The Effect of Internal Profile on Cannula Outflow

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Abstract: - One of the medical devices used during the open heart surgery in cardiopulmonary bypass (CPB) is the aortic curve-tip cannula. The aortic curve-tip cannula is also used in the extracorporeal membrane oxygenator (ECMO) to support patient in intensive care unit. There are few complications caused by the non – physiological jet or dispersed flow from the current cannula design. Thus, a novel designs approach to induce spiral flow and reduce the adverse effect on the aortic wall. The objective of this study is to compare the internal helical designs of curved-tip aortic cannula from three groove internal cannula design and three ribs internal cannula design against the standard cannula design; all with variation of straight and tapered body. A comparative study between six cannulae designs were carried out by computational fluid dynamics (CFD) in a steady state condition. Alls proposed internal helical designs have successfully induced spiral flow. The tapered body with 3 rib design was the best curved-tip aortic cannula design, since wall shear stress induced (2310 dyne/cm2) was below the critical value of wall shear stress (4500 dyne/cm2); while the outflow velocity was only slightly more than the standard cannula design. Also, the pressure drop across the cannula (66 mmHg) was significantly below the safe limit (100 mmHg).

Key-Words: - - spiral flow, aortic cannula design, internal helical design aortic curved-tip cannula, computational fluid dynamics, cardiopulmonary bypass.

1 Introduction

Aortic curved-tip cannula is a catheter device which is inserted in the aorta function to deliver the oxygenated blood from the heart lung machine (HLM) during the open heart surgery [1]. However, due to the non – physiological outflow pattern from current cannulae, there are some adverse effects detected such as sand blasting effect, hemolytic damaged and cerebral haemorrhage [2]. Furthermore, the current cannula design is unable to induce the physiological spiral flow in the aorta [4].

The design of the cannula affects the hydrodynamics condition of the outflow where a typical standard cannula design produces high velocity flow upon exiting the tip into the aorta. Plaque rupture formation or 'sand blasting' effect are also by the high outflow velocity of the single stream jetting, even the multiple jets outflow from the curved-tip cannula [3,5].

In order to reduce the outflow velocity, there are few types of cannula designs established such as soft – type flow cannula pattern and also dispersion – type cannula pattern [5]; unfortunately all of them are unable to induce the physiological spiral flow pattern. Despite inducing lower outflow velocity, among the flow stream pattern, large vortices were still present at the aortic [5]. Another commonly used cannula design is the end – hole cannula since it induce low forces and outflow velocity [3].

The formation of thromboembolism and hemodynamic effect is influenced by the cannula jetting outflow condition [5]. A hypothesis was formed saying that the unstable hemodynamic corresponds to lower velocity, unstable range of wall shear stress [2]. We are proposing that by inducing internal helical spiral in the cannula, the exit velocity and the sandblasting effect can be reduced. If the physiological flow profile within the aorta can be maintained or induced, then the impact to the patient during surgical operation using the cardiopulmonary bypass (CPB), as well as extra corporeal membrane oxygenator (ECMO) will be positive[9].

Thus, helical internal spiral curve-tip designs are proposed in this paper to investigate the effect of the design on the blood flow condition. Comparison between the spiral design and the standard design was made to determine any improvements of inducing spiral flow. Numerical analysis was conducted to compare and evaluate the merits of the spiral and design in a steady state flow condition. Attention was given to the flow characteristics by virtue of the spiral flow inducing design feature, such as pressure drop within the cannulae, outflow velocity at the test rig, flow pattern, and also the helicity density in order to confirm that the proposed designs managed to induce the physiological flow profile of blood in aorta.

2 Methodology

There are several studies relates to the blood characteristics and behavior using the Computational Fluid Dynamics (CFD) method [19, 20, 21]. Thus, CFD was employed to simulate flow inside a straight tube as a simplified blood wall vessel connected to selected cannulae designs in this study.

