The Effect of Parameter Variation on Spiral Flow Inducing Cannula Performances

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Abstract. Spiral flow-inducing cannula has been shown in previous research to exhibit a considerable effect on flow hemodynamic. However, there is still room for improvement. In this study, several design variations were tested to determine which variants were the best in terms of flow reduction. Computational Fluid Dynamics (CFD) software was used to simulate flow within a spiral flow-inducing cannula with several variations from chamber width and angle differences. The variants were compared against each other by using several flow parameters and a selection method was employed to determine which model was the best. It was found that a variant that has the widest chamber (14 mm) and biggest angle opening (70°) from the chamber to the cannula tube was the best in several parameters, and as such was chosen as the best variant. When compared with the standard straight cannula, the reduction in flow output was recorded to be 30% which is deemed significantly. In conclusion, spiral flow cannula recorded better hemodynamic effects with lower outflow velocity and wall shear stress value.

1. Introduction
A cannula is medical equipment typically used during the usage of a heart-lung machine (HLM) in open-heart surgery. Its purpose is for the blood to be drained from the patient, or to supply the patient body with the oxygenated blood from the HLM [1], which makes the cannula, particularly, the aortic cannula be an important one for the blood ingress to the aorta. However, the use of this medical device may result in many possible complications after surgery where it was reported about some cases of haemolytic damage, cerebral haemorrhage, and sandblasting effect occurred due to the non-physiological outflow condition [2]. There are also reports mentioning up to 25% of perioperative strokes are due to cerebral emboli that may likely be caused by high jet flow from the cannula bombarding the aorta wall [3], [4]. Several types of cannulae have been proposed and even used to reduce the adverse effect of high flow velocity into the aorta [5]–[8]. Although somewhat successful to reduce the high flow velocity, there still some room for improvement especially reduction in flow velocity and blood damage. Several studies have shown that flow ejected from the left ventricle during
systole is able to confer beneficial effects such as reducing turbulence intensity, aorta wall damage protection, inducing stable flow in the ascending aorta with its curved morphology, maintain flow mechanical forces for example wall shear stress (WSS), as well as beneficial in suppressing thrombosis and intimal hyperplasia [9]–[11]. This realization led to the creation of the spiral flow inducing cannula which is hypothesized to reduce flow velocity as well as blood damage by emulating physiological flow from the left ventricle. Some studies were carried out to test the hypothesis and the findings show a substantial reduction for the flow output as well several other haemodynamic parameters [12]–[14]. The purpose of this study is to further determine other design parameters that may show better output compared to previous studies by using a selection method.

2. Materials and Methods

2.1. Model Geometry

The models of the cannula have been designed by using SolidWorks version 2016 (Dassault Systèmes SolidWorks Corporation, Waltham, MA). The cannula models for this study contains straight cannula which is being commercialized in the market that has been used as the baseline for this and a variety of cannula models of spiral flow aortic cannula with an inlet chamber that has been designed by referring to spiral flow aortic cannula with an inlet chamber that has been done by Nofrizal et [12]. So, from this cannula, nine cannula models have been produced that are variety in the width and the angle of the inlet chamber.

All the model variants followed the base geometric parameters as shown as in Table 1. Figure 1 shows the standard straight cannula used as the performance benchmark and Figure 2 show the spiral flow aortic cannula with an inlet chamber that has been modified for nine other design variants with an inlet chamber, the modification has been done by changing the width and angle of an inlet chamber as shown in Figure 3. Additional parameters for the spiral flow cannula variants, particularly the width and the incline angle, were varied as shown in Table 2, forming nine different spiral flow cannula variants.

| Table 1. Parameters of straight and spiral flow cannula |
|----------------------------------------------------------|
| **Name of the Cannula**                                   | **Cannula Code** | **Inlet Diameter** | **Outlet Diameter** | **Body length** |
|-----------------------------------------------|------------------|-------------------|---------------------|-----------------|
| Straight Cannula                              | STC              | 10 mm             | 8 mm                | 250 mm          |
| Spiral Flow Aortic Cannula                    | SFC              | 10 mm             | 8 mm                | 200 mm          |

