Novel Aortic Cannula with Spiral Flow Inducing Design

Nadia S. Shafii, N. Darlis, Jeswant Dillon, Kahar Osman,Ahmad Zahran Md Khudzari, and E. Supriyanto

Abstract**—**Aortic cannula is one of the medical parts used in cardiopulmonary bypass (CPB) during medical operation, or used in conjunction with extracorporeal membrane oxygenator (ECMO) operation during patient support in intensive care unit. The existing stock designs produce jet flow or dispersed flow out of the cannula tip. Thus leading to few complications caused by the non – physiological flow. To reduce adverse effect on the aorta, as well as on red blood cells (RBC), a novel approach to induce spiral flow is proposed. The aim of this study to compare between internal helical curve tip aortic cannula designs comprised of three groove and three ribs, and standard curve tip aortic cannula design. Computational fluid dynamics (CFD) simulation between three cannula designs were carried out in steady state condition. Spiral flow was successfully induced by the proposed internal helical design. The pressure drop across the cannulae designs recorded below the safe limit, outflow velocity was reduced by 34.5%, while wall shear stress was also acceptable (30.8 Pa – 61.59 Pa – 215.6 Pa) which is below critical wall shear stress value.

Keywords—spiral flow, aortic cannula design, heart lung machine, internal helical design, computational fluid dynamics.

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I. Introduction

Aortic cannula is a special catheter device inserted in the aorta during open heart surgery and supply oxygenated blood to the aorta from heart lung machine (HLM) [1]. However, previous study discussing the use of aortic cannula reported that aortic cannula has its fair share of problem; there had been reported cases of haemolytic damage, sand blasting effect, and cerebral haemorrhage due to the non-physiological outflow condition [2]. One of the known limitations of thecurrent cannula in use is the inability to induce the natural spiral blood flow patterns which may create adverse effect on blood vessel [4].

The design of the cannula affects the hydrodynamics of the outflow where a typical stock cannula design produces high velocity flow upon exiting the tip into the aorta. High velocity outflow is highly influential to the formation of plaque rupture or 'sand blasting effect' induces by the single stream jetting or even multiple jets outflow from the aortic cannula [3, 5]. There are a few examples of cannula designs such as pattern soft-type flow cannula and dispersion-type cannula [5] aiming to reduce outflow velocity, but still introduce varieties of non-physiological flow. Despite producing low velocities, large vortices are present among the flow stream pattern induced located at the thoracic aorta [5]. Another design that is widely used is the end-hole curve cannula which disperses high forces and velocities outflow [3, 5].

The multiple cannula structures, cannula jet flow relates to the event of thromboembolism and also different hemodynamic effects [5]. It is hypothesized that by introducing a helical spiral profile within the cannula internal wall will help to reduce the unstable hemodynamic and sandblasting effects by inducing spiral flow which corresponds to lower velocity, low exit force and also stable wall shear stress [2]. The spiral outflow induced may contribute a positive impact to the pressure – flow condition especially during the operation of the cardiopulmonary bypass (CPB) as well as extra corporeal membrane oxygenator (ECMO) in the cardiac care intensive unit to maintain the physiological flow profile [9].

In this paper, a helical internal spiral cannula design is proposed which serve the purpose of inducing a spiral flow from the tip cannula to the aorta. Comparison between the spiral design and the stock design is 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 difference in the proposed design, out flow velocity at the test rig, flow pattern and also the helicity density in order to confirm that the proposed internal helical designs managed to induce the physiological flow profile of blood in aorta.

II. Methodology

A. Geometry: Characteristics of Models

The cannula were modeled into 3 designs;straight cannula (stock design), a spiral profiled cannula with 3 groove and a spiral profiled cannula with 3 ribs as illustrated in Figure 1. The parameters of the proposed designed are listed in Table 1.

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Each models was connected to a simple rigid tube wall vessel which represents the outflow to the aorta (inner diameter 24mm and length is 250mm) [10]. The parameters of the proposed design are listed in the Table 1.