2.1 Geometry: Models Geometry

The cannulae were modeled into six different designs: straight body cannula design (standard design), tapered body cannula design (standard tapered design), a spiral profiled straight body cannula with 3 groove, a spiral profile tapered body cannula with 3 groove, a spiral profiled straight body cannula with 3 ribs and a spiral profiled tapered body cannula with 3 ribs as illustrated in Fig. 2. Fig 1 shows the differences between the rib and groove internal helical designs. A simple rigid tube wall vessel connected to each of the curve-tip cannula models. The simple rigid tube wall vessel represents the aorta with internal diameter 25 mm and 200 mm length [10]. The parameters of the proposed design are listed in the Table 1, for the straight body and for the tapered body in Table 2.

Table 1 The parameters of proposed internal spiral aortic straight body cannula design.

Geometrical properties	**Curve-tip standard cannula**
Cannula length	250mm
Internal diameter	8mm [24 Fr]
External diameter	10mm
Spiral length	90mm
Spiral pitch, revolution	30,3

Table 2 The parameters of proposed internal spiral aortic tapered body cannula design.

Geometrical properties	**Curve-tip standard cannula**
Cannula length	250mm
Internal diameter	10 - 8mm [24 Fr]
External diameter	13 - 10mm
Spiral length	90mm
Spiral pitch, revolution	30,3

To ensure that the existence of spiral flow induced by the proposed designs, a detailed numerical simulation was done to analyse the output flow structure profile and attention is given at the tip of the curved cannula where different types of internal profile design will affect the outflow. As shown in Fig. 2, all of the curved-tip cannula designs are intended for adult physiology (24F). The standard cannula was used as control design where the general dimension setup of the proposed design profile was based upon.

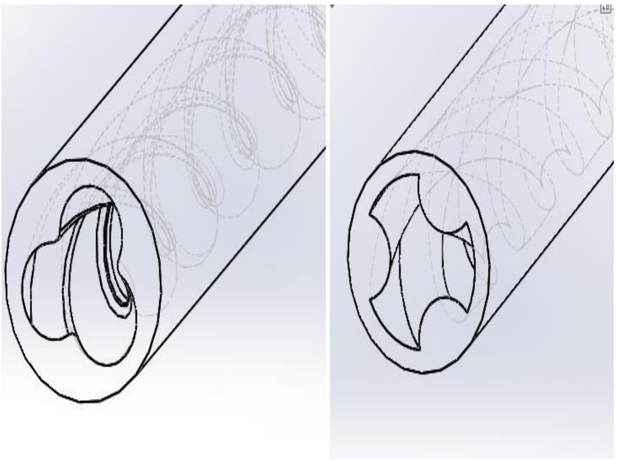

Fig. 1 Proposed internal spiral groove and rib design.

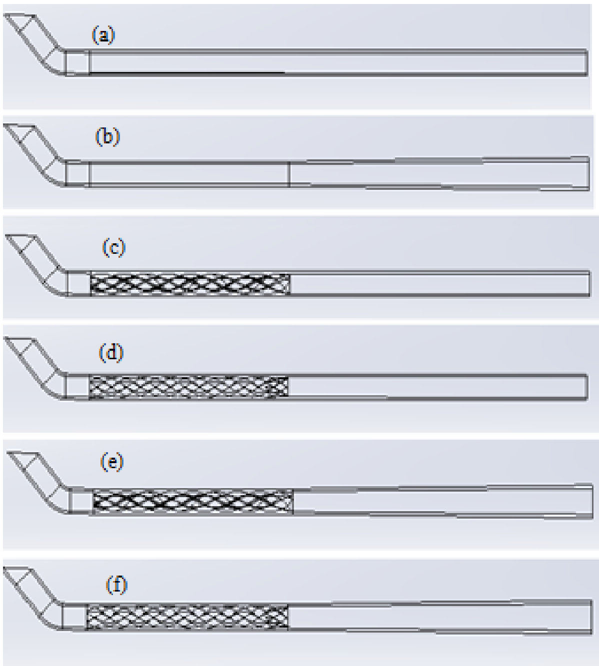

Fig. 2 (a) standard straight body, (b) standard tapered body, (c) 3 ribs straight body, (d) 3 grooves straight body, (e) 3 ribs tapered body and (f) 3 groove tapered body