**Figure 1.** Straight cannula

**Figure 2.** Spiral flow aortic cannula with an inlet chamber
Figure 3. Inlet chamber design, where W and A values were varied

Table 2. Variants of inlet chamber from SFC 1 until SFC 9

| Variants | Angle A |
|----------|---------|
|          | 50°     | 60°     | 70°     |
| Width, W (mm) |     |         |         |
| 10       | SFC 1   | SFC 2   | SFC 7   |
| 12       | SFC 2   | SFC 6   | SFC 8   |
| 14       | SRC 3   | SFC 6   | SFC 9   |

2.2. Computational Method
The models involved in the study are simulated using ANSYS CFX 14.0 software (Canonsburg, PA, USA). This software can simulate fluid flows in a virtual environment that provides reasonably reliable and accurate solutions across a wide range of applications.

2.3. Geometry Meshing
Fluid flow of the cannula models was simulated by using commercial ANSYS CFX 14.0 software (Canonsburg, PA, USA). The cannula was meshed with body/face sizing and inflation were used near to the wall surfaces to resolve the boundary layers of blood flow and to obtain more accurate results. Since the quality of mesh has significance impact on the accuracy of the numerical solutions, the skewness was used as mesh quality indicator to ensure the adequate overall mesh quality. A grid-independent test resulted with a mesh size between 1 and 3 million element meshes across the model variants.

2.4. Boundary Conditions
For all models, the steady mass flow rate of 0.088 kg/s equal to the normal adult’s heart pump’s flow rate which is 5 L/min was defined as the inlet flow rate. The walls were considered to be rigid, and no slip condition was applied to set the velocity of the fluid at the wall boundary to zero. The blood was modelled as a Newtonian blood, and the blood properties based on the properties used by Nofrizal et
The Shear Stress Transport (SST) turbulence model was utilized for the simulation. The SST is known to perform well in estimating flow separation under adverse pressure gradient. In addition, the wall functions (y+) which is a non-dimensional distance, is an important consideration in turbulence modelling for the proper size of the cells near domain walls. For SST turbulence model, fine mesh close to the wall, the y+ value was ensured to be less than 1 in this study.

### Table 3. The blood properties

| Properties               | Value   |
|--------------------------|---------|
| Density (kg/m3)          | 1060    |
| Viscosity (N.s/m2)       | 0.0036  |
| Specific heat (J/kg.K)   | 4182    |

2.5. **Output Performance Parameter**

The parameters that were analysed in this study are the output velocity, the pressure difference, the wall shear stress (WSS).

2.5.1. **Output Velocity.** Previous publications claimed that use of the standard straight cannula creates high velocities will result in event of atherosclerosis and thromboembolism formation in the blood due to high shear stress at the cannula wall [6, 7]. So, the outflow velocity from the cannula was considered as an output in this study. The outflow velocity was calculated directly from CFX post-processing for all models. Then, all models were compared to STC model.

2.5.2. **Pressure Drop.** Pressure drop is one of the main hemodynamic indicators for commercial aortic cannula. This indicates that a larger pressure drop will produce a higher velocity of blood flow from the cannula tip, and at a certain level it will cause blood damage due to high shear rate inside the cannula. In this study, the pressure drop along the variants was calculated by taking the difference in pressure at the inlet and outlet. Then the value was converted from Pascal (Pa) to millimeter mercury (mmHg) by multiplying by 0.0075 mmHg.

