Computational modelling of flow and tip variations of aortic cannulae in cardiopulmonary bypass procedure

Siti A Thomas¹, Shirly Empaling¹, Nofrizalidris Darlis², Kahar Osman³,⁴, Jeswant Dillon⁵, Ishkrizat Taib⁶, Ahmad Zahran Md Khudzari¹,⁴

¹Faculty of Biosciences & Medical Engineering, Universiti Teknologi Malaysia, 81310, UTM Johor Bahru, Johor, Malaysia
²Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, 86400, Parit Raja, Johor, Malaysia
³Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310, UTM Johor Bahru, Johor, Malaysia
⁴IJN-UTM Cardiovascular Engineering Centre, Institute of Human Centered Engineering, Universiti Teknologi Malaysia, 81310, UTM Johor Bahru, Johor, Malaysia
⁵Institut Jantung Negara, Jalan Tun Razak, 50400, Kuala Lumpur, Malaysia
⁶Flow Analysis Simulation and Turbulence Research Group, Faculty of Mechanical and Manufacturing, Universiti Tun Hussein Onn, 86400, Parit Raja, Johor, Malaysia

Email: iszat@uthm.edu.my⁶

Abstract. Aortic cannulation has been the gold standard for maintaining cardiovascular function during open heart surgery while being connected onto the heart lung machine. These cannulation produces high velocity outflow which may lead to adverse effect on patient condition, especially sandblasting effect on aorta wall and blood cells damage. This paper reports a novel design that was able to decrease high velocity outflow. There were three design factors of that was investigated. The design factors consist of the cannula type, the flow rate, and the cannula tip design which result in 12 variations. The cannulae type used were the spiral flow inducing cannula and the standard cannula. The flow rates are varied from three to five litres per minute (lpm). Parameters for each cannula variation included maximum velocity within the aorta, pressure drop, wall shear stress (WSS) area exceeding 15 Pa, and impinging velocity on the aorta wall were evaluated. Based on the result, spiral flow inducing cannulae is proposed as a better alternatives due to its ability to reduce outflow velocity. Meanwhile, the pressure drop of all variations are less than the limit of 100 mmHg, although standard cannulae yielded better result. All cannulae show low reading of wall shear stress which decrease the possibilities for atherogenesis formation. In conclusion, as far as velocity is concerned, spiral flow is better compared to standard flow across all cannulae variations.

1. Introduction

Over recent years, there has been an explosive growth of interest in the development and improvement of the aortic cannula. Aortic cannula is a surgical equipment that was inserted into the ascending aorta in conjunction with heart lung machine to drain the blood away from heart during the open heart surgery [1]. Establishing an arterial cannulation is an important events in cardiopulmonary bypass procedure as it maintain a normal circulatory flow of the blood within our body [2]. However, uses of
this medical device may result in many possible complication and even death [3]. This occurs mainly as the blood exit from the cannula with high jet velocity results in the sandblasting effect; which may lead to erosion of blood wall vessel, particularly dangerous for patient in which arteries is hardening followed by deposition of plague [4, 5]. These plague deposition has been implicated in the occurrence of postoperative stroke up to 25% [6].

Numerous research has been done to investigate the best design of aortic cannula used during the cardiac surgery [7]. Reduction in velocity and blood damage became their main objective. Uses of the existing cannula such as standard end-hole cannula, the soft-flow cannula, and the dispersion cannula in cardiac surgery however still results in event of thromboembolism and atherosclerosis development [8]. Studies have demonstrated that flow ejected into the aorta from the left ventricle is swirling around the central axis i.e. a spiral/helical flow. It is physiological and has many benefits in maintaining blood elements balance [9]. Few researches have tried to emulate spiral flow into the blood vessel flow with varying degrees [10]. Despite several researches conducted, only Meedos’ X-Flow Cannulae™ is in market. Although spiral flow cannula has been shown to offer better alternative, there are still some improvements that needs to be done especially on the range of flowrate and type of cannula tip that spiral flow are effective.