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

Geometrical properties	Curve standard cannula
Cannula length	250mm
Internal diameter	8mm [24 Fr]
External diameter	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 analyze the output flow structure and profile. Attention is given at the tip of the curved cannula where different types of internal profile design will affect the outflow. As shown in Figure 1 and 2, all of the curved cannula designs are intended for adult physiology. The stock cannula was used as control design where the general dimension setup of the proposed design profile was based upon.

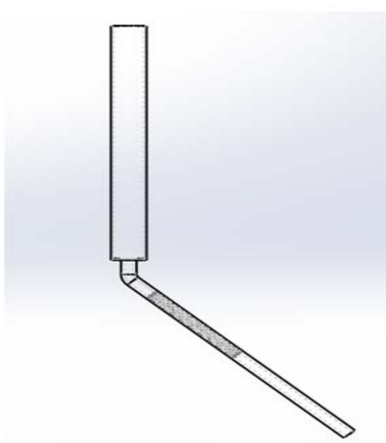

Figure 1: Simple rigid tube wall vessel connected with proposed cannula

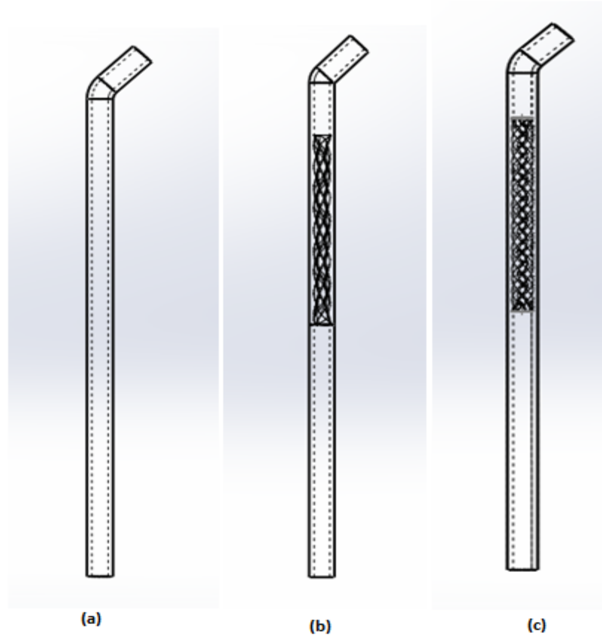

Figure 2: (a) straight cannula (stock design), (b) a spiral profiled cannula with 3 grooves, (c) a spiral profiled cannula with 3 ribs.

properties such as density of the blood = 1050kg/m^3, viscosity = 0.00345 Pa s, and it was assumed with non –slip and steady state boundary conditions [11]. The wall boundary condition of the models was assumed to be a rigid body at the cannula wall and also the outflow tube body while neglecting the gravitational effects [11].

The selection of boundary conditions was based on the physiological blood flow distribution in the aorta. The flow rate in the aorta used from the previous study stated that the net flow ranged is between 4.5 and 5.5L/min [11]. It is based on the condition of each patient such as their 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 aorta [7].

The flow simulated in this study was modeled using 3D incompressible Navier-Stokes equations [11]. A suitable turbulence model 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]. Computational simulation continues after completing the meshing process with 800k to 950k nodesas below Figure 3 for all designs.

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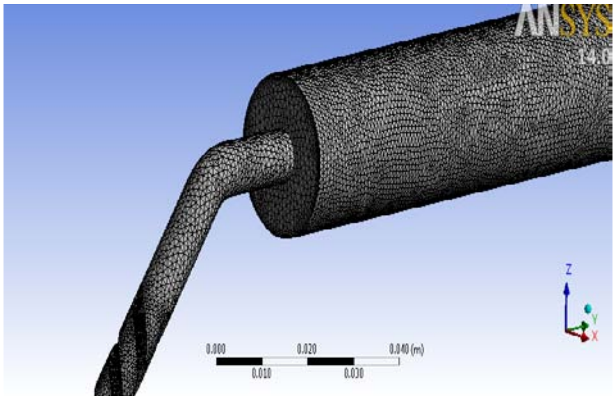

Figure 3: Simple completed meshing

C. Output Measurement

There are several performances and parameters of the hemodynamics observed and measured according to the inlet and outlet set up at the boundary conditions [11]**.** Comparison between the results of the stock design and the proposed designs discussed further based on few characteristics such as velocity of the profile flow, pressure difference, effect of wall shear stress and the helicity flow profile formation. Area-weighted average helicity density H_a will be calculated to determine the existence of spiral flow induced. The 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 result data, the velocity streamlines from the inlet of the curve cannula into the test rig tube was deemed to be important and used to qualitatively determine the extent of spiral flow intensity. The pressure difference was measured along the cannula. Other flow characteristic parameters measured were the outflow velocity in the rig test, and wall shear stress. It is important that the level of wall shear stress from the induced spiral helical flow is kept at a reasonable level, since high wall shear stress leads to hemolysis formation [11].

