ANALYSIS OF HEMODYNAMIC EFFECT ON DIFFERENT STENT STRUT CONFIGURATION OF PHYSICAL AND PHYSIOLOGICAL CONDITION IN FEMORAL POPLITEAL ARTERY

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I dedicate this thesis to my beloved emak, ayah, kakyum, abang ewan, kak zureen, umar and not to be forgotten, this thesis is also dedicated to my handsome supervisors, Ts Dr Ishkrizat bin Taib

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ABSTRACT

Peripheral arterial disease (PAD) is a narrowing of the peripheral arteries that might result in blockage if not immediately treated. Normally, an invasive technique called stenting is used at the stenosed arterial region to restore normal blood flow. However, it promotes the formation of thrombosis on the stented artery due to the presenting flow recirculation. However, the rate of thrombosis growth was reported to be different for both genders. This is due to an increase in body surface area, body mass index, and weight of the body. Furthermore, different vascular regions have presented different flow characteristics that highly depend on the vascular physical condition. Thus, this study aims to investigate the effect of the physiological and physical conditions of men and women with different hemodynamic parameters on the strut configuration in femoral popliteal artery. Five different stent strut configurations were modelled and inserted into the femoral popliteal artery. The computational fluid dynamic (CFD) method was implemented to solve the continuity and Nevier Stokes equations. The hemodynamic performance of the stent was analysed based on hemodynamic parameters consisting of time-averaged wall shear stress (TAWSS), time-averaged wall shear stress gradient (TAWSSG), oscillatory shear index (OSI), and relative residence time (RRT). According to the observations, the distal region of the stented femoral popliteal artery had more dominant flow re-circulation than the proximal region. The high void area contributed to less growth of the thrombosis. The pictorial selection method was used to evaluate the best hemodynamic stent performance based on a scoring system. In all cases, Type I stents showed the best hemodynamic parameter performance over the other stented femoral popliteal artery with an average score of 4.14, followed by Type III, Type V, Type II, and Type IV with an average score of 3.47, 3.10, 2.97, and 1.31, respectively.

ABSTRAK

Penyakit arteri periferal (PAD) ialah penyempitan arteri periferi yang mungkin tersumbat jika tidak dirawat dengan segera. Biasanya, teknik invasif melalui stent dilaksanakan di kawasan arteri stenose untuk memulihkan aliran darah kembali normal. Keadaan ini boleh menggalakkan pembentukan trombosis pada arteri stented disebabkan oleh peredaran semula aliran yang ditunjukkan. Walau bagaimanapun, kadar pertumbuhan trombosis dilaporkan berbeza untuk kedua-dua jantina; lelaki dan wanita. Ini disebabkan oleh peningkatan luas permukaan badan, indeks jisim badan, dan berat badan. Oleh itu, kajian ini bertujuan untuk menyiasat kesan keadaan fisiologi dan fizikal lelaki dan wanita dengan parameter hemodinamik yang berbeza terhadap konfigurasi tupang dalam *femoral popliteal artery*. Lima konfigurasi tupang stent berbeza telah dimodelkan dan dimasukkan ke dalam *femoral popliteal artery*. Kaedah dinamik bendalir pengiraan (CFD) telah dilaksanakan untuk menyelesaikan persamaan kesinambungan dan N-S. Prestasi hemodinamik stent dianalisis berdasarkan parameter hemodinamik yang terdiri daripada tegasan ricih dinding purata masa (TAWSS), kecerunan tegasan ricih dinding purata masa (TAWSSG), indeks ricih berayun (OSI) dan masa tinggal relatif (RRT). Daripada pemerhatian, kawasan distal FPA stent menunjukkan peredaran semula aliran dominan berbanding dengan kawasan proksimal. Kawasan lompang yang tinggi menyumbang pertumbuhan trombosis yang lebih rendah. Kaedah pemilihan bergambar digunakan untuk menilai prestasi stent hemodinamik terbaik berdasarkan sistem pemarkahan. Dalam semua kes, stent Jenis I menunjukkan bahawa prestasi parameter hemodinamik terbaik berbanding yang lain stent FPA dengan skor purata 4.14 diikuti oleh Jenis III, Jenis V, Jenis II dan Jenis IV dengan skor masing-masing 3.47, 3.10, 2.97 dan 1.31. Akhirnya, prestasi terbaik stent telah dikira untuk stent Jenis 1 yang meramalkan untuk mengurangkan pertumbuhan trombosis kira-kira 50 peratus berbanding dengan yang lain.

