Journal of Engineering Research and Education
Volume 17, 2025 [1-13]

Computational Fluid Dynamics Simulation of Spiral Flow Inducing Cannula Tip Variations

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ABSTRACT

Aortic cannulation has been the established method for sustaining cardiovascular performance during open-heart surgery while linked to the heart lung machine (HLM). However, this approach's swift outflow might have negative repercussions on the patient, including detrimental effects on the aorta's inner wall and harm to blood cells. Introducing an off-center inlet in relation to a chamber's central axis at the cannula entry point has proven to generate a spiral flow pattern. Every cannula displays minimal measurements of wall shear stress, reducing the likelihood of atherogenesis development. In this study, two models, namely ST-Type 11 and CT-Type 1, outshone the rest, showcasing the most favorable velocity profiles at 1.0275 ms-1and 0.8956 ms-1, respectively, for the straight and curved tip cannula. Moreover, when evaluating wall shear stress performance, the ST-Type 11 and CT-Type 9 variants displayed the most significant values, measuring at 9.6592 Pa and 11.1582 Pa, surpassing other cannula configurations. The findings suggest that cannulae designed to generate spiral flow are put forth as better options, given their capacity to reduce outflow speed. The wall shear stress readings in all cannulae are modest, which reduces the likelihood that atherogenesis would emerge. In conclusion, spiral flow outperforms normal flow in terms of velocity profile across all cannulae variants.

Keywords: Aortic Cannulation, Cardiovascular Engineering, Hemodynamic, Spiral Flow, Wall Shear Stress.

1. INTRODUCTION

During open-heart surgery conducted with the use of aortic cannulation for Cardiopulmonary Bypass (CPB), arterial cannulation is performed at the ascending aorta to deliver blood with oxygen from the heart-lung machine (HLM) to the patient's body. It produces a high jet velocity when it exits the cannula tip since it has the lowest cross-sectional area among the extracorporeal circuit's components [1]. This rapid and focused flow causes the sandblasting effect which is the constriction and hardening of arteries as a result of an excessive build-up of plaque around the arterial walls, when it strikes the inner walls of the aorta [2]. These events are associated with the formation of atheromatous emboli, which can increase the risk of stroke by as much as 25% [3].

Cannulas are often used extensively in medical procedures, either in the operating room or on the ward, to transfer fluids between the patient and the machine. There are several varieties of cannula, each intended for a specific purpose. Cannulas are usually used in pairs, one for drainage and one for return. During CPB, a variety of commercially available cannula types are utilised,

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such as arterial, which restores oxygenated blood to the rest of the human body, venous, which drains blood without oxygen from the body, and cardioplegia, which provides a cardiac arrest supply solution. The oxygenated blood from HLM was delivered to the human body using an aortic cannula, as this study concentrated on arterial cannulation at the ascending aorta.

A number of arteries, including the femoral, axillary, and ascending aorta, are frequently chosen for arterial cannulation sites. The choice of artery depending on several elements, including the ability of the clinician to cannulate, the positioning of the patient, pathophysiologic characteristics, risk of injury to nearby structures or neurons, and thrombotic propensity [4]. The subclavian or femoral arteries were the most commonly used cannulation site in the early days of CPB [5], but now days, the ascending aorta is typically used [6]. Even for patients with Type A Acute Aortic Dissection, the benefits of this method are readily available, safer, and do not necessitate a second incision [7] [8] [9] [10].

Previous studies have been conducted with the aim of enhancing aortic cannulas and minimizing complications in blood flow related to their design aspects. These factors include the impact of cannula length [11], adjustments made to the cannula tip (involving multiple and dispersed stream modifications) [12][13], and a recent focus on creating a design that promotes the development of spiral flow [14]. It's worth noting that physiological blood flow within the thoracic aorta naturally exhibits characteristics of spiral flow [15].

Various documented benefits of this spiral flow pattern in the thoracic aorta including the flow stability in term of its direction in curved pathways, reducing lateral forces, decreasing turbulence near the vessel walls, lowering shear stress, and minimizing oscillating stress near the vessel walls. Additionally, there is a potential benefit in preventing the formation of atherosclerotic plaque [16][17]. Nevertheless, there remains uncertainty regarding which design is most effective at inducing spiral flow that closely mimics the physiological pattern. This investigation was undertaken to assess the innovative design proposed could passively induce spiral flow without compromising the effectiveness of the cannula by comparing the designs through numerical analysis with previous studies [18][19][20].