III. RESULTS

Figure 4 and 5 below illustrate the streamline of the flow patterns after completing the CFD simulation. . In Figure 5, the right part shows the spiral flow pattern induced from the internal helical design of curve tip cannula, while Figure 4 shows the flow pattern of the stock design.The graph in Figure 6 shows the area-weighted helicity density, Ha, along the test rig tube for all cannula type tested. The maximum value of helicity density for the 3 groove designs is 20m/s^2, while the 3 rib cannula is recording a maximum value of 19.5 m/s^2 ; however, there was no value recorded from the stock cannula design. The helicity density for both spiral and groove design declines gradually along the test rig tube as the distance gets farther from the tip.

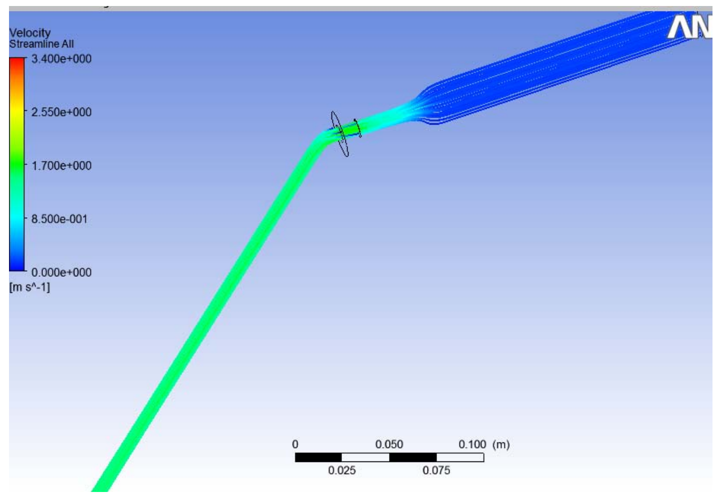

Figure 4: Standard curve cannula (stock design) Velocity streamline

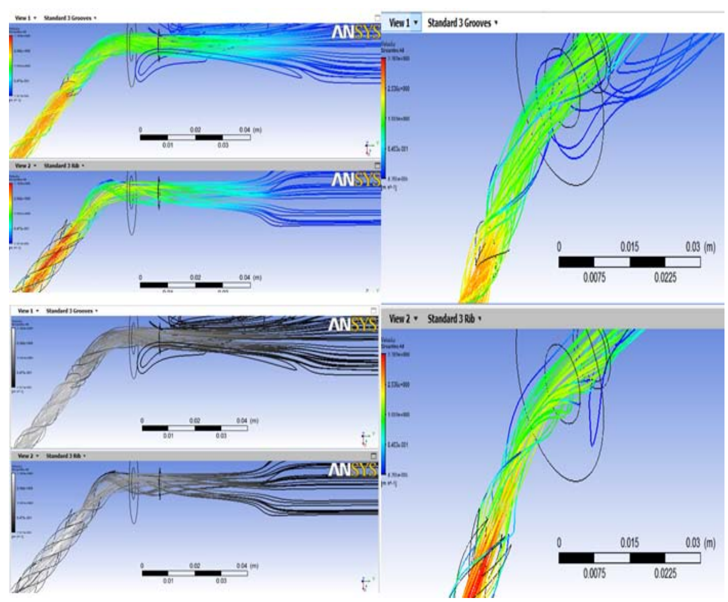

Figure 5: 3 Groove internal curve cannula design and 3 Rib (lower part) internal curve cannula velocity streamline

