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FLOW CHARACTERISTICS OF BIFURCATED CAROTID ARTERY AT DIFFERENT PHYSIOLOGICAL CONDITIONS

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ABSTRACT

The carotid artery had been studied as one of the common sites of stenosis occurrences due to its bifurcated morphology. It has been reported to influence arterial haemodynamic flow patterns which could lead to the development of regions prone to stenosis. Stenosis development in the bifurcated carotid artery might be asymptomatic but in severe cases may lead to serious ischemic events causing a higher rate of morbidity and mortality in patients. With the use of computational fluid dynamic (CFD) investigation, this study aims to examine the hemodynamic characteristics of the bifurcated carotid artery. This study focuses on the velocity and wall shear stress (WSS) distribution at both the systolic and diastolic phases. The study is done using a simplified model of a bifurcated carotid artery under two different physiological conditions; normal blood pressure (NBP) and high blood pressure (HBP). Based on the observation, the bifurcation of the carotid artery leads to the formation of turbulence flow which increases the low WSS distribution promoting regions susceptible to atherosclerotic plaque formation. HBP showed a greater low WSS distribution compared to NBP condition hence, a higher risk for stenosis development.

KEYWORD

Hemodynamic, bifurcated carotid artery, computational fluid dynamic (CFD), stenosis

INTRODUCTION

Carotid artery stenosis can be defined as a progressive narrowing of the carotid artery due to atherosclerosis. It is characterized by local thickening of the interior arterial wall. Carotid artery disease was responsible for 10 to 20% of stroke cases. Thus effective intervention is critical to avert primary and secondary stroke incidents. According to Phan et al. (2012), the carotid artery is considered one of the preferential sites where atherosclerotic plaques would form hence leading to the formation of stenosis. The development of atherosclerotic plaques that causes stenosis is influenced by vascular fluid dynamics (Phan et al., 2012).

In a study done by Woo et al. (2017), hypertension was accounted to be one of the highest risk factors of carotid artery stenosis, which 48.6% for males and 51.3% for females. This was compared with other risk factors, including diabetes mellitus, hyperlipidemia, and smoking. Studies done showed hypertension as a vital factor in stenosis progression by focusing on the affiliation between carotid intima-media thickening (c-IMT) with systolic (SBP) and diastolic blood pressure (DBP) (Woo et al., 2017).

This study drives to utilized CFD simulation on 3D simplified model in order to investigate the hemodynamic characteristics in the bifurcated artery. Through the application of CFD, haemodynamic parameters are employed as markers for identifying plaque progression regions. Low velocity of blood flow in the artery contributed to a low WSS which further assists in atherosclerotic wall thickenings along with the proliferative degeneration modification. The correlation of blood flow velocity with WSS distribution showed that velocity and WSS is a reasonable parameter to be observed as a predictor of stenosis occurrence. The simulation was done with different physiological conditions; NBP and HBP.

METHODOLOGY

A simplified model of a bifurcated carotid artery was designed using ~~a~~ CAD software (Solidworks 2018) and was reviewed based on previous studies by Datta and Rakesh (2010). The model was designed with a 60 mm CCA inlet, 4.4 mm internal carotid artery (ICA) inlet and 3.6 mm external carotid artery (ECA) inlet.

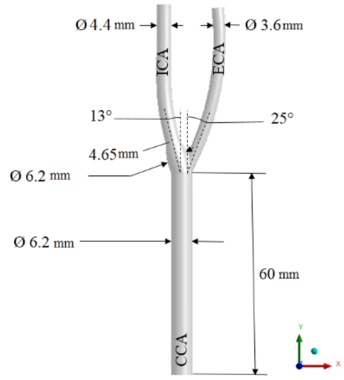


Figure 1: Simplified model of the bifurcated carotid artery.

In this study, the simulated blood was considered to be incompressible Newtonian fluid with blood density (ρ) of 1060 kg/m3 and viscosity (μ) of 0.0035 Pa s (Saufi et al, 2023). No-slip boundary condition was imposed along the rigid carotid arterial wall. The blood flow velocity inlet was taken in a study by Azhim et al (2013) with the highest velocity magnitude during the peak-systolic phase (0.36 s), and the lowest velocity magnitude was at the end-diastolic phase (0.27 s) for both NBP and HBP conditions.