Professor Peter Stonebridge et al. introduced the concept of spiral flow in 1991 when they reported that, using angioscopy, 51 out of 75 infrainguinal arteries studied showed spiral-like flow. Very weak spiral folds were also found in normal and minimally diseased arteries [21]. Additionally, it is thought that blood flow spiral topologies might shield the artery wall from damage caused by a decrease in laterally directed stresses. Using multiple Doppler ultrasound, Stonebridge et al. conducted an in vivo study in 1996 to investigate biplanar arterial blood flow. They also noted the benefits of spiral laminar flow, including the potential to reduce turbulence in the tapering branching arterial tree and at stenos and to positively impact the mechanism of endothelial damage and repair [22].

Subsequently, Stonebridge et al. conducted a second study in 2004 to examine the impact of stenosis with spiral and without spiral flow patterns by applying the effect of magnetic resonance imaging. This came to the conclusion that, in comparison to non-spiral flow, spiral flow produced lower stresses acting on the vessel wall and greatly reduced the turbulence induced by stenosis [23]. At last, in 2012, a first-in-man medium-term outcome utilising a novel graft with spiral laminar flow inducing was published by Stonebridge et al. for patients in need of an infrainguinal bypass graft [24]. They produced a list of known spiral laminar flow-related hemorheological characteristics that may be advantageous. Therefore, the motivation of this paper is to establish the critical geometrical parameters of spiral aortic cannula configurations through parametric study and validation for further improvement.

2. MATERIALS AND METHOD

2.1 Computational and Numerical Modelling

The commercial software ANSYS CFX 14.0 (Canonsburg, PA, USA) was used to model the flow characteristics in cannulae. This solution works on a spatially rectangular computational mesh created in the Cartesian coordinate system, with the planes orthogonal to its axes, by applying a vertex-centered finite volume technique to the governing equations. Mass conservation and momentum conservation are the physical rules that explain the aorta and cannulation issue. The incompressible Navier-Stokes equation that follows controls the flow;

$$\nabla . \mathrm{u} = 0 \tag{1}$$

$$\rho\left(\frac{\delta u}{\delta t} + u.\nabla u - f\right) = \mu\nabla^2 u - \nabla p \tag{2}$$

The variable u is the flow vector, ρ represent the density of the fluid used in the flow, while p is the pressure and μ is the fluid viscosity. Several design elements were used in this investigation, such as spiral curved and spiral straight tip cannulas. SolidWorks was used to create eleven cannulae with various geometries, including the spiral curved tip cannula and spiral straight tip cannula seen in Figure 1. Table 1 tabulates each cannula's design geometry.


a) Straight tip cannula with spiral inducer
b) Curved tip cannula with spiral inducer
c) Spiral flow inducer

Figure 1. a) Straight tip cannula with spiral inducer; b) Curved tip cannula with spiral inducer; c) Spiral flow inducer

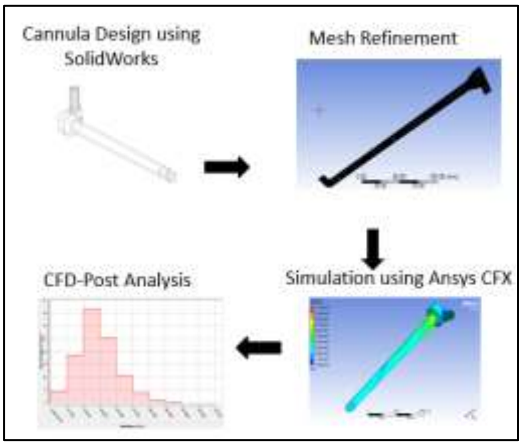

Figure 2. Graphical representation of the spiral flow aortic cannula simulation

Table 1 Geometry properties of spiral straight and curved tip cannula

Type of Cannula	Inducer Diameter Width (mm)	Inducer Diameter Tip (mm)
ST-Type 1	20	10
ST-Type 2	20	20
ST-Type 3	25	10
ST-Type 4	25	15
ST-Type 5	25	20
ST-Type 6	30	10
ST-Type 7	30	15
ST-Type 8	30	20
ST-Type 9	35	10
ST-Type 10	35	15
ST-Type 11	35	20
CT-Type 1	20	10
CT-Type 2	20	20
CT-Type 3	25	10
CT-Type 4	25	15
CT-Type 5	25	20
CT-Type 6	30	10
CT-Type 7	30	15
CT-Type 8	30	20
CT-Type 9	35	10
CT-Type 10	35	15
CT-Type 11	35	20