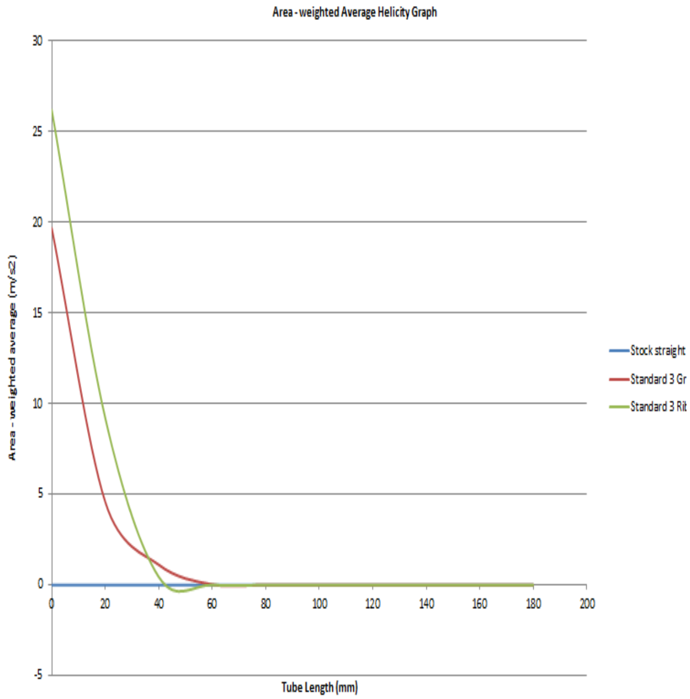

Figure 6: Velocity Helicity Graph

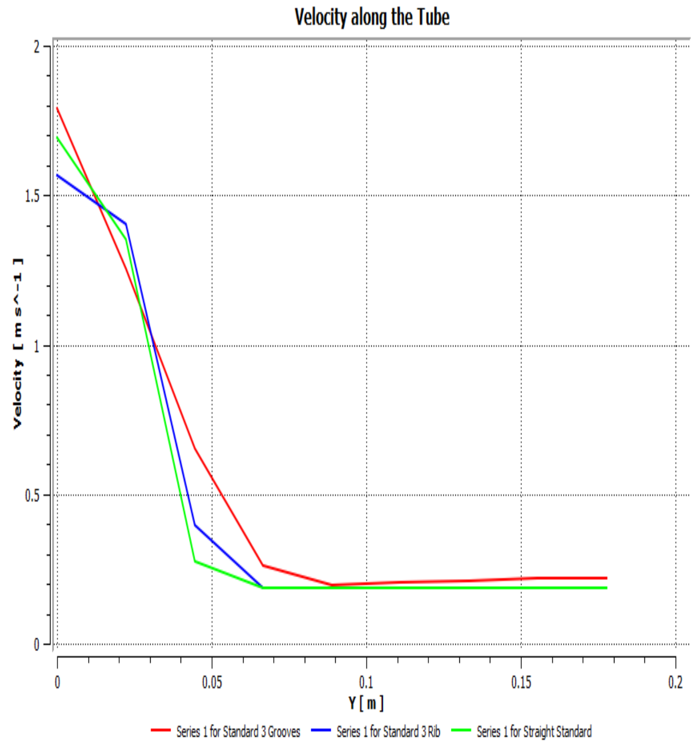

Figure 8: Flow Velocity in tube
Rig Test from all three cannulae designs

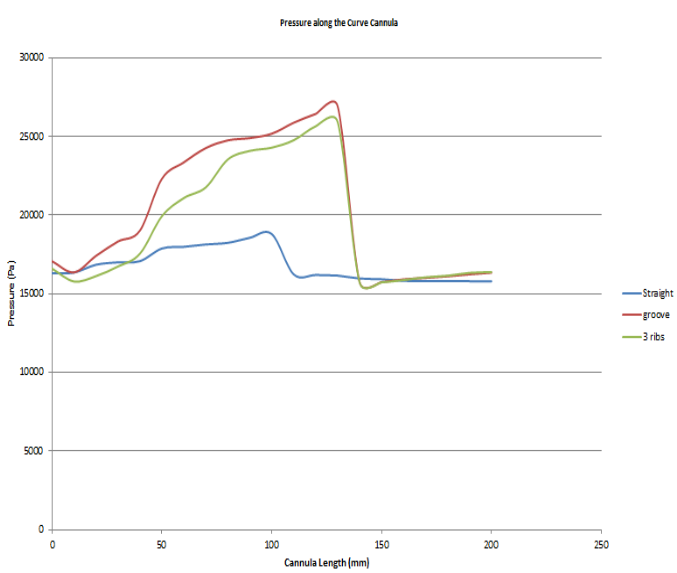

Figure 7: Pressure Differences at Cannula between Standard 3 Groove And 3 Rib Designs Graph