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LIST OF SYMBOLS AND ABBREVIATIONS

E_d	-	End-diastolic
D	-	Diameter
P_d	-	Peak-diastolic
i_1	-	First incisura
Ne	-	Normalised relative error
Rt	-	Rating
S_j	-	Weighted score summation
S_1	-	Peak-systolic
w	-	Weightage
FPA	-	Femoral Popliteal artery
φ_{perc}	-	Area distribution percentage of haemodynamic parameter
φ_{ref}	-	Reference area distribution percentage of haemodynamic parameter
PAD	-	Peripheral arterial disease
TAWSS	-	Time average wall shear stress
∇	-	Vector differential operator
CAD	-	Computer-aided design
CFD	-	Computational Fluid Dynamic
TAWSSG	-	Time average wall shear stress gradient
OSI	-	Oscillatory shear index
RRT	-	Relative residence time
NBP	-	Normal blood pressure
DBP	-	Diastolic Blood pressure

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

The restriction of blood flow in the femoral popliteal artery (FPA) will cause severe disease in patients known as peripheral artery disease (PAD). Peripheral artery disease is intimately related to chronic inflammatory processes resulting in the formation of lipid plaques or stenosis within arterial walls [1]. The standard treatment of arterial stenosis is by stenting, which effectively props open the artery and thereby restores blood flow in the diseased vessel [2]. However, in the first month after stent implantation, the restenosis or re-blockage in the artery has already occurred due to atherosclerosis and the growth of thrombosis [3]. Atherosclerosis is the hardening of the arterial wall caused by a build-up of fatty material, while thrombosis is the formation of a blood clot within the lining of an artery, especially in a stented artery. This abnormality of blood movement makes the fatty materials deposit near the stent strut configuration. An arterial injury causes the arterial wall to undergo an episodic process of thrombus formation, arterial inflammation, neointimal hyperplasia, and stent remodelling [4].

A previous study found that a different strut arrangement accelerated atherosclerosis and thrombosis development significantly. The considerable advancement is owing to the fact that each stent has its own strut configuration, which presents variable flow characteristics near the strut [5]. Thus, the significant progress allows the hemodynamic performance of the stent to be predicted. However, Nordstrom *et al* (2008) [6] mentioned that, the rate of thrombosis was different between men and women due to increased body surface area, body mass index, and weight for men than women. Furthermore, different vascular regions have presented different flow characteristics that highly depend on the vascular physical condition [7]. Hence, this study was aimed at determining the flow phenomenon near the geometrical pattern of the stent strut configuration to predict the thrombosis growth for different genders and physiological conditions.

The flow process of this research was divided into two sections; simulation and evaluation procedures. In simulation, the simplified geometry of the femoral popliteal artery was developed using computer-aided design (CAD) software to predict the hemodynamic effects of the different stent strut configurations. The computational fluid dynamic (CFD) method was implemented in the modelling to predict the flow behavior by solving the continuity and Navier-Stoke equations. The computed tomography method could predict the potential risk of restenosis and wall shear stress distribution in stented arteries [8]. In the second process, this study proposed a detailed analysis and assessment to predict the favorable hemodynamic stent performances among the stents by comparing the hemodynamic variable effects on five different types of commercial stent strut configurations. The hemodynamic variables considered were time-averaged wall shear stress (TAWSS), time-averaged wall shear stress gradient (TAWSSG), oscillating shear index (OSI), and relative residence time (RRT). The stent performance evaluation known as the Stent Pictorial Selection Method was used, adapted from the Concept Selection Method by Ulrich *et al* (2003) [9] which originally evaluates the concept design of a product. Four different evaluation processes were applied in the selection method, consisting of screening, rating, weighting, and scoring processes. The evaluation method is able to detect the best stent strut configuration with the lowest score of restenosis development.

1.2 Problem Statement

Over the past decades, endovascular technologies have been evolving rapidly, and innovative revascularization strategies such as stenting have been proposed for peripheral artery disease (PAD) [10]. However, it is still debatable about the suitable design of stent strut configuration due to the restenosis effect after the stenting procedure. Previous clinical studies have shown that the incidence of restenosis after stenting varies with stent design and deployment configuration. Differences in stent design contribute to disparity in wall shear stress distribution as the presence of stent struts in the arterial wall creates local flow disturbances between the strut edges protruding into the lumen [11]. The increase in the rate of restenosis a few months after stent implantation caused the severity of the disease to increase as well as diverge the blood from the main direction of the flow. This phenomenon may promote the formation of thrombosis on the stented artery due to the presence of flow recirculation. Nordstrom *et al* (2008) [6] mentioned that the rate of thrombosis was different between men and women due to increased body surface area, body mass index, and weight for men than women.

Furthermore, different vascular regions have presented different flow characteristics that highly depend on the vascular physical [5,6]. Additionally, based on previous studies, the haemodynamic parameters have a specific threshold or range of values to indicate the activity of atherosclerosis and thrombosis that reflect the restenosis development [12,13,14,15,16,17]. Different critical hemodynamic parameters affect the different flow characteristics due to the variety of stent strut configurations in the femoral popliteal artery. Thus, the evaluation of restenosis development induced by the flow recirculation due to the misaligned direction of blood flow for different genders and physiological conditions is identified as the main issue in the present study.