2.2 Boundary Condition

The ANSYS CFX was then used to import the drafted cannulae for simulation. Newtonian blood flow was simulated using a no-slip wall boundary condition that was rigid and impermeable, with constant hemodynamic values of density = 1056.4 kg/m3 and viscosity = 0.0036 Pa s [25]. 4.5L/min is the flow rate that is utilised. Within the CFX Software, the Navier-Stokes equation arising from this modelling is solved. Shear stress transfer (SST) served as the simulation's turbulence model. A grid independence test was conducted, and the results indicated that 3 million nodes was enough to conduct a numerical examination of the model that was well-balanced. With almost 3 million nodes for every design, the meshing process was finished, and computational simulation starte

2.3 Output Measurement

The hemodynamic output parameters have been obtained by using the boundary condition set. The velocity, shear strain rate, and wall shear stress are those haemodynamic parameters. More over 15 Pa of wall shear increases the risk of hemolysis and endothelial lesion [26]. At the end of a straight line that extended from the cannula tip to the aortic wall, the velocity was measured.

2.4 Validation of Numerical Simulation

The flow created by the aortic cannula model inside the simplified model was measured and visualised using a Particle Imaging Velocimetry (PIV) instrument for the purpose of numerical model validation. Due to its vast measuring range, non-intrusive nature, and ability to record instantaneous flow fields, PIV measurement is the most often used technique for flow visualisation on aortic cannula towards the aorta as well as validation purposes. The experiment was carried out at the Gifu College, National Institute of Technology (NIT), Motosu-city, Gifu, Japan.

The experimental loop was set up to forecast the cannula region's flow characteristics, and the findings are utilised to validate previously examined numerical results. Since silicone is a transparent material, the loop is constructed up of a silicone replica of an aortic cannula. A transparent model is required in order to use a PIV-charged coupling device (CCD) camera for particle tracking. Two centrifugal pumps are connected to the silicone cannula model at the model's primary pulmonary artery and aortic inlet. To monitor the flow rate of aqueous glycerol solution into the cannula model, each intake is connected to a single flow metre. To keep the flow rate into the model constant, the flow rate is manually adjusted using control valves. The reservoir tank received the aqueous glycerol solution that was combined with spherical particles straight from the outputs.

The fluid media in this experiment is an aqueous glycerol solution flowing steadily. In order to decrease the measurement error caused by refraction by the model and the aqueous solution, glycerol is employed and combined with water to modify the refraction index to match the model. The needed aqueous glycerol solution is made by mixing glycerol and water in a 3:1 ratio. Nevertheless, the mixture's high glycerol concentration caused it to have higher viscosity and density than blood. For flow tracking, 10 μm of silver-coated spherical particles were added as a seed to the solution.

A CCD camera capable of measuring up to 120,000 frames per second (FPS) at 640 by 480 resolution made up the PIV system. In order to produce a plane of measurement on the area, a 532 nm 1W laser connected with a slit is used to light the cannula region. With this configuration, the aqueous glycerol solution is combined with silver-coated spherical glass particles, and the movement of these particles is tracked to determine the measurement. Afterwards, the tracked particle movement is translated using the PIV system manufacturer's software (DITECT Flownizer) to get the flow velocity. In this study, the PIV experimental loop were set up as shown in Figure 3.