In this study, we proposed a straight and curved tip design of cannula in conjunction with the flow characteristics; standard flow (forward flow) and the spiral flow. The study aim was to determine which variations is the best in reducing the velocity, low pressure drop, wall shear stress and the impinging velocity onto the wall of aorta.

2. Numerical modelling

2.1. Geometry: Characteristics of Models

There were three different design factors: 1) cannula tip (straight and curved), 2) flow induced (straight flow and spiral flow), and 3) flowrate out of the cannula. These 3 design factors lead to a full factorial design of experiments. Eight cannulae of different tips were designed using SolidWorks; straight tip cannula, curved tip cannula, straight and curved tip cannula with spiral inducer as illustrated in Figure 1. Geometrical properties of each cannula are listed in Table 1. Each cannula was connected to patient specific aorta model as shown in Figure 2. The patient specific aorta was modelled from a healthy male from Insitut Jantung Negara (IJN). The original image was a Computed Tomography (CT) scan which has undergone image processing using a commercial software (Mimics, Materialise Inc., Leuven, Belgium).

![Figure 1](image-url)
For the design factor of flowrate, three levels were chosen: 3, 4 and 5 liter per minute (lpm). Overall, there were 12 variations (2 × 2 × 3) from which all were tested numerically. Since the simulations were done using computer, no replications was carried out.

| Cannula         | Geometrical properties                      |
|-----------------|---------------------------------------------|
| Straight tip    | Cannula length : 270mm Inlet diameter : 10mm Outlet diameter: 8mm |
| Curved tip      | Cannula length : 270mm Inlet diameter : 10mm Outlet diameter: 8mm |

**Table 1.** Geometrical properties of each cannula designed

2.2. **Computational Models**
Flow characteristics in cannulae was simulated by using commercial code: ANSYS CFX 14.0 software (Canonsburg, PA, USA). This solver using a vertex centered finite volume method governing equations on a spatially rectangular computational mesh designed in the Cartesian coordinate system with the planes orthogonal to its axes. Additional refining was completed in specified blood regions, at the arterial surfaces during calculation. The time derivatives are approximated with an implicit second-order accurate in both space and time. Both flow rates inlet and pressure outlet are computed to solve the continuity and Navier-Stokes equations. Hence, the physical laws describing the problem of aorta and cannulation are the conservation of mass and the conservation of momentum. The flow is governed by the following incompressible Navier-Stokes equation:
\[ \nabla \cdot \mathbf{u} = 0 \]

\[ \rho \left( \frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} - f \right) = \mu \nabla^2 \mathbf{u} - \nabla p \]  

where \( \mathbf{u} \) is the flow vector, \( \rho \) is the density of the fluid used in the flow, \( p \) is the pressure and \( \mu \) is the fluid viscosity.

Newtonian fluid was considered in this simulation due to the shear rate of blood in aorta was calculated more than 100/s. Thus, the turbulence model was imposed in predicting flow characteristics during cannulation procedure. The turbulence model used in simulation was the shear stress transport (SST). Grid independence test was carried out which showed that 3 million nodes was sufficient to carry out a well-balanced numerical study on the model. Computational simulation proceeded after completing the meshing process with more than 3 million of nodes for all designs as shown in Figure 3.

2.3. Boundary Condition

The drafted cannulae were then imported into ANSYS CFX software to be simulated. Newtonian blood flow with constant haemodynamic properties of density = 1056.4 kg/m\(^3\) and viscosity = 0.0036 Pa s was simulated with no-slip wall boundary condition which was assumed rigid and impermeable [11]. The flow rates used is 3L/min, 4L/min and 5L/min and maximum iteration of 10000. The resulting Navier-Stokes equation of this modelling is solved within the framework of the CFX Software. The turbulence model used in the simulation was shear stress transport (SST). Grid independence test was carried out which showed that 3 million nodes was sufficient to carry out a well-balanced numerical study on the model. Computational simulation proceeded after completing the meshing process with more than 3 million of nodes for all designs as shown in Figure 3.