Figure 7 illustrates the total pressure measured along the cannula. There was slightly pressure difference occurred in standard cannula compare to the pressure reduction along the internal helical profiled cannula. Pressure along the stock desgn curve cannula shows the lowest pressure recorder about below 25000 pascal compared to the others optimized curve cannula.

Next, an outflow measurement on the velocity output is shown in Figure 8. The measurement was taken along the rig test tube to find the flow of each cannula's outflow other than comparing the outflow velocities. The results showed that the highest outflow velocity was by groove cannula followed by standard cannula design and lastly rib cannula design.

Higher outflow jets of standard cannula tip produce single stream provoke plaque rupture or sand blasting [2]. The outflow velocity recorded along the rig test tube for the 3 groove cannula was1.8m/s which is the highest velocity compared to the standard and 3 rib cannula velocity which are 1.65m/s and 1.55 m/s respectively. Previous study reported that spiral flow help in lowering the velocity outflow, and reduce the effect of high jetting to the aorta wall [15].

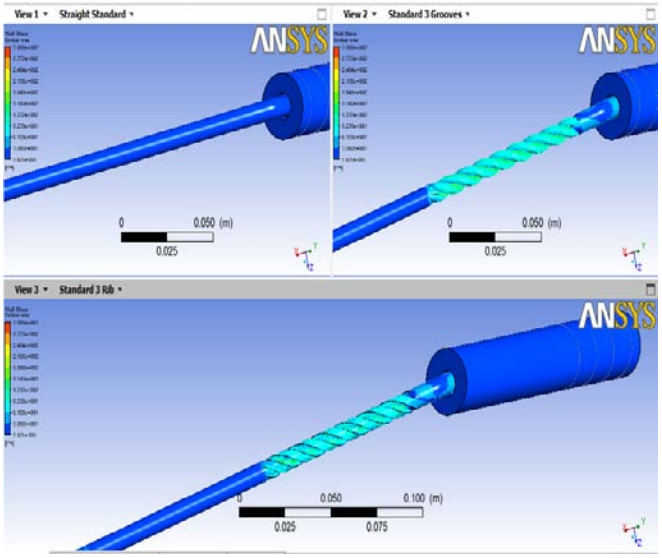

Figure 9: Shear Stress at all Cannula

Creating and inducing high exit velocities and also straight jet flow profile is the possible cause of adverse effects including the cerebral hemorrhage, rupture of the aorta wall side effects while using the cannula during open heart surgery or cardiopulmonary bypass.

In Figure 9, the shear stress of each cannula measured as table below 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]. Both proposed designs (3 grooves and 3 ribs) show that the maximum value of wall shear stress is well below the critical level as shown in Table 2.

Table 2: The shear stress measured

Cannula Design	Shear stress Pa (dyn/cm^2)
Standard	3.425^{-005}–30.800 Pa (0.000342- 308.0 dyn/cm^2)
3 Groove	61.59 – 215.6 Pa (615.9 – 2156.0 dyn/cm^2)
3 Rib	61.59– 154.0 Pa (615.9 -1540.0 dyn/cm^2)

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

IV. CONCLUSION

This paper focused on investigating possibility of inducing spiral flow with the use of novel cannula design for medical operations. The use of computational fluid dynamics provides a clear visualization of swirl flow with the use of K-e turbulence model. The proposed design; 3 grooves and 3 rib designs proved to be capable of inducing a spiral flow which is the physiological flow pattern to the aorta. Compared to the stock design of curved-tip cannula, there were improvements in wall shear stress level, pressure drop within the cannula body, as well as reduced outflow velocity.

Future development of this design would proceed to experimental verification to further validate the spiral flow formation.

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