1.3 Objective

i. To determine the hemodynamic effect on different stent strut configurations in femoral popliteal artery during the physical and physiological conditions for men and women.
ii. To analyze critical hemodynamic parameters affecting the flow characteristic due to different stent strut configurations in femoral popliteal artery
iii. To evaluate the stent performance due to the hemodynamic effect on different stent strut configurations in the femoral popliteal artery

1.4 Scope of study

i. The conditions involved are physical condition and physiological condition for normal blood pressure (NBP) state were involved.
ii. Five different strut configuration open type cell stent which have larger gaps uncovered were considered.
iii. A simplified model of femoral popliteal artery was studied.
iv. A stent strut configuration was implanted in the interior of a vessel of femoral popliteal artery
v. The computational fluid dynamic (CFD) method was considered in this study.

1.5 Significance of study

Stents are deployed to physically reopen stenotic regions of arteries and to restore blood flow [18]. However, different stent strut configurations contribute to different blood characteristics that lead to stent thrombosis and atherosclerosis. The growth of thrombosis and atherosclerosis can be predicted through the flow recirculation at the stent strut configuration in femoral popliteal artery [19]. Nevertheless, the rate of thrombosis was different between men and women due to increased body surface area, body mass index, and weight for men than women [6]. Besides, the physical condition also contributes towards the flow recirculation of the stent [7]. The flow recirculation varies according to the geometrical patterns of stent strut configuration with different physical conditions. Thus, the specific geometry of strut configuration was numerically studied to present hemodynamic stent performance. The analyzed hemodynamic performances of stents are able to elucidate strut configuration with a low possibility of restenosis activity of atherosclerosis and thrombosis due to flow behavior in the femoral popliteal artery [5]. This analysis can be achieved by applying an evaluation system that is implemented specifically for stent strut configuration. Thus, this study is able to assist the medical practitioner for choosing the best stent strut configuration for the physiological condition of both genders and physical condition.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Advances in stent technology have improved the safety and efficacy of stent devices. Despite these advances, restenosis and device thrombosis remain a major concern and are still affecting long-term clinical outcomes [20]. Flow recirculation and flow disturbances have been shown to increase the risk of thrombosis. Thus, a study about the prediction of the growth of thrombosis by analysing the flow characteristic was reviewed based on previous work. The parameter considered were OSI, RRT, $TAWSS_{low}$, $TAWSS_{high}$, $TAWSS_{normal}$ and TAWSSG.

This hemodynamic variable was identified to predict the formation of thrombosis, which would contribute to the performance of several stent configurations. In addition, understanding hemodynamic effect due to different gender was focused as well in obtaining the knowledge and ideas for this current study. This is due to the fact that height, weight, BMI and whole blood were different in men than in women. Besides, men and women are also thought to significantly differ at the cellular and molecular levels, with gender differences reported in platelet function and coagulation factor activities [2,22,23]. In addition, throughout this study, the physical condition also be considered. This is due to healthy adults do not exhibit local variations of wall shear stress in the Superficial Femoral artery at rest, but segmental differences in wall shear stress occur after exercise [7].

2.2 Effect of exercise on hemodynamic in FPA

In 2011 Schlager *et al* [7] conducted in vivo study on wall shear stress in the superficial femoral artery of healthy adults and its response to postural changes and exercise. The purpose of this study was to investigate the profile of peak wall shear stress and mean wall shear stress along the FPA axis in healthy adults at rest. Following postural changes after exercise in order to identify segmental variations of wall shear stress that might contribute to the typical distribution of atherosclerotic lesions later in life. After exercise, peak and mean wall shear stress increased in all segments. The researcher concluded that healthy adults do not exhibit local variations of wall shear stress in the Superficial Femoral artery at rest, but segmental differences in wall shear stress occur after exercise as shown in Table 2.1.

Table 2.1: Peak systolic velocity (PSV) in the superficial femoral and popliteal artery in healthy subjects [7]

	AT REST	AFTER EXERCISE	P-VALUE
Proximal SFA	0.88 (0.76-0.97)	1.38(1.24-1.66)	<0.0001
Proximal Hunter's canal	0.90(0.82-1.05)	1.37(1.19-1.55)	<0.0001
Distal Hunter's canal	0.91(0.76-1.07)	1.369(1.17-1.49)	<0.0001
Popliteal artery	0.890(0.74-1.03)	1.65(1.31-1.83)	<0.0001
Proximal Hunter's canal	0.70(0.63-0.82)	1.34(1.10-1.59)	<0.0001

The force that flowing blood exerts on the vessel wall, has emerged as a local risk factor being involved in atherogenesis and arterial remodelling**.** Wall shear stress is determined by flow velocity and whole blood viscosity and is inversely related to the vessel diameter [22]. Recent studies have found that peak wall shear stress and mean wall shear stress vary depending on location and exercise workload. In addition, peak systolic velocity was higher in females than in males in the popliteal artery after exercise. This is due to the different height, weight, BMI, whole blood viscosity, haematocrit, haemoglobin and red blood cell count were higher in men than in women [7]. Thus, the difference formation of stenosis for gender deserve further discussion.