2.2 Boundary Condition and Governing Equation

The boundary condition essential for accurate CFD simulation was based on the physiological blood flow distribution in the aorta. The net flow range in the aorta is 4.5L/min and 5.5L/min which are based on the patient's data (weight and age). The velocity inlet of the models was set at normal value of 4.5L/min and the outlet pressure was set 120mmHg to simulate physiological condition at the aorta [7]. For steady state simulation process, the flow medium was assumed as Newtonian fluid and also incompressible flow with a non – slip wall condition. The Newtonion fluid assumptions for the blood are 1060kg/m^3 for the density, and 0.00345 Pa s for the viscosity [11, 19]. The wall boundary condition of the cannulae models and also the outflow tube body was assumed to be a rigid body, while neglecting the gravitational effects [11].

The flow simulated in this study was modeled using 3D incompressible Navier-Stokes equations [11, 19]. K – Epsilon RNG was chosen while setting up the simulation process in the ANSYS FLUENT 14.0 (Ansys. Inc., Canonburg, PA, USA), a general flow computational fluid dynamics (CFD) software. The turbulence model was selected due to the suitability of the model for the swirl flow simulation [17]. Cannulae models connected to the test rig were simulated using the CFD software with 500k to 800k nodes, depending on models, as below Fig.3.

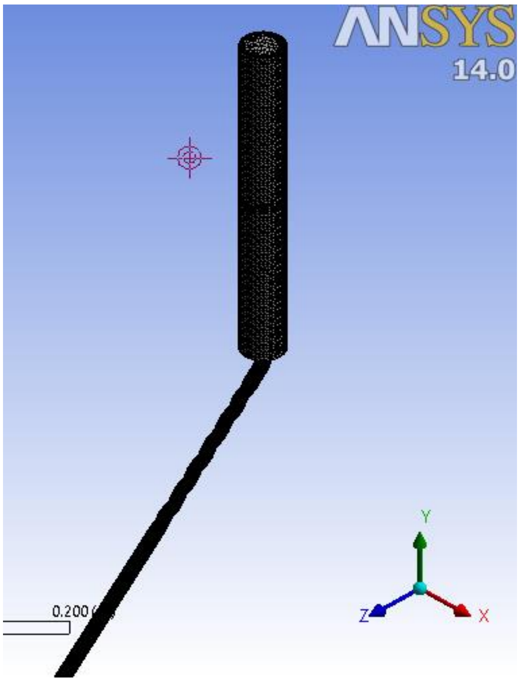

Fig.3 Completed mesh of proposed cannula connected to a test rig tube.

2.3 Output Measurement

There are several performances and parameters of the hemodynamics observed and measured according to the inlet and outlet boundary conditions [11]. Comparison between the results of the standard design and the proposed designs discussed further is based on flow characteristics such as outflow velocity from cannula tip, pressure drop, effect of wall shear stress, and the helicity flow profile formation. Area- weighted average helicity density H_a was calculated to determine and quantify the formation of the spiral flow induced. The helicity density formula used is [18]:

$$Ha = \frac{1}{S}\int Hd\, dS \qquad (1)$$

S is the cross sectional area, H_d is helicity density which is defined by scalar product equation as below:

$$Hd = \vec{V}.(\nabla\, x\, \vec{V}) \qquad (2)$$

From the simulated results, visualization of streamlines was done to improve detection of stagnation area and the blood clotting formation tendency [11]. From this study, the velocity streamlines from the inlet of the curved-tip cannula into the test rig tube was deemed to be important, and used to qualitatively determine the extent of spiral flow intensity. It is important to note that the level of wall shear stress from the induced spiral helical flow has to be kept at a reasonable level, since high wall shear stress leads to hemolysis formation and others adverse effect [11, 21].