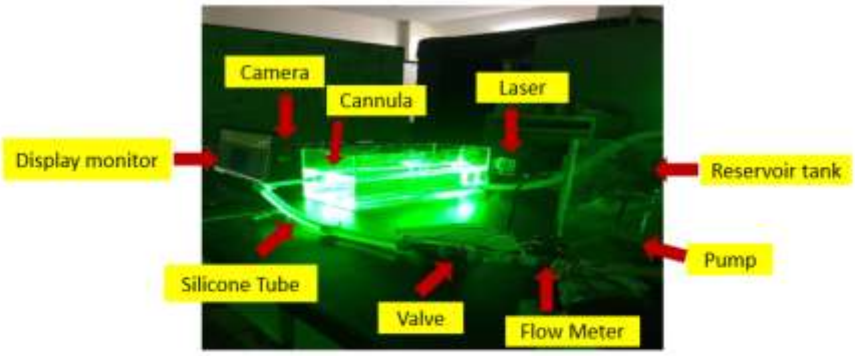

Figure 3. PIV experimental loop set up

3. RESULTS AND DISCUSSION

3.1 Velocity Profile Analysis

Figures 4 and 6 unveil a depiction of the average velocity within the spectrum of spiral flow cannulae, differentiating between the straight and curved tip configurations. Notably, the compilation of all spiral straight tip cannulas, ranging from ST-Type 1 to ST-Type 12, exhibits a uniform average velocity of 1.0498 ms-1. Amongst these, the champion of minimal velocity emerges as ST-Type 11, characterized by the gentlest flow at a velocity of 1.0828 ms-1, closely followed by ST-Type 10. On the other hand, in the domain of spiral curved tip cannulas, an intriguing pattern unfolds, as all cannulas collectively yield an average velocity profile of 1.0805 ms-1.

Yet, CT-Type 1 rises to the forefront, boasting a superior velocity distribution at an impressively restrained 0.8956 ms-1, with CT-Type 9 not far behind, recording a velocity value of 1.05216 ms-1. These findings corroborate the hypothesis that broader cannula widths contribute to a moderation in output velocity for the proposed spiral flow inducing cannulas. This reduced outflow velocity carries with potential to ameliorate the sandblasting effect exerted on the surrounding of the aorta, and may even mitigate the risk of blood damage in the process.