2.3 Stenosis of man and women in FPA

Atherosclerosis is a term that refers to the thickening and hardening of arteries, which can result in diminished and restricted blood flow over time. Simply put, arterial thickening develops as a result of the accumulation of plaque in the intima of the arterial wall, which gradually expands, hence narrowing the arterial lumen. Plaques can burst into the lumen in advanced cases, resulting in thrombosis, blood clot formation, occlusion of the artery, and restriction of blood flow [4]. As illustrated in Figure 2.1, the age and gender adjusted risk factors for PAD are comparable to the classic risk factors for atherosclerosis, including cigarette smoking, diabetes, hyperlipidaemia, hypertension, hyperhomocysteinemia, and chronic renal insufficiency.

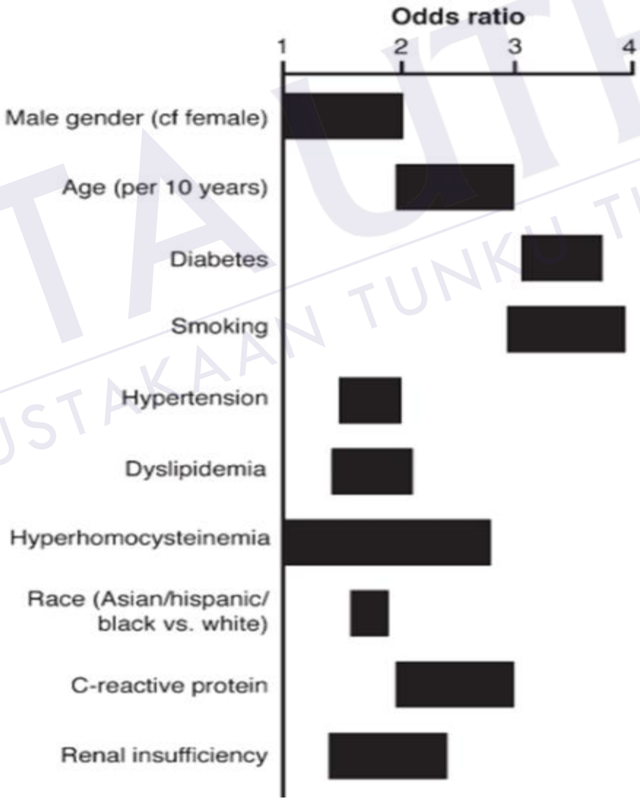

Figure 2.1: Approximate range of odds ratios for risk factors for symptomatic peripheral arterial disease [25]

REFERENCES

1. Bentzon, J. F., Otsuka, F., Virmani, R., & Falk, E. (2014). Mechanisms of plaque formation and rupture. *Circulation Research*, *114*(12), pp. 1852–1866.
2. Chen, X., Assadsangabi, B., Hsiang, Y., & Takahata, K. (2018). Enabling angioplasty-ready "Smart" Stents to detect in-stent restenosis and occlusion. *Advanced Science*, *5*(5), pp. 1700560.
3. Murphy, J., & Boyle, F. (2010). Predicting neointimal hyperplasia in stented arteries using time-dependant computational fluid dynamics: a review. *Computers in biology and medicine*, *40*(4), pp. 408-418.
4. Cohen, B. J., & DePetris, A. (2013). *Medical terminology: An illustrated guide*. Lippincott Williams & Wilkins.
5. Paisal, M. S. A., Adnan, S. F. S., Taib, I., Abdullah, M. K., Nordin, N., Seri, S. M., & Darlis, N. (2017). Flow Characteristics Near to Stent Strut Configurations on Femoropopliteal Artery. *IOP Conference Series: Materials Science and Engineering*. IOP Publishing, pp. 012147.
6. Nordstrom, S. M., & Weiss, E. J. (2008). Sex differences in thrombosis. *Expert Review of Hematology*, *1*(1), pp. 3-8.
7. Schlager, O., Giurgea, A., Margeta, C., Seidinger, D., Steiner-Boeker, S., Van Der Loo, B., & Koppensteiner, R. (2011). Wall shear stress in the superficial femoral artery of healthy adults and its response to postural changes and exercise. *European Journal of Vascular and Endovascular Surgery*, *41*(6), pp. 821-827.
8. Gökgöl, C., Diehm, N., Räber, L., & Büchler, P. (2019). Prediction of restenosis based on hemodynamical markers in revascularized femoro-

popliteal arteries during leg flexion. *Biomechanics and modeling in mechanobiology*, *18*(6), pp. 1883-1893.

9. Ulrich, K. T. (2003). *Product design and development*. Tata McGraw-Hill Education.

10. Seman, C. M. H. M. C., Marzuki, N. A., Darlis, N., Marsi, N., Salleh, Z. M., Ishak, I. A., Sukiman, S. L. (2020). Comparison of Hemodynamic Performances Between Commercially Available Stents Design on Stenosed Femoropopliteal Artery. *CFD Letters*, *12*(7), pp. 17-25.

11. Johari, N. H., Hamady, M., & Xu, X. Y. (2020). A computational study of the effect of stent design on local hemodynamic factors at the carotid artery bifurcation. *Artery Research*, *26*(3), pp. 161-169.