3 Result and Discussion

The comparison observed from the hemodynamic factors such as velocity of the outflow, helicity density of the outflow to ensure the ability of the optimized cannula induce spiral flow, and also pressure condition. These results were obtained from the computational simulation of the proposed designs.

3.1 Velocity Streamline

The velocity streamline of the flow patterns of each proposed curved-tip cannula design are shown from Fig. 4 to Fig 9. The standard models flow pattern of both curve-tip cannula standard design are shown in Fig 4 and 5, where there were no vortices being developed within the test rig, and velocity streamline maintained a straight path after expanding distal to the curved-tip. The effect of the internal helical design of the straight and tapered body curve-tip cannula on the velocity streamline are illustrated in Fig 6, Fig 7, Fig 8 and Fig. 9, where spiral flow was induced within the test rig.

Spiral flow pattern development are said to be due to the muscle heart fiber arrangements , twisting in a counter clockwise direction during systole and in clockwise direction during diastole which lead to diastolic recoil [4, 18]. The effect of aorta body torsion is also affecting the helical flow formation down the descending aorta [18]. Thus, it is important to ensure that the outflow of the aortic cannula used during the CBP is able to emulate the physiological flow to decrease the adverse effect on blood cells. Based on the velocity streamline of the proposed curved-tip cannula designs, it was discovered that both groove and rib internal profile design managed to induce the physiological spiral outflow compared to the outflow out of the standard curve-tip cannula in Fig 4 and 5.

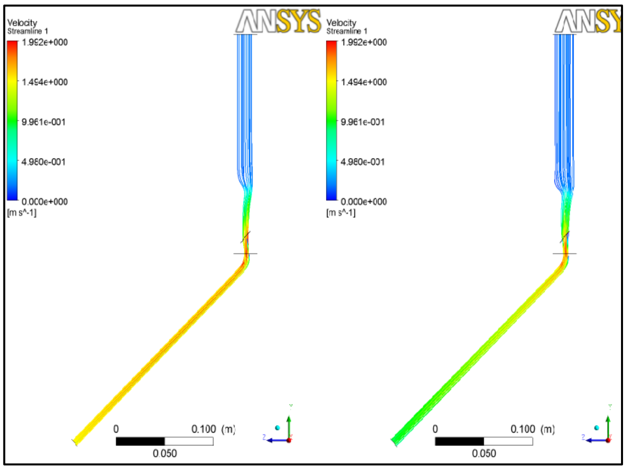

Fig. 4 Standard straight (left) and tapered body (right) curved-tip cannula velocity streamline.

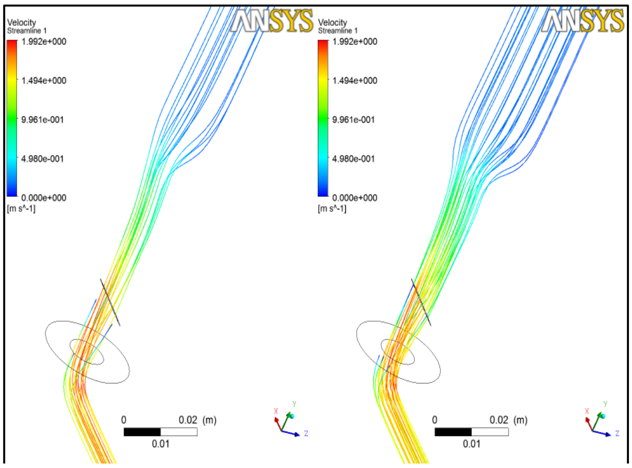

Fig. 5 Standard straight (left) and tapered body (right) curve cannula velocity streamline focused at the tip.

