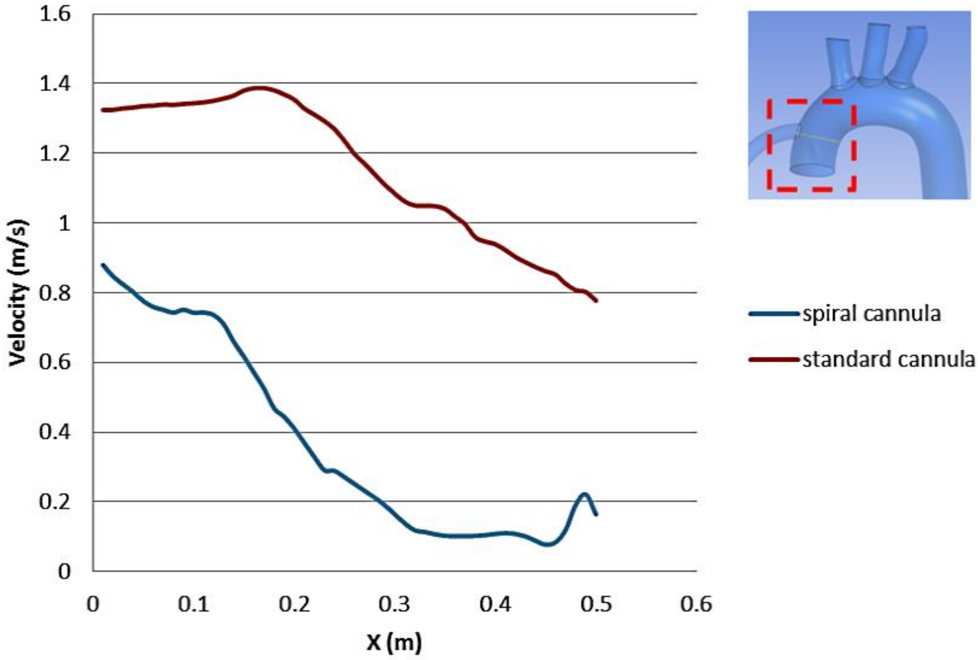


Fig. 4 - Velocity distribution graph for 3 cm anastomosis site (5 liter/min) along Line 1

Table 2 - Average WSS value for all variants

Anastomosis site	LVAD outflow cannula	Average WSS on aorta wall (Pa) Inlet mass flow rate	
		5 litre/min	**6 litre/min**
2cm from ST-junction	Standard	2.15	2.97
	Spiral	2.04	2.92
3cm from ST-junction	Standard	2.25	3.18
	Spiral	2.33	3.06

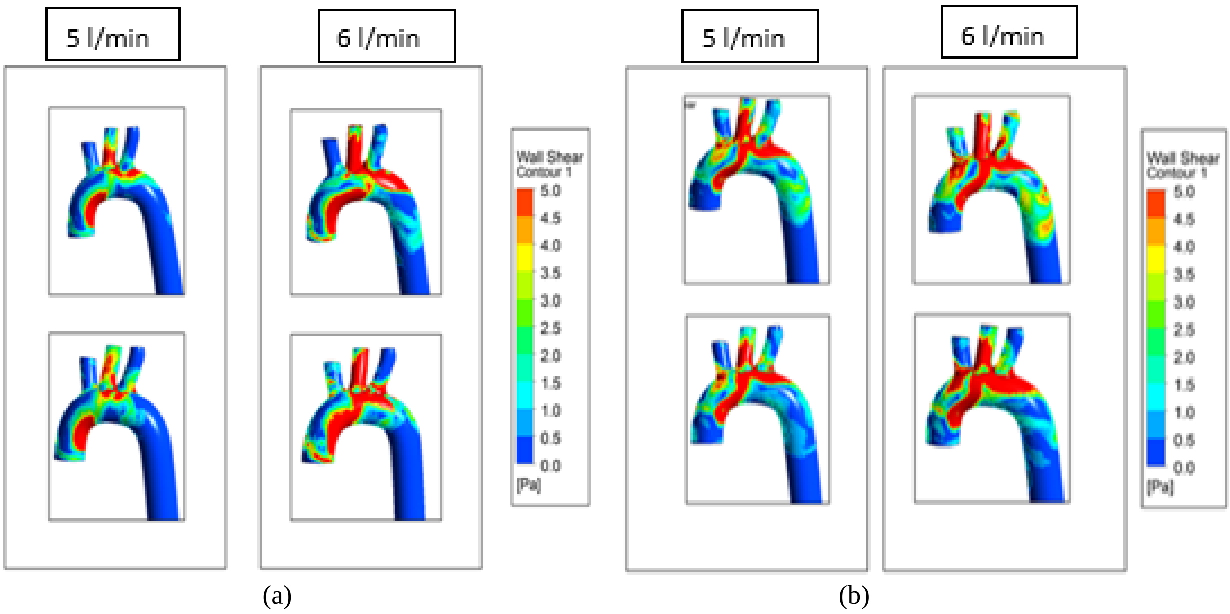


Fig. 5 - WSS contour for (a) 2 cm anastomosis site; (b) 3 cm anastomosis site. The upper row is for standard cannula while the lower row is for spiral cannula

3.3 Discussion

High velocity emerged from the cannula outlet can cause cannula malfunction such as cannula kinking and distortion. To a further extent, the high velocity can lead to sandblasting effect that may cause stroke as the thrombi formed travel from the aorta to the brain. A study conducted by Grinstein, et al., [14] showed that an outlet velocity exceed 2.73 m/s has caused a distortion in Heartmate 2 outflow cannula. It can be seen that in the current study, none of the velocity has exceeded the stated value and spiral cannula present a lower value. This might be caused by the loss of kinetic energy during conversion of fluid from axial flow to a spiral flow in the spiral inducing chamber. From the validation done with Caruso et al. [5], a difference of 10% peak velocity has been observed, with the present study having a peak velocity of 1 m/s and the previous one had 1.1 m/s.

Wall shear stress (WSS) is said to play a significant role in helping the aortic endothelial cells to serve the desired homeostatic function in response to mechanical and chemical stimuli. Low WSS values (< 0.5 Pa) can promote atherosclerosis [7], [15], [16] while high WSS value (1-2 Pa) will cause the elongation of endothelial cells and assist in the release of athero-protective substances. The current study showed no low WSS values recorded. However, from the contour plots, the region of low WSS were recorded along the descending aorta, but not in the crucial region which are the aortic arch and epiaortic vessels. This result is consistent with the findings of Malek et al. [17] which stated that WSS of > 1.5 Pa will produce an athero-protective phenotype. With the presence of a spiral inducing chamber, the area with low WSS value is reduced in the 2 cm anastomosis site. The high percentage value in the 3 cm anastomosis site might be due to the effect of the height of cannula insertion which causes a bigger tangential force exerted on the intimal wall of the aorta.

4. Conclusion

As for the conclusion, the spiral LVAD cannula has established an overall better outcomes in terms of hemodynamic performances. The height of anastomosis location has affected the results, and it can be seen that in this study, 2 cm anastomosis site gives a better results compared to 3 cm anastomosis site. This study can be further expand with bigger flowrate values, as LVAD can be operating up to 10 litre/min [18]. Furthermore, the aorta wall is considered to be rigid and the pulsatile flow of the left ventricle is being neglected. Last but not least, other hemodynamic parameters can also be considered such as haemolysis index and oxygen distribution.

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