12. Malek, A. M., Alper, S. L. and Izumo, S. (1999). Hemodynamic Shear Stress and Its Role in Atherosclerosis. *Jama*, 282(21), pp. 2035–2042.

13. Murphy, J. and Boyle, F.(2009). Comparing Stent Design Using Computational Fluid Dynamics to Predict Wall Shear Stress Based Parameters. *Bioengineering 15 Conference*. Ireland.

14. LaDisa, J. F., Guler, I., Olson, L. E., Hettrick, D. A., Kersten, J. R., Warltier, D. C. and Pagel, P. S. (2003). Three-Dimensional Computational Fluid Dynamics Modeling of Alterations in Coronary Wall Shear Stress Produced by Stent Implantation. *Ann. Biomed. Eng.*, 31(8), pp. 972–980.

15. Nandini, D., Schoephoerster, R. T. and Moore Jr, J. E.(2009). Comparison of Near-wall Hemodynamic Parameters in Stented Artery Models. *J. Biomech. Eng.*, 131(6), pp. 1–22.

16. Balossino, R., Gervaso, F., Migliavacca, F. and Dubini, G.(2008). Effects of Different Stent Designs on Local Hemodynamics in Stented Arteries. *J. Biomech*, 41(5), pp. 1053–1061.

17. He, Y., Duraiswamy, N., Frank, A. O. and Moore, J. E. (2005). Blood Flow in Stented Arteries: A Parametric Comparison of Strut Design Patterns in Three Dimensions. *J. Biomech. Eng.*, 127(4), pp. 637–647.

18. Jiménez, J. M., & Davies, P. F. (2009). Hemodynamically driven stent strut design. *Annals of biomedical engineering*, *37*(8), pp. 1483-1494.

19. Paisal, M. S. A., Taib, I., Arifin, A. M. T., & Mahmod, M. F. (2019). Evaluation system on haemodynamic parameters for stented carotid artery: Stent pictorial selection method. *International Journal of Integrated Engineering*, *11*(1).

20. Fortier, A., Gullapalli, V., & Mirshams, R. (2014). A. Review of biomechanical studies of arteries and their effect on stent performance. *IJC Heart & Vessels*, *4*, pp. 12-18.

21. Rothwell, P. M., Coull, A. J., Silver, L. E., Fairhead, J. F., Giles, M. F., Lovelock, C. E., & Mehta, Z. (2005). Population-based study of event-rate, incidence, case fatality, and mortality for all acute vascular events in all arterial territories (Oxford Vascular Study). *The Lancet*, *366*(9499), pp. 1773-1783.

22. Kyrle, P. A., Minar, E., Bialonczyk, C., Hirschl, M., Weltermann, A., & Eichinger, S. (2004). The risk of recurrent venous thromboembolism in men and women. *New England Journal of Medicine*, *350*(25), pp. 2558-2563.

23. McRae, S., Tran, H., & Schulman, S. (2007). Effect of patient's sex on risk of recurrent venous thromboembolism: A meta-analysis. *Journal of Vascular Surgery*, *45*(2), pp. 436.

24. Silver, A. E., & Vita, J. A. (2006). Shear Stress–Mediated Arterial Remodeling in Atherosclerosis: Too Much of a Good Thing? *Circulation*, *113*(24), pp. 2787-2789.

25. Kasapis, C., & Gurm, H. S. (2009). Current approach to the diagnosis and treatment of femoral-popliteal arterial disease. A systematic review. *Current cardiology reviews*, *5*(4), pp. 296-311.

26. Kaazempur-Mofrad, M. R., & Ethier, C. R. (2001). Mass transport in an anatomically realistic human right coronary artery. *Annals of Biomedical Engineering*, *29*(2), pp. 121-127.

27. Qiu, Y., & Tarbell, J. M. (2000). Numerical simulation of oxygen mass transfer in a compliant curved tube model of a coronary artery. *Annals of biomedical engineering*, *28*(1), pp. 26-38.

28. Tarbell, J. M. (2003). Mass transport in arteries and the localization of atherosclerosis. *Annual review of biomedical engineering*, *5*(1), pp. 79-118.