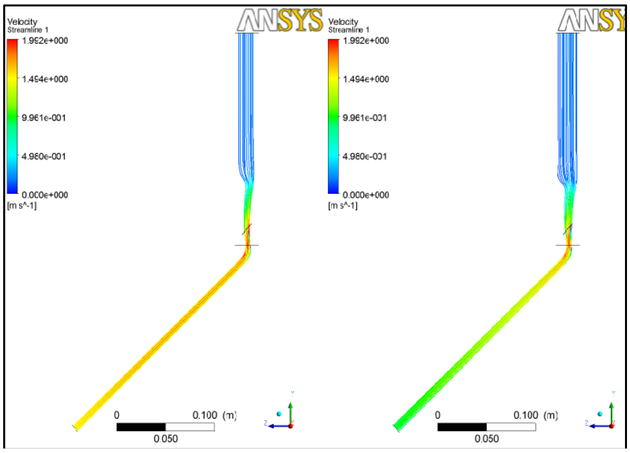

Fig. 6 Overall straight body 3 groove internal curve-tip cannula design (left) and straight body 3 rib curve-tip cannula (right) streamline

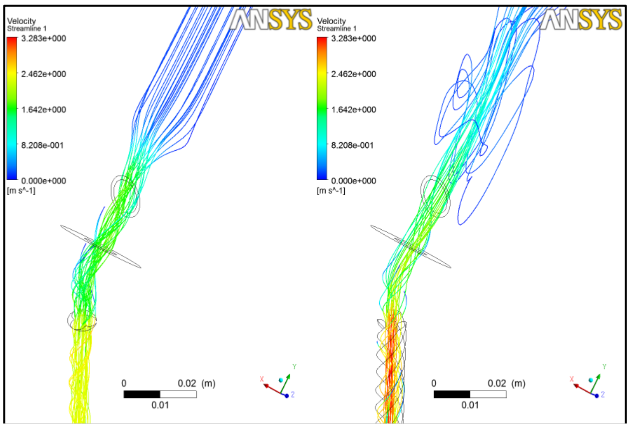

Fig. 7 Straight body 3 groove internal curve-tip cannula design (left) and straight body 3 rib curve-tip cannula (right) velocity streamline focused at the tip.

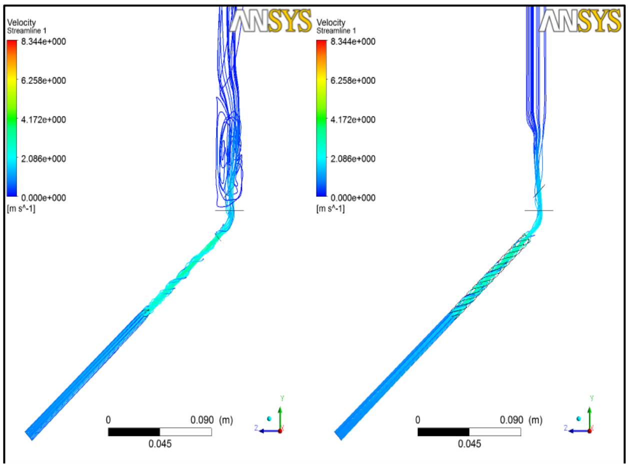

Fig. 8 Overall tapered body 3 groove curve-tip cannula design (left) and tapered body 3 rib curve-tip cannula (right) velocity streamline.

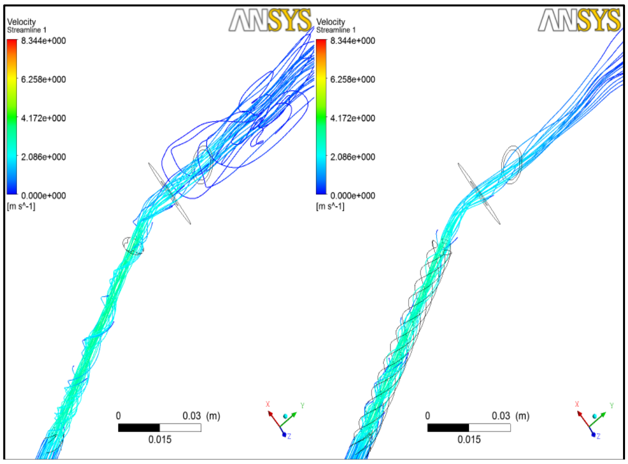

Fig. 9 Tapered body 3 groove internal curve-tip cannula design (left) and tapered body 3 Rib curve-tip (right) cannula velocity streamline focused at the tip.