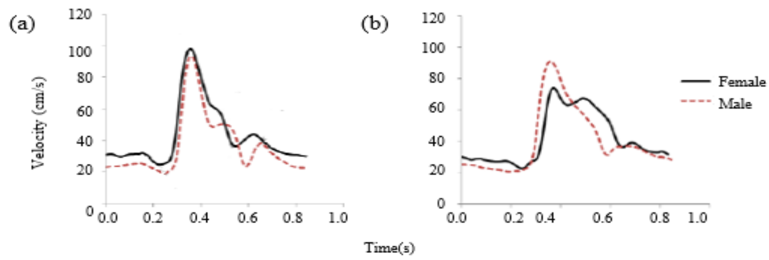


Figure 2: Velocity waveform a) NBP b) HBP.

The simulations were computed in ANSYS Fluent to solve the Navier-Stokes and continuity equation. The equation for an incompressible Newtonian fluid with constant viscosity and the continuity equation applied to constant density would be as written in Equation 1 and 2.

$$\rho \frac{Dv}{Dt} = -\nabla p + \mu \nabla^2 v + \rho g \quad \text{(Eq. 1)}$$

$$\rho \nabla \cdot \vec{v} = 0 \quad \text{(Eq. 2)}$$

RESULT AND DISCUSSION

A study conducted by Paisal et al. (2018) was used to verify the numerical simulation of the present study. The mean velocity profile data was taken along the diameter of the CCA inlet and used for comparison. The verification process was required to determine whether the carotid artery model set-up implementation using the software accurately generated a solution of the haemodynamic in the carotid artery. The current numerical simulation configuration was deemed adequate as the average relative error between the numerical simulations demonstrated merely a minor difference of 6.43%.

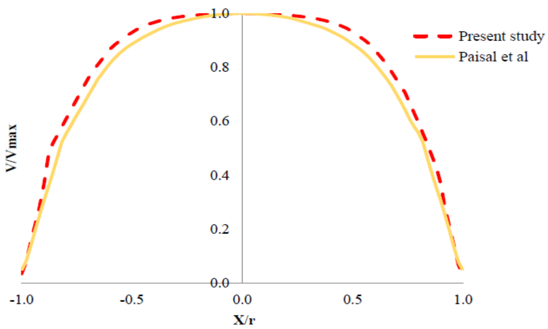
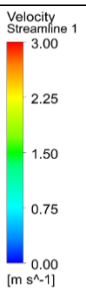
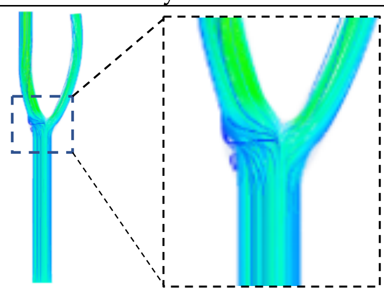
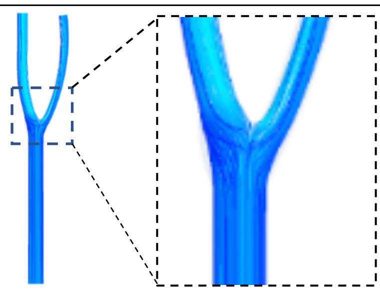
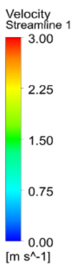
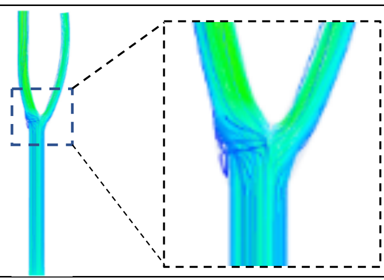
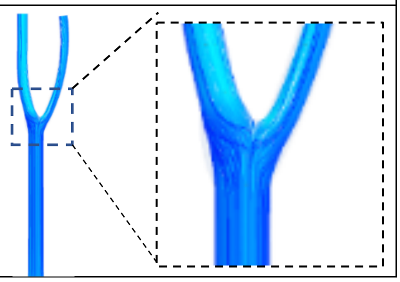


Figure 3: Inlet means velocity profile of the present study and Paisal et al. (2018).