29. Wood, N. B., Zhao, S. Z., Zambanini, A., Jackson, M., Gedroyc, W., Thom, S. A., & Xu, X. Y. (2006). Curvature and tortuosity of the superficial femoral artery: a possible risk factor for peripheral arterial disease. *Journal of applied physiology*, *101*(5), pp. 1412-1418.
30. Scholten, F. G., Warnars, G. A., Willem, P. T. M., & van Leeuwen, M. S. (1993). Femoropopliteal occlusions and the adductor canal hiatus, Duplex study. *European Journal of Vascular Surgery*, *7*(6), pp. 680-683.
31. Walsh, D. B., Powell, R. J., Stukel, T. A., Henderson, E. L., & Cronenwett, J. L. (1997). Superficial femoral artery stenoses: characteristics of progressing lesions. *Journal of vascular surgery*, *25*(3), pp. 512-521.
32. Stoeckel, D., Pelton, A., & Duerig, T. (2004). Self-expanding nitinol stents: material and design considerations. *European radiology*, *14*(2), pp. 292-301.
33. Siewiorek, G. M., Finol, E. A., & Wholey, M. H. (2009). Clinical significance and technical assessment of stent cell geometry in carotid artery stenting. *Journal of Endovascular Therapy*.
34. Frank, A. O., Walsh, P. W., & Moore Jr, J. E. (2002). Computational fluid dynamics and stent design. *Artificial organs*, *26*(7), pp. 614-621.
35. Wüstenhagen, C., Borowski, F., Grabow, N., Schmitz, K. P., & Stiehm, M. (2016). Comparison of stented bifurcation and straight vessel 3D-simulation with a prior simulated velocity profile inlet. *Current Directions in Biomedical Engineering*, *2*(1), pp. 293-296.
36. Stiehm, M., Brede, M., Quosdorf, D., & Leder, A. (2013). On the creation of wall shear stress by helical flow structures in stented coronary vessels. *BioNanoMaterials*, *14*(1-2), pp. 109-115.
37. Johari, N. H., Hamady, M., & Xu, X. Y. (2020). A computational study of the effect of stent design on local hemodynamic factors at the carotid artery bifurcation. *Artery Res*, *26*(3), pp. 161-169.
38. Wüstenhagen, C., Pfensig, S., Siewert, S., Kaule, S., Grabow, N., Schmitz, K. P., & Stiehm, M. (2018). Optimization of stent designs regarding the thrombosis risk using computational fluid dynamics. *Current Directions in Biomedical Engineering*, *4*(1), pp. 93-96.

39. Ng, J., Bourantas, C. V., Torii, R., Ang, H. Y., Tenekecioglu, E., Serruys, P. W., & Foin, N. (2017). Local hemodynamic forces after stenting: implications on restenosis and thrombosis. *Arteriosclerosis, thrombosis, and vascular biology*, *37*(12), pp. 2231-2242.

40. LaDisa Jr, J. F., Olson, L. E., Guler, I., Hettrick, D. A., Kersten, J. R., Warltier, D. C., & Pagel, P. S. (2005). Circumferential vascular deformation after stent implantation alters wall shear stress evaluated with time-dependent 3D computational fluid dynamics models. *Journal of applied physiology*, *98*(3), pp. 947-957.

41. Gundert, T. J., Marsden, A. L., Yang, W. and LaDisa, J. F. (2012). Optimization of cardiovascular stent design using computational fluid dynamics. *Journal of biomechanical engineering*. *134*(1), pp. 011002.

42. Taib, I., Kadir, M. R. A., Azis, M. H. S. A., Md Khudzari, A. Z. and Osman, K. (2013). Analysis of Hemodynamic Differences for Stenting Patent Ductus Arteriosus. *Journal of Medical Imaging and Health Informatics*, *3*(4), pp. 555–560.

43. Duraiswamy, N., Schoephoerster, R. T. and Moore, J. E. (2009). Comparison of near-wall hemodynamic parameters in stented artery models. *Journal of biomechanical engineering*, *131*(6), pp. 061006.

44. Murphy, J. and Boyle, F. (2010). Predicting neointimal hyperplasia in stented arteries using time-dependant computational fluid dynamics: a review. *Computers in biology and medicine*, *40*(4), pp. 408–18.

45. Pant, S., Bressloff, N. W., Forrester, A. I. J. and Curzen, N. (2010). The influence of strut-connectors in stented vessels: a comparison of pulsatile flow through five coronary stents. *Annals of biomedical engineering*, *38*(5), pp. 1893– 907.

46. Pache, J., Kastrati, A., Mehilli, J., Schühlen, H., Dotzer, F., Hausleiter, J., Fleckenstein, M., Neuman, F. J., Sattelberger, U., Schmitt, C., Müller, M., Dirschinger, J. and Schömig, A. (2003). Intracoronary stenting and angiographic results: Strut thickness effect on restenosis outcome (ISAR-STEREO-2) trial. *Journal of the American College of Cardiology*, *41*(8), pp. 1283–1288.

47. Mauri, L., Silbaugh, T. S., Garg, P., Wolf, R. E., Zelevinsky, K., Lovett, A., Varma, M. R., Zhou, Z. and Normand, S.-L. T. (2008). Drug-eluting or bare-metal stents for acute myocardial infarction. *The New England journal of medicine*, *359*(13), pp. 1330–1342.

48. Alwi, M., Choo, K.-K., Radzi, N. a. M., Samion, H., Pau, K.-K. and Hew, C.-C. (2011). Concomitant stenting of the patent ductus arteriosus and radiofrequency valvotomy in pulmonary atresia with intact ventricular septum and intermediate right ventricle: early in-hospital and medium-term outcomes. *The Journal of thoracic and cardiovascular surgery*, *141*(6), pp. 1355–61.

49. Mauri, L., Silbaugh, T. S., Garg, P., Wolf, R. E., Zelevinsky, K., Lovett, A., Varma, M. R., Zhou, Z. and Normand, S.-L. T. (2008). Drug-eluting or bare-metal stents for acute myocardial infarction. *The New England journal of medicine*, *359*(13), pp. 1330–1342.