![Figure 3. Patient specific aorta model when finished meshing process](image)

2.4. Output Measurement

Several output parameter of haemodynamic has been acquired based on the boundary condition set. Those haemodynamic parameters are: maximum velocity inside the aorta (termed as flow output), the impinging velocity on the aorta wall, pressure drop and the percentage of wall shear stress that exceeded 15 Pa have been obtained. Wall shear that exceeded 15 Pa has higher chances of causing haemolysis and endothelial lesion [7]. The impinging velocity was taken at a point at the end of a straight line from cannulae tip until the aorta wall. The overall process of the system can be summarized as shown in Figure 4.
2.5. Selection of Best Cannulae Group

All results will then be used for determining the best group of cannulae. The value from each parameter will then be ranked, where the smaller the value is the better result. A weighted scale will then be applied to the rank number of each group, this is called the scoring process. It is decided that the weighted scale for each parameters are: 1) flow output: 40%, 2) impinging velocity: 30%, 3) WSS $>15$ Pa (%): 15%, and 4) pressure drop: 15%. These scale is justified due to the importance of velocity on the haemolysis as well as damage on aorta blood wall.

3. Results and Discussion

Although the flow rates were varied into 3 lpm, 4 lpm and 5 lpm, the output results were then averaged to yield new results for easier analysis. Table 2 is the original data for all 12 variations, while the averaged data within the same group is presented in Table 3. The maximum velocity inside the aorta for straight cannula shows a lower reading compared to curved tip cannula independent to their flow type. Straight tip cannula with spiral inducer showed the lowest velocity which is 1.61 m/s followed by straight tip cannula, curved tip cannula with spiral inducer and curved tip cannula with velocity of 1.68 m/s, 1.73 m/s and 1.88 m/s respectively. Figure 5 shows the velocity streamline for each cannula.

![Figure 4. Block diagram of the processes of the system](image)

### Table 2. Flow output for all variations. The unit is in (m/s)

| FLOW OUTPUT (m/s) | FLOW RATE (lpm) | TIP STRAIGHT | TIP CURVE |
|-------------------|-----------------|-------------|-----------|
|                   | 3               | 1.30        | 1.46      |
| STANDARD          | 4               | 1.66        | 1.85      |
| FLOW TYPE         | 5               | 2.09        | 2.32      |
| SPIRAL            | 3               | 1.22        | 1.29      |
|                   | 4               | 1.58        | 1.71      |
|                   | 5               | 2.03        | 2.18      |
Table 3. Averaged flow output from cannulae. The unit is in (m/s)

| FLOW OUTPUT (m/s) | STRAIGHT | CURVED |
|-------------------|----------|--------|
| STANDARD          | 1.68     | 1.88   |
| SPIRAL            | 1.61     | 1.73   |

Figure 5. Velocity streamline of cannula: (a) straight tip; (b) curved tip; (c) straight tip with spiral inducer; (d) curved tip with spiral inducer. These images are from simulation of 5 lpm.

Although all instances in Figure 5 show some degree of spiral flow (even from straight cannula tip), it is much more noticeable at the descending aorta. However, overall, the spiral flow is much more pronounced for cannulae with spiral flow inducing chamber (Figure 5(c) and 5(d)).

Table 4 shows the complete result for impinging velocity. For impinging velocity, both curved and straight cannula with spiral inducer showed lower reading compared to the others with 0.38 m/s and 0.43 m/s respectively. It was the followed by curved tip cannula and straight tip cannula of standard flow with slightly higher velocity reading.

Next, the pressure drop was measured by taking the differences between static pressure at the inlet and outlet of the cannula. High pressure can cause adverse effect. The optimum pressure drop should be below 100 mmHg [12]. All cannula yielded results below 100 mmHg, with straight tip cannula having the lowest pressure drop of 10.21 Pa, followed by curved tip cannula, straight tip

Table 4. Impinging velocity of cannulae groups

| IMPINGING VELOCITY (m/s) | STRAIGHT | CURVED |
|--------------------------|----------|--------|
| STANDARD                 | 0.52     | 0.43   |
| SPIRAL                   | 0.43     | 0.38   |
cannula with spiral inducer and curved tip cannula with spiral inducer having 12.75 Pa, 31.41 Pa and 33.31 Pa respectively.