The graph in Fig. 10 below shows the quantification of the spiral flow induced from the curve-tip cannula. The area – weighted helicity density, H_a was measured along the simplified wall vessel. The standard body with 3 groove designs recorded highest helicity density value (51.45 m/s^2) followed by the standard body with 3 groove design (29.32 m/s^2). For the 3 groove and 3 rib tapered body cannula designs, the helicity density value is 1.5m/s^2 and 31 m/s^2, while for the standard straight and tapered body cannula design, no value recorded for helicity density. The proposed tapered body cannula design shows higher helicity density compared to the straight body since the area along the cannula body became smaller as it goes from inlet to outlet part of the cannula. As the outflow distance gets farther from the cannula tip, the helicity density index decline gradually along the simplified wall vessel. However, by comparing the internal groove and the internal rib design, it was evident that the rib design was able to induce spiral flow profile farther along the test rig tube than the groove design. Thus, rib type internal profile ensures that the spiral flow can be maintained longer, which may help flow within the aorta.

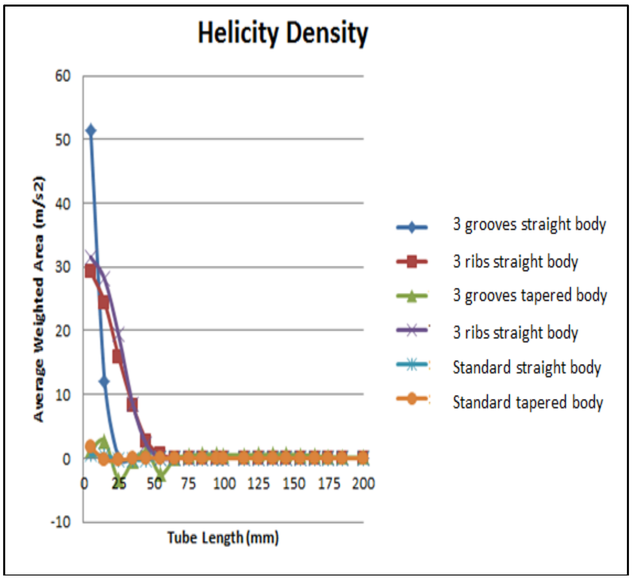

Fig. 10 The helicity density index of all proposed designs. The highest H_a performance was by straight 3 groove, although the value dropped fairly fast as flow moves along the test rig tube

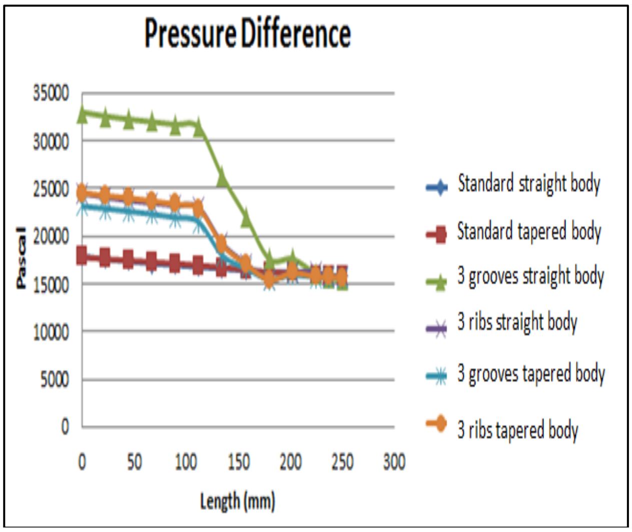

Fig. 11 Pressure Differences at Cannula between Standard 3 Groove and 3 Rib Designs Graph