50. Gundert, T. J., Marsden, A. L., Yang, W., Marks, D. S. and LaDisa, J. F. (2012). Identification of hemodynamically optimal coronary stent designs based on vessel caliber. *IEEE transactions on bio-medical engineering*, *59*(7), pp. 1992–2002.

51. Wernick, M. H., Jeremias, A. and Carrozza, J. P. (2006). Drug-eluting stents and stent thrombosis: a cause for concern? *Coronary artery disease*, *17*(8), pp. 661– 665.

52. LaDisa, J. F., Olson, L. E., Hettrick, D. A., Warltier, D. C., Kersten, J. R., & Pagel, P. S. (2005). Axial stent strut angle influences wall shear stress after stent implantation: analysis using 3D computational fluid dynamics models of stent foreshortening. *Biomedical engineering online*, *4*(1), pp. 1-10.

53. Chiu, J., C. Chen, P. Lee, C. Yang, H. Chuang, S. Chien, and S. Usami. (2003). Analysis of the effect of disturbed flow on monocytic adhesion to endothelial cells. *J. Biomech*. *36*, pp. 1883–1895.

54. Gundert T. J., Dholakia, R., McMahon, J. D. and LaDisa, J. F. (2013). Computational Fluid Dynamics Evaluation of Equivalency in Hemodynamic Alterations Between Driver, Integrity, and Similar Stents Implanted into an Idealized Coronary Artery. *J. Med. Device.*, *7*(1), pp. 11004.

55. Poon, E. K., Barlis, P., Moore, S., Pan, W. H., Liu, Y., Ye, Y & Ooi, A. S. (2014). Numerical investigations of the haemodynamic changes associated with stent malapposition in an idealised coronary artery. *Journal of biomechanics*, *47*(12), pp. 2843-2851.

56. Suess, T., Anderson, J., Danielson, L., Pohlson, K., Remund, T., Blears, E. & Kelly, P. (2016). Examination of near-wall hemodynamic parameters in the renal bridging stent of various stent graft configurations for repairing visceral branched aortic aneurysms. *Journal of vascular surgery*, *64*(3), pp. 788-796.

57. Fan, Z., Liu, X., Zhang, Y., Zhang, N., Ye, X., & Deng, X. (2021). Hemodynamic Impact of Stenting on Carotid Bifurcation: A Potential Role of the Stented Segment and External Carotid Artery. *Computational and Mathematical Methods in Medicine, 2021*.

58. Wang, I. C., Huang, H., Chang, W. T., & Huang, C. C. (2021). Wall shear stress mapping for human femoral artery based on ultrafast ultrasound vector Doppler estimations. *Medical Physics*, *48*(11), pp. 6755-6764.

59. Ferrarini, A., Finotello, A., Salsano, G., Auricchio, F., Palombo, D., Spinella, G. & Conti, M. (2021). Impact of leg bending in the patient-specific computational fluid dynamics of popliteal stenting. *Acta Mechanica Sinica*, *37*(2), pp. 279-291.

60. Youssefi, P., Gomez, A., He, T., Anderson, L., Bunce, N., Sharma, R., Figueroa, C. A. and Jahangiri, M. (2016). Patient-Specific Computational Fluid Dynamics – Assessment of Aortic Hemodynamics in a Spectrum of Aortic Valve Pathologies. *J. Thorac. Cardiovasc. Surg*, *153*(1), pp. 8–20.

61. Frydrychowicz, A., Stalder, A. F., Russe, M. F., Bock, J., Bauer, S., Harloff, A. & Markl, M. (2009). Three-dimensional analysis of segmental wall shear stress in the aorta by flow-sensitive four-dimensional-MRI. *Journal of Magnetic Resonance Imaging: An Official Journal of the International Society for Magnetic Resonance in Medicine*, *30*(1), pp. 77-84.

62. DePaola, N., Gimbrone Jr, M. A., Davies, P. F., & Dewey Jr, C. F. (1992). Vascular endothelium responds to fluid shear stress gradients. *Arteriosclerosis and thrombosis: a journal of vascular biology*, *12*(11), pp. 1254-1257.