Figure 6 shows the wall shear stress of the cannula and aorta for cannulae groups at 5 lpm. Based on previous study, wall shear stress in the aorta must not exceed 15 Pa, to prevent vascular damage [13]. It can be seen from Figure 6 that all simulations show similar trend, whereas most of the aorta wall has low WSS reading, while the maximum WSS value can be found at the ascending aorta, especially within the surrounding of three arterial branches. Site directly distal to the left subclavian artery also show a concentrated area of elevated WSS value compared to its surrounding, suggesting that would be the point where flow is focused i.e. the sandblasting area. Percentage of WSS exceeding 15 Pa has been calculated and presented in Table 6. Curved cannula tip with spiral inducer showed the highest percentage among all with 1.75 %.

**Table 5. Averaged pressure drop for all four conditions**

| PRESSURE DROP (Pa) | STRAIGHT | CURVED |
|-------------------|----------|--------|
| STANDARD          | 10.21    | 12.75  |
| SPIRAL            | 31.41    | 33.31  |

**Figure 6.** Wall shear stress of aorta: (a) straight tip; (b) curved tip; (c) straight tip with spiral inducer; (d) curved tip with spiral inducer. These images are from simulation of 5 lpm.
Table 6. Percentage of WSS more than 15 Pa.

| WSS > 15 Pa (%) | STRAIGHT | CURVED |
|-----------------|----------|--------|
| STANDARD        | 1.41     | 0.91   |
| SPIRAL          | 1.47     | 1.75   |

3.1. Selection of best cannula group

All results were then ranked in each category in an ascending manner, where the best one was ranked the first as shown in Table 7. After that each rank value is multiplied by the weighted percentage set earlier. The resulting value for each category and for each group were summed up, resulting in the final ranking of best cannula group. As tabulated in Table 7, the cannula with straight tip with spiral inducer was ranked at number one, with accumulated mark of 1.9. This can be attributed to the group being first in the velocity output which carried higher weightage than the rest. Although in the other category (WSS > 15 Pa, and Pressure Drop), cannulae group with spiral flow inducer, group 3 has not fared well, as well as group 4, the most important part that contributed to the net value was from the velocities (velocity output and impinging velocity).

In this study, three different design factors were investigated. The effect on haemodynamic within the aorta by varying different levels of each design factors revealed interesting findings. The sandblasting effect due to high jet flow from cannula tip has been shown to affect healthy aorta wall in animal testing. It is imperative that jet flow and associated adverse effect on aorta wall as well as on blood be minimised. For easier analysis, the results from variations of input velocity into the cannulae were averaged. By averaging the results for three, four and five lpm, it gave a general idea of output from just variations of cannulae tip and type of flow. As far as velocity from the cannula is concerned, cannulae with spiral flow showed a much reduced flow velocity output. This coincide with results by Pekkan et al.

Table 7. Selection of the best cannula group

|                   | Velocity Output | Impinging Velocity | WSS > 15 Pa | Pressure Drop | SUM RANK |
|-------------------|-----------------|--------------------|-------------|---------------|----------|
|                   | Rank            | Weighted 40%       | Rank        | Weighted 30%  | Rank     | Weighted 15% | Rank | Weighted 15% | Rank |
| Straight tip      | 2               | 0.8                | 4           | 1.2           | 2        | 0.3          | 1    | 0.15         | 2.45  |
| Curved tip        | 4               | 1.6                | 2           | 0.6           | 1        | 0.15         | 2    | 0.3          | 2.65  |
| Straight tip      | 1               | 0.4                | 2           | 0.6           | 3        | 0.45         | 3    | 0.45         | 1.9   |
| Curved tip with   | 3               | 1.2                | 1           | 0.3           | 4        | 0.6          | 4    | 0.6          | 2.7   |
| inducer           |                 |                    |             |               |          |              |      |              |       |

4. Conclusion

This paper focus are on the cannula design variations of three design factors for cannula and its haemodynamic effect. All cannulae were implanted at the ascending aorta to simulate flow condition during cardiopulmonary bypass. Based on the results, spiral flow was definitely induced for cannula with the spiral flow inducer. Cannulae with spiral flow inducer generally were better in term of
velocity factors, while cannulae without spiral flow inducer were better in other haemodynamic parameters. After the scoring process, it emerged that the cannulae of straight tip with spiral flow inducer was the best group compared to others.