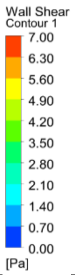
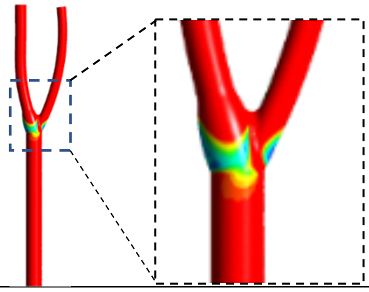
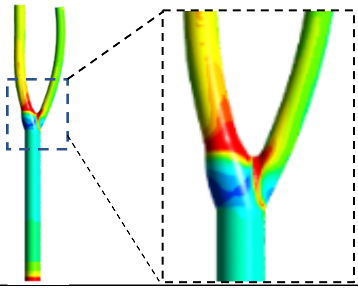
The result shown in table 1 demonstrated the velocity distribution at both the systolic and diastolic phases under physiological conditions of NBP and HBP. The blood in the body generally displayed a laminar flow. Nevertheless, the transition from laminar to turbulent flow appears as a result of the bifurcation. At the peak velocity magnitude of the systolic phase, helical movement or swirling motion was observed at the point of bifurcation near the carotid artery sinus. A reduction in blood flow has been seen in these areas with ~~a~~ such swirling motion. Besides, the turbulent flow becomes less erratic as it passes through the bifurcated region and flows distally to the ECA and ICA. At the diastolic phase, such turbulence flow was not prominent due to the low velocity. The HBP condition demonstrated a slightly greater swirling movement as compared to the NBP condition.

Table 1: Velocity distribution in bifurcated carotid artery.

		Systolic	Diastolic
Normal blood pressure			
High Blood pressure			

From the observation in Table 2, high WSS distribution was shown throughout the bifurcated carotid artery of the systolic phase at both NBP and HBP conditions. In comparison to the diastolic phase, high WSS distribution was more prominent at the point of bifurcation and along the inner wall of ICA. Under NBP and HBP conditions of both phases, low WSS distribution was mainly concentrated at the sinus of the carotid artery. Yet, the HBP condition exhibited a much greater low WSS distribution compared to NBP at both cardiac phases. A High WSS value higher than 7 Pa shown at the point of carotid bifurcation has been associated with an increased risk for arterial injury and leads to high shear thrombosis formation. A Low WSS value of less than 1 Pa and slower movement of blood flow regions exhibited at the sinus region provided apt conditions for the build of atherosclerotic plaque.

Table 2: Wall shear stress (WSS) distribution in bifurcated carotid artery.

<table>
<tr><th></th><th>Systolic</th><th>Diastolic</th></tr>
<tr><td>Normal blood pressure
</td><td></td><td></td></tr>
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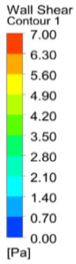
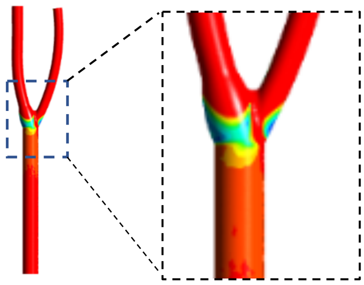
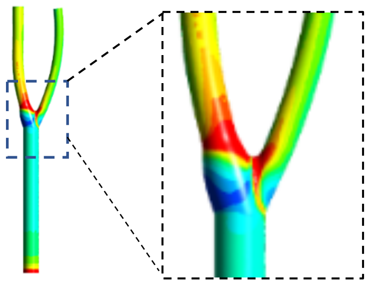
</td><td></td><td></td></tr>
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CONCLUSION

The bifurcation exhibited by the carotid artery has been recognized to affect blood flow behaviour. The turbulence formation due to the bifurcation of the carotid artery increases the low WSS distribution which promotes regions susceptible to atherosclerotic plaques development. Flow characteristics such as velocity and WSS used in this simulation has great significance in predicting atherosclerotic plaque prone regions in the carotid artery. The result obtained showed that the increase in blood flow velocity corresponds to the increase in WSS distribution. The result also confirmed that the HBP condition has shown a more favourable state for the formation of thrombosis and is determined as a critical risk factor for carotid artery stenosis development.

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