2.5.3. **Wall Shear Stress.** Wall shear stress (WSS) is a common predictor for the performance of medical devices towards vascular wall. The WSS distribution for cannula carried out in this study was for Newtonian fluid, and proportional to the gradient of velocity, \( \frac{du}{dy} \) (shear rate) multiplied by \( \mu \), dynamics viscosity, and given by in equation (1):

\[
\tau = \mu \frac{du}{dy} \tag{1}
\]

for planar condition, and if it is for cylindrical structure, typically equation (2) is used, where \( Q \) is the flowrate, while \( r \) is the radius of the vessel:

\[
\tau = \frac{4\mu Q}{\pi r^3} \tag{2}
\]

3. **Results and Discussion**

There were nine different models of cannulae design with spiral inducer chamber that have been proposed. The steady flow simulation was implemented, and the results were collected and analyzed.

3.1 **Outflow Velocity Analysis**

Previous research discussed that the common cannula used nowadays induce high velocity and high wall shear stress which prompt the formation of atherosclerosis and thromboembolism severity [5], [6]. In Figure 4, the output velocity results from all simulations are shown. The STC recorded the highest output velocity, and was clearly higher than the other variants; while the lowest was the SFC9. In average, only two variants (SFC6 and SFC9) showed significant differences compared to the other
variants, which is also less than the average value for all variants (2.30 m/s) as shown by the orange dotted horizontal line on Figure 4.

![Figure 4. Outflow velocity comparison for the spiral flow cannula models with STC. The orange dotted line indicates the average pressure drop across the cannula](image)

Table 4 shows the output velocity performance of all spiral flow cannula with inlet chamber models and reference straight cannula. The STC model yielded an output velocity of 2.64 m/s, and it can be seen in the table the overall trends with either increasing angle A or increasing width W. This STC is inverse to the result showed by clinical study [17]. There is one variant which is similar to one of Nofrizal et al. model which is the SFC4, however Nofrizal et al. result was 1.89 m/s for the same design (Width = 10 mm, Angle = 60°), resulting in difference of 20.5% [16]. When the simulation between this study and Nofrizal et al. study was scrutinized, it was found out that Nofrizal et al. inserted the tip of cannula into a generalized aorta model, while the cannula in this study was not connected to any structure. This may contribute to the significant difference between this study and Nofrizal et al. study. Regardless, the authors think that this also can serve as a validation for this study.

At the end of the vertical column is the average value of outflow velocity focusing on the effect of increasing width only, while the last horizontal row shows the average outflow velocity when the angle A was increased. It can be seen here that increasing width reduced the outflow velocity; the same trend was shown when the angle was increased from 50° to 70°. The overall average i.e., the grand mean value is 2.3 m/s which is less than STC value which is 2.64 m/s by 12.9%. This means that invariably that the spiral-inducing chamber contributes as a whole to the reduction of the outflow velocity. Of all the variants, the SFC9 recorded the lowest outflow velocity at 1.84 m/s with a significant 30% reduction.

Table 4. Outflow velocity across the cannulae for STC and spiral flow inducing cannula variants.

| Outflow Velocity (m/s) | Width, W (mm) | 50° | 60° | 70° | Average |
|------------------------|---------------|-----|-----|-----|---------|
| **STC**                | 2.64          |     |     |     |         |
| **Width, W (mm)**      | 10            | 2.42| 2.38| 2.45| 2.42    |
|                        | 12            | 2.39| 2.38| 2.37| 2.38    |
|                        | 14            | 2.40| 2.14| 1.84| 2.13    |
| **Average**            | 2.40          | 2.30| 2.22| 2.30|         |

Next, Figure 5 illustrates the comparison of the outflow performance between the spiral flow cannula and reference model, STC.
The velocity line showed in Figure 5 for (a) STC model, no spiral flow formation showed and at end of the cannula tip, the velocity is high with red color. Spiral flow formed with lower velocity induced at the end of the cannula tip for both (b) SFC7 and (c) SFC9 compared to the STC model. Model SCF7 and SCF9 have the same angle, 70° for the inlet chamber but different in the width. This result support that larger width will help to reduce the output velocity of the proposed spiral-inducing cannula. Low outflow velocity may reduce the sandblasting effect onto the aorta wall and possibly on blood damage as well.