Acknowledgement
This research has been funded in part using Ministry of Higher Education Fundamental Research Grant Scheme : R.J1300000.7809.4F588. The authors would also like to express their appreciation to Hairul Lail Ismail from MJIIT, UTM for his technical assistance with the preparation of prototype model.

References
[1] Blauth C I, Cosgrove D M, Webb B W, Ratliff N B, Boylan M, Piedmonte M R, Lytle B W and Loop F D 1992 Atheroembolism from the ascending aorta. An emerging problem in cardiac surgery The Journal of thoracic and cardiovascular surgery 103(6) 1104-11 discussion 1111-2
[2] Kaufmann T A S, Schlanstein P, Moritz A and Steinseifer U 2014 Development of a Hemodynamically Optimized Outflow Cannula for Cardiopulmonary Bypass Artificial Organs 38(11) 972-978
[3] Magner J B 1971 Complications of aortic cannulation for open-heart surgery Thorax 26(2) 172-173
[4] Minakawa M, Fukuda I, Yamazaki J, Fukui K, Yanaoka and Inamura T 2007 Effect of cannula shape on aortic wall and flow turbulence: hydrodynamic study during extracorporeal circulation in mock thoracic aorta Artificial organs 31(12) 880-886
[5] Goto T, Inamura T, Shirota M, Fukuda W, Fukuda W, Daitoku K, Minakawa M and Ito K 2016 Hydrodynamic evaluation of a new dispersive aortic cannula (Stealthflow) Journal of Artificial Organs 1-7
[6] Katz E S, Tunick P A, Rusinek H, Ribakove G, Spencer F C and Kronzon I 1992 Protruding aortic atheromas predict stroke in elderly patients undergoing cardiopulmonary bypass: experience with intraoperative transesophageal echocardiograph Journal of the American College of Cardiology 20(1) 70-77
[7] Menon P G, Antaki J F, Undar A and Pekkan K 2013 Aortic outflow cannula tip design and orientation impacts cerebral perfusion during pediatric cardiopulmonary bypass procedures Annals of biomedical engineering 41(12) 2588-2602
[8] Groeters R K, Steeg D A V, Stewart M J, Thieman K C and Schneider R F 2003 Echocardiographic comparison of the standard end-hole cannula, the soft-flow cannula, and the dispersion cannula during perfusion into the aortic arch The Annals of thoracic surgery 75(6) 1919-1923
[9] Stonebridge P A, Hoskins P R, Allan P L and Belch F F 1996 Spiral laminar flow in vivo Clinical Science 91(1) 17-21
[10] Shafii N S, Darlis N, Dillon J, Osman K and Khudzari A Z M 2014 The Effect of Internal Profile on Cannula Outflow Revolution 30 3
[11] Neidlin M, Sonntag S J, Schmitz-Rode T, Steinseifer U and Kaufmann T A S 2016 Investigation of hemodynamics during cardiopulmonary bypass: A multiscale multiphysics fluid–structure-interaction study Medical engineering & physics 38(4) 380-390
[12] Kira Y, Kochel P J, Gordon E E and Morgan H E 1984 Aortic perfusion pressure as a determinant of cardiac protein synthesis American Journal of Physiology-Cell Physiology 246(3) C247-C258
[13] Avrahami I, Dilmoney B, Hirshorn O, Brand M, Cohen O, Shani L, Nir R and Bolotin G 2013 Numerical investigation of a novel aortic cannula aimed at reducing cerebral embolism during cardiovascular bypass surgery Journal of biomechanics 46(2) 354-361