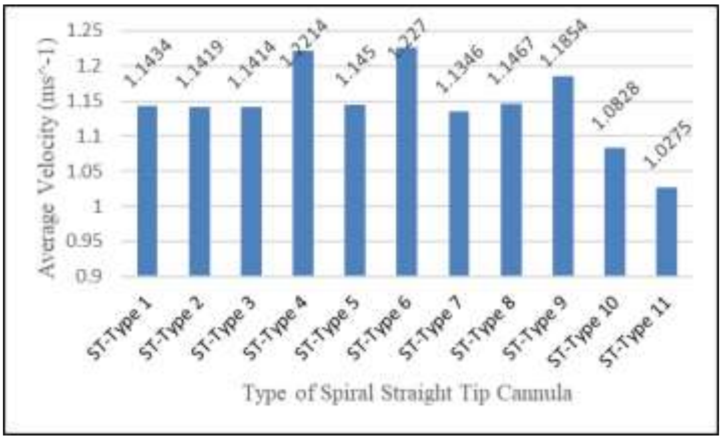

Figure 4. Average velocity of all spiral straight tip cannula

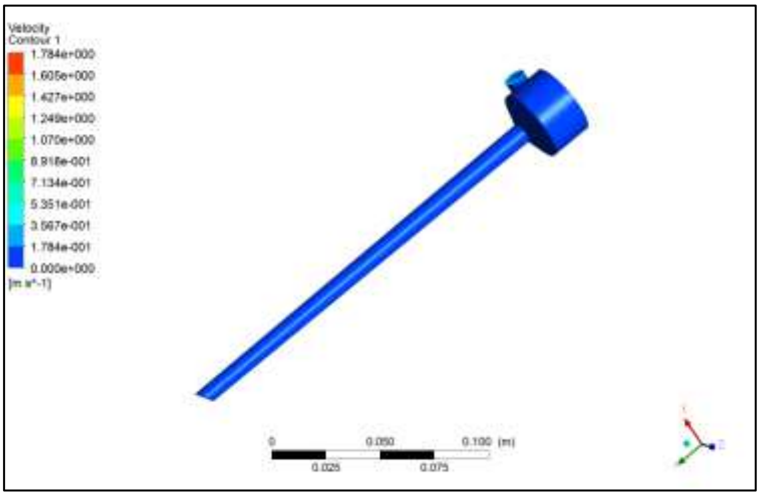

Figure 5. The best average velocity of spiral straight tip cannula, ST-Type 11

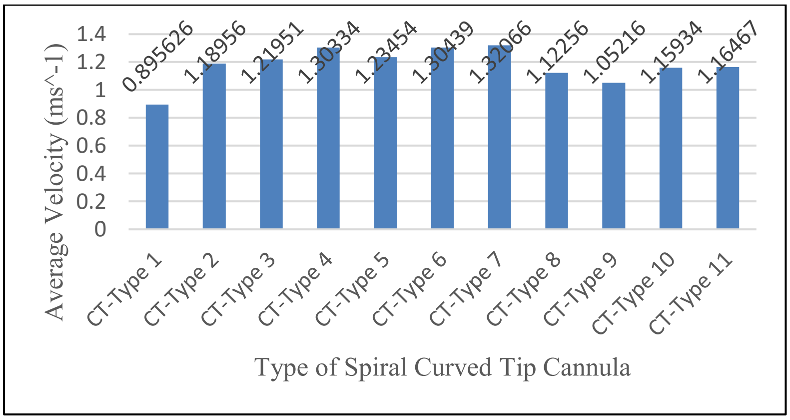

Figure 6. Average velocity of all spiral curved tip cannula

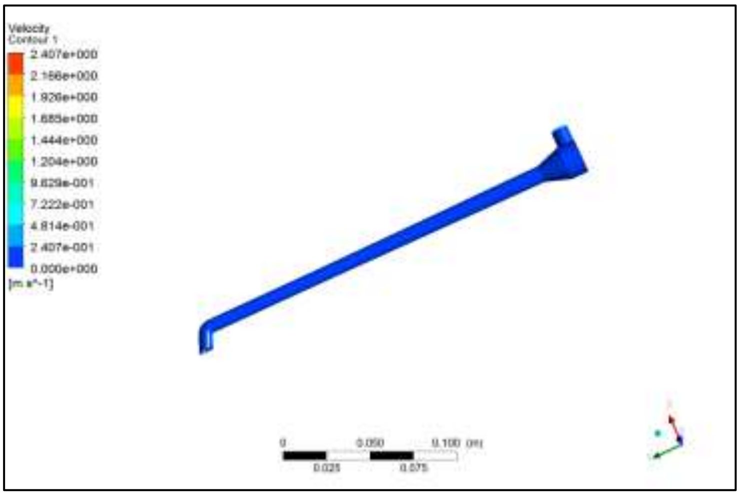

Figure 7. The best average velocity of spiral curved tip cannula, CT-Type 1

3.2 Wall Shear Stress Analysis

Figure 8 and 10 represents the average wall shear stress of all spiral flow cannula, the straight and curved tip respectively. The average wall shear stress of all spiral straight tip cannula ST-Type 1 to ST-Type 12 is 10.2045 Pa. The ST-Type 11 shows the lowest wall shear stress, 9.6592 Pa followed by the ST-Type 10 with the wall shear stress of 10.1876 Pa. While, for the spiral curved tip cannula, the average wall shear stress of all the cannula was 11.6020 Pa. For the curved tip cannula, the CT-Type 9 yield the best wall shear stress distribution with 11.1582 Pa followed by CT-Type 11 with its wall shear stress value of 11.6124 Pa. Estimating the wall shear stress is a typical technique used to forecast how well medical devices would function in relation to vascular walls. The direction of blood flow from the cannula in relation to the vascular wall and its orientation have a significant impact on WSS measurements [1]. Since the simplified model is merely a straightforward tube, evaluating a large number of alternatives requires a high priority for outflow velocity. These outcomes underscore the concept that cannulas with a broader width profile potentially cultivate superior wall shear stress characteristics. Such refined performance could potentially pave the way for minimizing the abrasive 'sandblasting effect' on the aorta wall and contribute to a more blood-friendly environment.