3.2 Pressure Drop Analysis

Pressure drop is one of the crucial hemodynamic indicators used for aortic cannula performance. The blood damage potential risk due to the high shear rate and high velocity will increase if a larger pressure drop resulted in the cannula. Recommended and safe value for pressure drop induce by aortic cannula is below 100mmHg as stated in previous study did by Brodman et al, [18]. A pressure gradient with more than 100mmHg at 4L/min flow rate is considered unsafe to be used since it was said to be able to increase the hemolysis risk [9]. The overall result of the pressure drop of the spiral flow cannula and STC model is shown in Figure 6. Contrary to the variant's results, STC yielded the lowest pressure drop across the cannula, almost half of the average of other variant's results (51.4 mmHg, shown by the orange dotted lines across Figure 6). The highest pressure drop among the proposed cannula with a value of 61.70 mmHg was recorded by SFC7, this model has the highest width and angle of the inlet chamber as in Figure 7. Figure 7 illustrates the contour of the highest pressure that was observed at the SFC7 model.
which is 61.70 mmHg while the lowest pressure is the STC model. This is possibly due to increasing in the resistance towards blood flow from the spiral flow chamber structure. As resistance increases, the pressure drop will increase but still below the critical value of 100 mmHg.

![Figure 6](image)

**Figure 6.** Pressure drop comparison for the spiral flow cannula, the orange dotted line indicates the average pressure drop across the cannula.

![Figure 7](image)

**Figure 7.** Pressure contour; a) STC, b) SFC7

| Pressure Drop (mmHg) | Angle A |
|----------------------|---------|
| **STC** 26.68 | 50° | 60° | 70° | Average |
| Width, W (mm) | 10 | 51.2 | 58.9 | 61.7 | 57.3 |
| | 12 | 46.3 | 48.2 | 51.4 | 48.6 |
| | 14 | 44.0 | 45.7 | 55.2 | 48.3 |
| Average | 47.2 | 51.0 | 56.1 | 51.4 |

Table 5 shows the effect of increasing angle A, and width W, on the nine variants pressure drop. As opposed to the STC result of 26.68 mmHg, the effect of angle and width on average yield a grand mean of 51.4 mmHg, almost half of STC result. The highest pressure drop was 61.7 mmHg (SFC7), while the lowest pressure drop amongst the variants was 44 mmHg (SFC3). Although the spiral flow-inducing cannula increased the pressure drop across the cannula, as compared with STC, the increase still is less than 100 mmHg, hence, all variants are deemed to be acceptable to be used.
3.3 Wall Shear Stress Analysis

Wall shear stress (WSS) is very crucial to understand the impact of outflow to the aorta wall. The WSS will increase when the velocity gradient between a wall and the cannula centre increases. Furthermore, this study involved steady and non-slip wall condition where the WSS magnitude depend on increment of the fluid velocity moving from the wall vessel to the centre area [19]. In Figure 8, the overall results of WSS are shown. Compared to STC, the average value of variants is higher at 182.5 Pa. The variant that yielded the highest WSS was the SFC4 (width 10 mm, 60°), while the lowest was SFC9 (width 14 mm, 70°). The highest WSS occurred at the connection area between the inlet chamber and the cannula body as indicated by the black arrow in Figure 9.