Table 3 The pressure difference along the cannula for ach design

Model	Pressure Drop (mmHg))
Standard Straight	16.08
Standard Tapered	15.32
Straight 3 Groove Design	133.52
Straight 3 Rib Design	65.91
Tapered 3 Groove Design	55.79
Tapered Rib Design	66.67

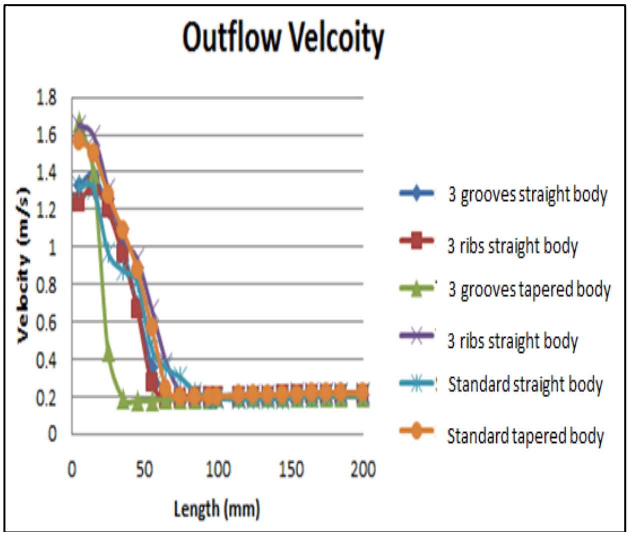

Fig. 12 Flow Velocity in tube rig test from all three cannulae designs

Fig. 11 illustrates the total pressure measured along the cannula. There was only a slight pressure difference in standard cannula compared to the pressure reduction recorded along the internal helical profiled cannula. Both control designs (straight and tapered) recorded a low pressure drop at 2500 Pascal (<20mmhg), compared to the other types of proposed curved-tip cannula. The safe limit for the pressure drop in a cannula is below 100 mmHg [22]. The pressure drop must not exceed the safe limit to avoid any adverse effect on the blood cells. In this study, the straight body 3 groove curved-tip cannula design recorded pressure drop beyond the safe limit (> 130 mmHg), as in Table 3 compared to the other proposed designs, which may lead to possible haemolysis.

Next, measurement of the velocity output is shown in Fig. 12. The velocity measurement was taken along the rig test tube for comparison purposes. The proposed helical flow inducing cannula outflow velocity were shown to be just slightly more than the standard straight body and tapered body outflow velocity. The outflow velocities for the 3 groove and 3 rib straight body cannulae were only about 0.7% from the standard straight type cannula, and a slightly higher difference (6%) between the proposed tapered body cannulae design (groove and rib) and the standard tapered body cannula design.

Previous study reported that spiral flow help in lowering the velocity outflow, and most importantly in reducing the effect of high jetting on to the aorta wall [15], while higher outflow jets of standard cannula tip produce single stream provoke plaque rupture or sand blasting [2]. Other study also attributing high exit velocities, and also straight jet flow profile as the possible causes of adverse effects while using the cannula during open heart surgery or cardiopulmonary bypass, including the cerebral haemorrhage, rupture of the aorta wall side effects [10]. The proposed designs have a slightly higher outflow velocity compared to the standard cannula due to the reduction of internal area of the proposed cannula design. The outflow velocity increase is deemed to be not significant since helical flow induced might offset the outflow velocity effect.

In Fig. 13, the wall shear stresses of each cannula are illustrated, while the value recorded is shown in Table 3. It was reported that the critical value of shear stress that can cause hemolysis of blood cells is 450 Pa (4500 dyne/cm^2) [13]. Higher wall shear stress within the cannulae wall is due to the high flow velocity inside the cannula. The proposed internal profiles reduce the area within the cannulae increasing the velocities range thus the wall shear stress increase as a consequence.