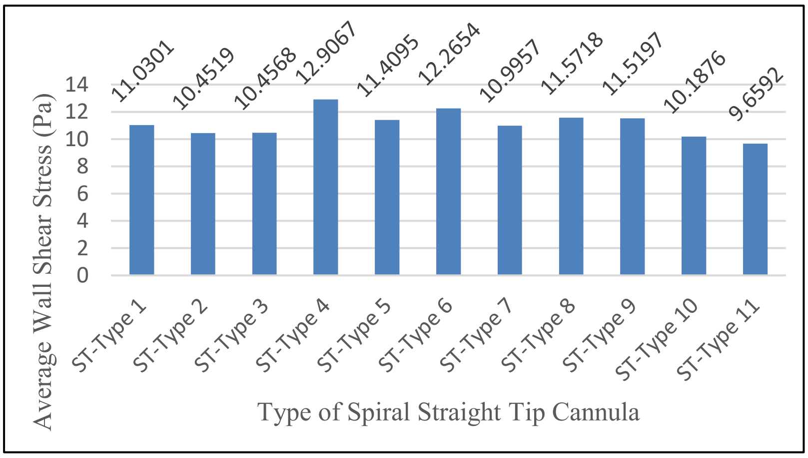

Figure 8. Average wall shear stress of all spiral straight tip cannula

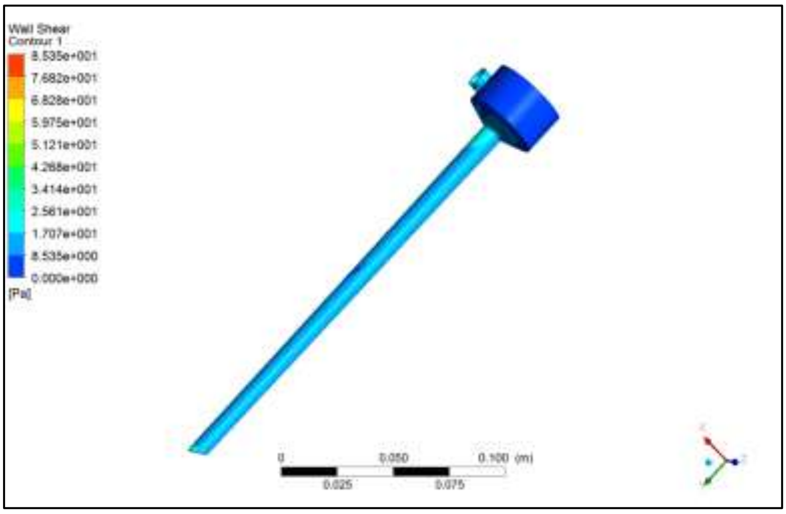

Figure 9. The best average wall shear stress of spiral straight tip cannula, ST-Type 11

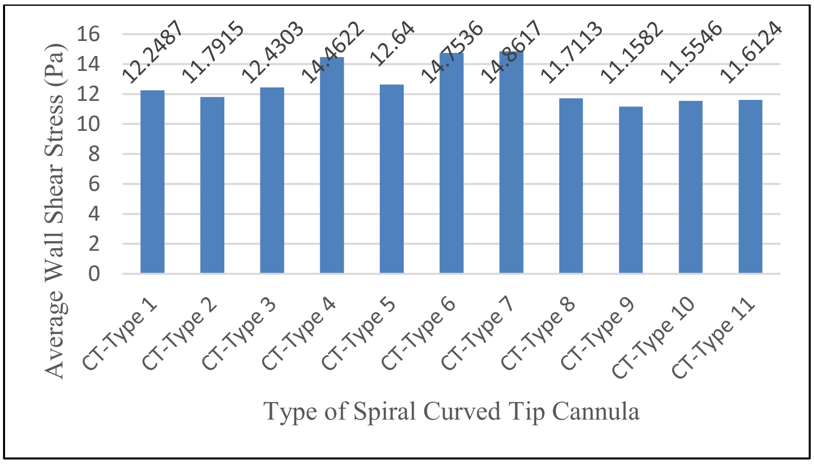

Figure 10. Average wall shear stress of all spiral curved tip cannula

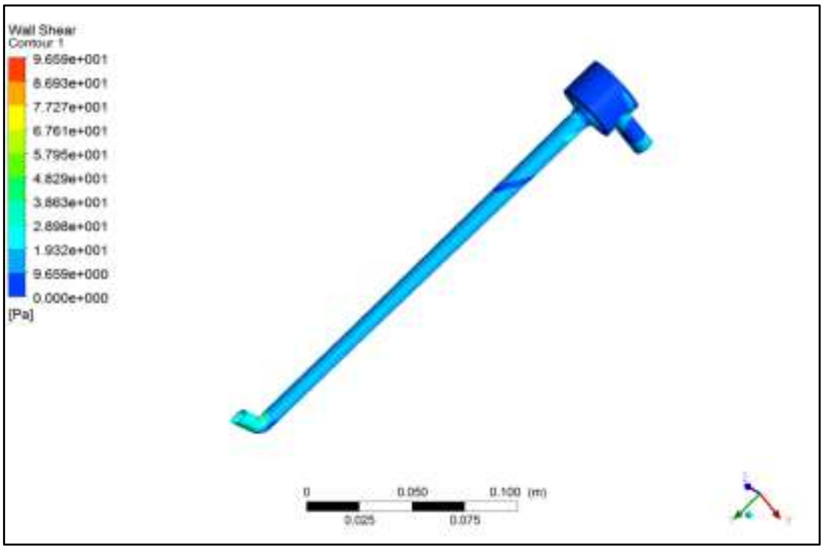

Figure 11. The best average wall shear stress of spiral curved tip cannula, CT-Type