![Figure 8](image1.png)

**Figure 8.** Wall Shear Stress (WSS) comparison for the spiral flow cannula, the orange dotted line indicates the average pressure drop across the cannula

![Figure 9](image2.png)

**Figure 9.** Wall shear stress contour for SFC9

Table 6 shows the effect of both width and angle variations on cannulae flow. The STC WSS was only 26.68 Pa, whereas the average WSS due to the width and angle design was 182.5 Pa, more than seven-fold. Among all variants, the SFC9 is the lowest WSS value compared to the STC and other propose cannulae models yielding 49.7 Pa, roughly double to STC value. This is most probably contributed by both the wider chamber and the higher degree. From Table 6, by increasing the angle of the chamber, the average value of WSS is on the decreasing trend, although for 60° it increased before...
decreasing when the chamber angle was 70°. The increasing width of the chamber also contributing to a downward trend for the WSS results.

Table 6. Wall shear stress across the cannulae for STC and spiral flow inducing cannula variants.

| Wall Shear Stress (Pa) | Angle A | Width, W (mm) |
|------------------------|---------|---------------|
|                        |         | 10            |
| STC                    | 105     | 203.6         |
|                        | 50°     | 240.2         |
|                        | 60°     | 237.9         |
|                        | 70°     | 227.2         |
|                        | Average | 180.5         |
|                        |         | 12            |
|                        |         | 168.5         |
|                        |         | 194.7         |
|                        |         | 198.2         |
|                        |         | 187.1         |
|                        |         | 14            |
|                        |         | 169.5         |
|                        |         | 180.4         |
|                        |         | 49.7          |
|                        |         | 133.2         |
|                        |         | Average       |
|                        |         | 180.5         |
|                        |         | 205.1         |
|                        |         | 161.9         |
|                        |         | 182.5         |

3.4 Design Selection Method

This method was used to choose the best-proposed cannula with an inlet spiral chamber from CFD simulations. The STC is the reference model and this method involved two stages which are the screening and scoring process. The screening process is a process to eliminate any designs which recorded hemodynamic value beyond the safe threshold value. If the value of a variant parameter result exceeds the STC result, this will result in a (+) mark, and vice-versa. Any model with a (+) net score was selected for the next process. Once the process is completed, there was no model eliminated during this screening process as in Table 7. Only SFC9 scores the highest net score 3 thus this model was assumed as the best model which gives the best and better performance for all hemodynamic parameters compared to the STC model. Thus, the scoring process was not continued since the best model or cannula design was successfully selected in this screening method, which is SFC9 with a clear difference.

Table 7. The concept of screening matrix process. The (+) and (-) score was given based on each variant result in respective column against control model which was STC

| Model | Outflow Vel. | Pressure Diff. | WSS | Sum of (+) | Sum of (-) | Net Score |
|-------|--------------|----------------|-----|------------|------------|-----------|
| STC   | 0            | 0              | 0   | 0          | 0          | 0         |
| SFC1  | +            | +              | -   | 2          | 1          | 1         |
| SFC2  | +            | +              | -   | 2          | 1          | 1         |
| SFC3  | +            | +              | -   | 2          | 1          | 1         |
| SFC4  | +            | +              | -   | 2          | 1          | 1         |
| SFC5  | +            | +              | -   | 2          | 1          | 1         |
| SFC6  | +            | +              | -   | 2          | 1          | 1         |
| SFC7  | +            | +              | -   | 2          | 1          | 1         |
| SFC8  | +            | +              | -   | 2          | 1          | 1         |
| SFC9  | +            | +              | 3   | 0          | 3          | 3         |

4. Conclusion

This study began with the design of the straight cannula and nine variants by changing the width and the angle of the inlet chamber using a Computational Aided Design (CAD) software. All the models were evaluated numerically using a commercial Computational Fluid Dynamics (CFD) software package. Hemodynamic parameters such as output velocity, wall shear stress, and pressure drop were used to evaluate the variant's performances and implemented a design selection method to finalize the best-proposed cannula with an inlet spiral inducer. Consequently, variant SFC9 was the best model which recorded the lowest outflow velocity and wall shear stress value and resulted in a pressure difference not more than the safe limit. In addition, the SFC9 variant was able to reduce 30% of outflow velocity which may indirectly reduce the jetting flow and sandblasting effect.
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