However, Table 4 shows that most of the wall shear stress values of the cannula designs are below the critical level.

As far as the spiral flow inducing cannulae design is concerned, the tapered body recorded lower wall shear stress level compared to the standard designs, and this may reduce the risk of adverse effect on the wall. The internal design of rib showed stable and lower wall shear stress range which is less than 2500 dyne/cm2, compared to the grove design either in the straight body or tapered body.

Thrombosis formation also relates to the flow pattern; as mentioned in earlier studies, the formation of spiral flow could prevent adverse effects on blood cells especially on the platelets activation [16, 21]. By introducing an internal helical profile in the cannula, the induced spiral flow has the potential to lower acute thrombus [16].

Thus, the rib design of the tapered body is preferable since the wall shear stress range is within the critical limit. Furthermore, based on the streamline result, the rib design illustrated the ability of inducing spiral flow profile farther than the groove design. Other than that, the tapered 3 ribs cannula design also has recorded pressure difference below 100 mmHg and only a slightly higher outflow velocity.

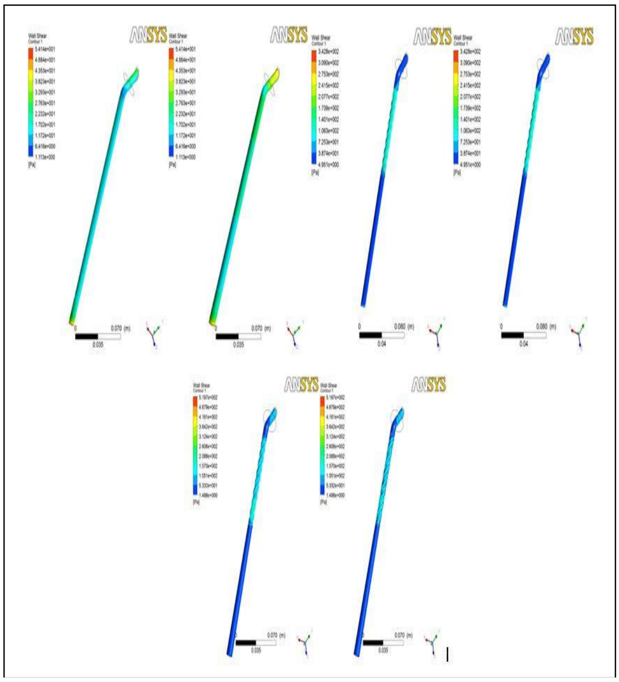

Fig. 13 Wall shear stress at all cannula wall.

Table 4 The wall shear stress measured

Cannula Design	**Wall shear stress Pa / (dyne/cm^2)**
Standard Straight	1.11– 54.13 Pa/ (11.1 - 541.3dyn/cm^2)
Standard Tapered	3.326 – 30.75 Pa/ (33.26 – 307.5 dyne/cm^2)
Standard 3Grooves	4.95 – 342.84 Pa/(49.5–3428.4 dyn/cm^2)
Standard 3 Ribs	1.019 - 258.79 Pa/ (10.19 - 2587.9 dyn/cm$^{2)}$
Tapered 3 Groove	0.05113 – 250.171 Pa/ 0.55113 – 2501.7 dyn/cm^2)
Tapered 3 Rib	0.424431 – 231.46 Pa/(4.24431 – 2314.6 dyn/cm^2

4 Conclusion

This paper focused on several variant of cannula design to investigate the possibility of inducing spiral flow and its effect.
Compared to the standard cannulae designs, there were no significant improvements in wall shear stress level, pressure drop within the cannula body, as well as reduction of outflow velocity. However, it was proven that the spiral flow was induced in all proposed models. Among all the proposed designs, the tapered 3 rib design was the best design: able to induce spiral flow farther, acceptable pressure drop value (< 100 mmHg), and lowest wall shear stress (< 4500dyne/cm^2).

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