3.3 Particle Image Velocimetry (PIV) Analysis

The numerical result has been validated by experimental investigation utilising PIV. As seen in Figure 12, Figure 13, Figure 14 and Figure 15, flow velocity at the cannula's cross-sectional area is measured at four distinct planes, namely plane 1 (inlet part), plane 2 (front part), plane 3 (middle part) and plane 4 (outlet part). The numerical modelling result shows comparable flow behaviour, with a recirculating zone of flow detected close to the cannula wall. At plane 1, the average velocity vector was 0.2025 ms-1, while at plane 2, 0.2119 ms-1 was observed. The velocity vector at plane 3 and plane 4 was 0.9771 ms-1 and 0.4821 ms-1. The average velocity of all the plane yielded 0.9368 ms-1. As illustrated, the flow velocity over the cannula in numerical modelling is, however, somewhat underestimated in comparison to the actual findings, yet it can be clearly seen that the average velocity vector for all the planes shows only little difference on the velocity vector yielded comparing to numerical output.

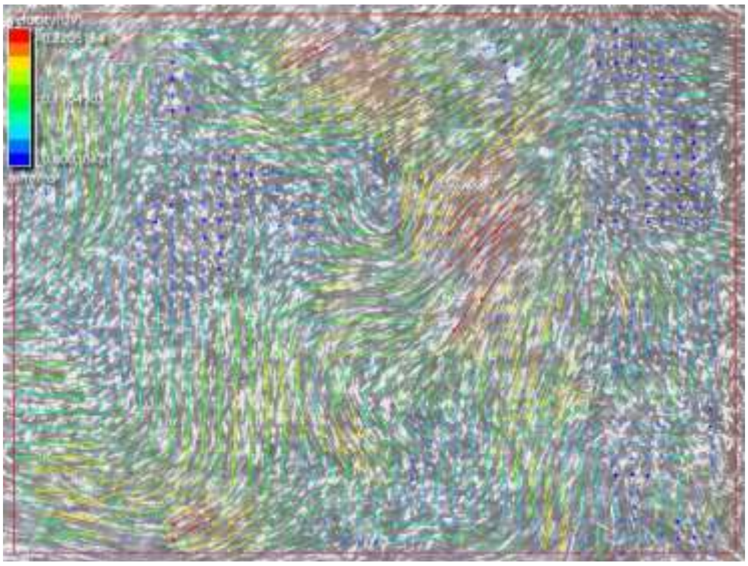

Figure 12. Contour plot of flow behaviour in cannula at Plane 1

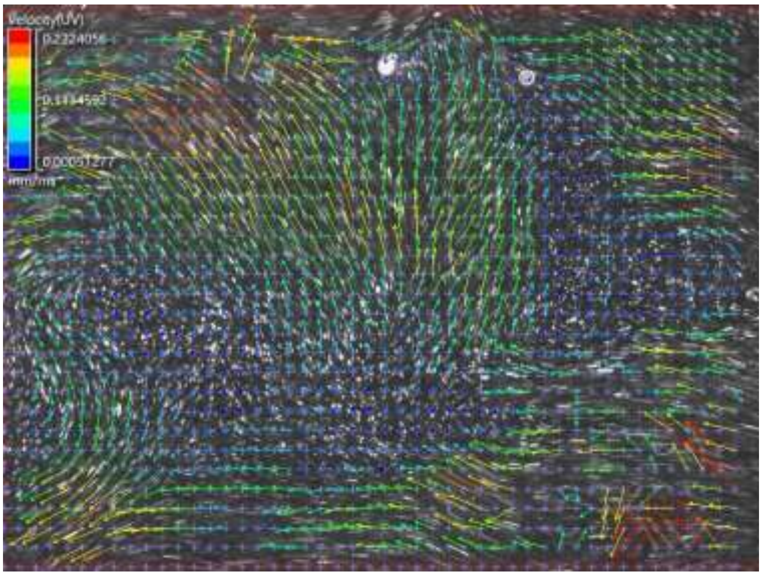

Figure 13. Contour plot of flow behaviour in cannula at Plane 2

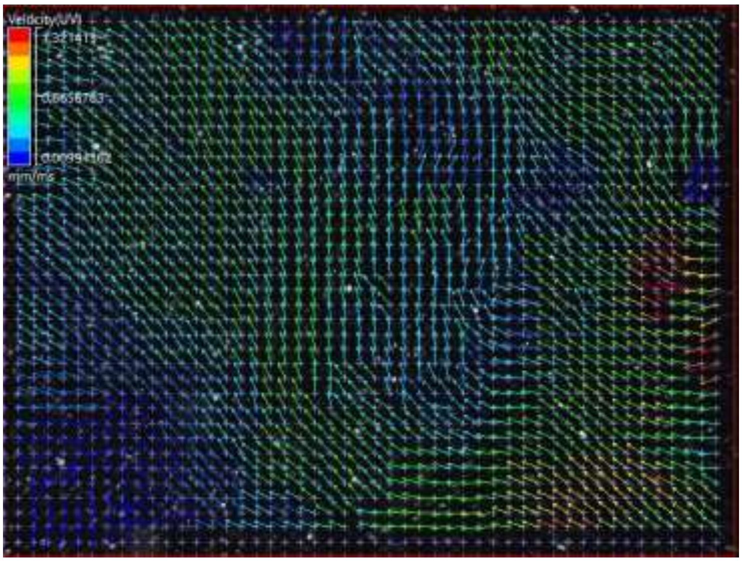

Figure 14. Contour plot of flow behaviour in cannula at Plane 3

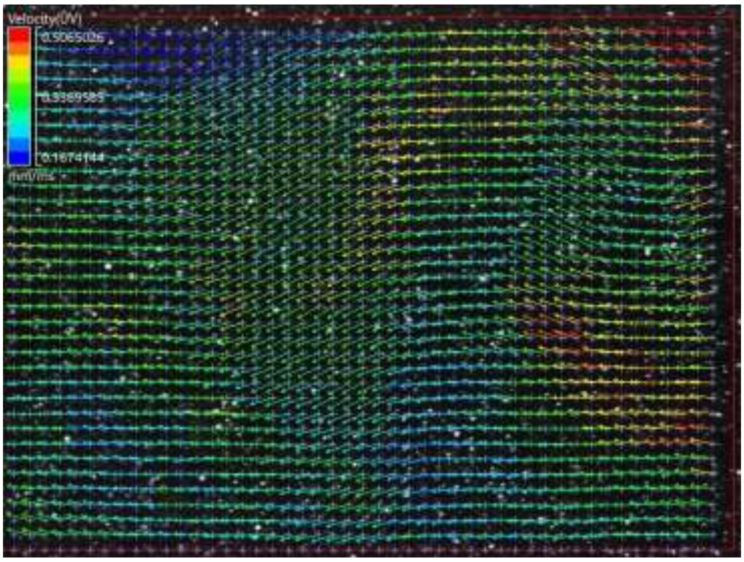

Figure 15. Contour plot of flow behaviour in cannula at Plane 4

4. CONCLUSION

This research project embarked on a journey of design and innovation, commencing with the creation of a spiral straight and curved tip cannula as the baseline, and subsequently developing 11 distinct variants by making adjustments to the width and inlet chamber angle through the use of commercial CAD software. Each of these models underwent a comprehensive numerical evaluation facilitated by a cutting-edge commercial CFD software package. The performance assessment of these cannula variants hinged on vital hemodynamic outputs, velocity profile and wall shear stress. An intricate design selection method was systematically applied to determine the most optimal cannula design, ultimately leading to the selection of the finest proposed cannula, one equipped with an inlet spiral inducer. In this context, two models, namely ST-Type 11 and CT-Type 1, outshone the rest, showcasing the most favourable velocity profiles at 1.0275 ms-1 and 0.8956 ms-1, for the straight and curved tip cannula. Moreover, when evaluating wall shear stress performance, the ST-Type 11 and CT-Type 9 variants displayed the most significant values, measuring at 9.6592 Pa and 11.1582 Pa, surpassing other cannula configurations.

The findings suggest that cannulae designed to generate spiral flow are put forth as better options, given their capacity to reduce outflow speed. The wall shear stress readings in all cannulae are modest, which reduces the likelihood that atherogenesis would emerge. In conclusion, spiral flow outperforms normal flow in terms of velocity profile across all cannulae variants.

ACKNOWLEDGEMENTS

This work was supported by the Ministry of Higher Education Malaysia and by extension Universiti Teknologi Malaysia Internal Tier 1 Grant Scheme the with grant number [Grant no: Q.J130000.2509.19H19]. The authors would like to thank the members of Biofluid Lab and Ergonomic Lab, Department of Biomedical Engineering and Health Sciences, Faculty of Electrical Engineering, Universiti Teknologi Malaysia for technical support in completing this research.

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