63. Chen, Z., Yu, H., Shi, Y., Zhu, M., Wang, Y., Hu, X. & Gao, W. (2017). Vascular remodelling relates to an elevated oscillatory shear index and relative residence time in spontaneously hypertensive rats. *Scientific reports*, *7*(1), pp. 1-10.
64. Martin, D., & Boyle, F. (2015). Sequential structural and fluid dynamics analysis of balloon-expandable coronary stents: a multivariable statistical analysis. *Cardiovascular engineering and technology*, *6*(3), pp. 314-328.
65. Khan, M. F., Quadri, Z. A., & Bhat, S. P. (2013). Study of Newtonian and non-Newtonian effect of blood flow in portal vein in normal and hypertension conditions using CFD technique. *Int J Eng Res Technol*, *6*, pp. 974-3154.
66. Lee, T. S., Liao, W., & Low, H. T. (2003). Numerical simulation of turbulent flow through series stenoses. *International journal for numerical methods in fluids*, *42*(7), pp. 717-740.
67. Prado, C. M., Ramos, S. G., Elias Jr, J., & Rossi, M. A. (2008). Turbulent blood flow plays an essential localizing role in the development of atherosclerotic lesions in experimentally induced hypercholesterolaemia in rats. *International journal of experimental pathology*, *89*(1), pp. 72-80.
68. Manual, U. D. F. (2009). *ANSYS FLUENT 12.0. Theory Guide.*
69. Jahangiri, M., Saghafian, M., & Sadeghi, M. R. (2015). Numerical study of turbulent pulsatile blood flow through stenosed artery using fluid-solid interaction. *Computational and mathematical methods in medicine*, *2015*.
70. Zhu, C., Seo, J. H., & Mittal, R. (2018). Computational modelling and analysis of haemodynamics in a simple model of aortic stenosis. *Journal of Fluid Mechanics*, *851*, pp. 23-49.
71. Kabir, M. A., Alam, M. F., & Uddin, M. A. (2018). A numerical study on the effects of reynolds number on blood flow with spiral velocity through regular arterial stenosis. *Chiang Mai J. Sci*, *45*(6), pp. 2515-2527.
72. Saqr, K. M., Tupin, S., Rashad, S., Endo, T., Niizuma, K., Tominaga, T., & Ohta, M. (2020). Physiologic blood flow is turbulent. *Scientific reports*, *10*(1), pp. 1-12.

73. Arzani, A. (2018). Accounting for residence-time in blood rheology models: do we really need non-Newtonian blood flow modelling in large arteries?. *Journal of The Royal Society Interface*, *15*(146), pp. 20180486.
74. Johnston, B. M., Johnston, P. R., Corney, S., & Kilpatrick, D. (2004). Non-Newtonian blood flow in human right coronary arteries: steady state simulations. *Journal of biomechanics*, *37*(5), pp. 709-720.
75. Muniandy, K. (2013). *Non-Newtonian Computational Fluid Dynamics (CFD) Modeling on Blood Clot Extraction*. Universiti Teknologi PETRONAS: Bachelor degree thesis.
76. Kagadis, G. C., Skouras, E. D., Bourantas, G. C., Paraskeva, C. A., Katsanos, K., Karnabatidis, D., & Nikiforidis, G. C. (2008). Computational representation and hemodynamic characterization of in vivo acquired severe stenotic renal artery geometries using turbulence modeling. *Medical engineering & physics*, *30*(5), pp. 647-660.
77. Jozwik, K., & Obidowski, D. (2010). Numerical simulations of the blood flow through vertebral arteries. *Journal of Biomechanics*, *43*(2), pp. 177-185.
78. Benim, A. C., Nahavandi, A., Assmann, A., Schubert, D., Feindt, P., & Suh, S. H. (2011). Simulation of blood flow in human aorta with emphasis on outlet boundary conditions. *Applied Mathematical Modelling*, *35*(7), pp. 3175-3188.
79. Moreno, C., & Bhaganagar, K. (2013). Modeling of stenotic coronary artery and implications of plaque morphology on blood flow. *Modelling and Simulation in Engineering*, *2013*.
80. Mahalingam, A., Gawandalkar, U. U., Kini, G., Buradi, A., Araki, T., Ikeda, N. & Suri, J. S. (2016). Numerical analysis of the effect of turbulence transition on the hemodynamic parameters in human coronary arteries. *Cardiovascular diagnosis and therapy*, *6*(3), pp. 208.
81. Kareem, A. K., Gabir, M. M., Almoayed, O. M., Ismail, A. E., Taib, I., Darlis, N., Ali, I. R., Conditioning, A., (2020). Pahat, B., Tun, U., & Onn, H. Mathematical Selection Approach for. Technology Reports of Kansai University, 62(10), 6041–6051
82. Robbins S. P. and Coulter, M.(2012). *Management*, 11th edition. Upper Saddle River: Prentice Hall.

83. Kaha, A., Paisal, M. S. A., Arifin, A. M. T., Asmuin, N., Haq, R. H. A., Chatpun, S. & Osman, K. (2018). Lumped Parameter Modelling in Femoral Popliteal Artery for Normal and Severe Conditions. *International Journal of Integrated Engineering*, *10*(5).
84. Molina-Aiz, F. D., Fatnassi, H., Boulard, T., Roy, J. C., & Valera, D. L. (2010). Comparison of finite element and finite volume methods for simulation of natural ventilation in greenhouses. *Computers and electronics in agriculture*, *72*(2), pp. 69-86.
85. Ahsaas, S., & Tiwari, S. (2016). Numerical Simulation of Blood Flow through Asymmetric and Symmetric Occlusion in Carotid Artery. *Proceedings of the 3rd International Conference on Fluid Flow, Heat and Mass Transfer (FFHMT'16). Ottawa, Canada*, pp. 170-8.
86. Johnston, B. M., Johnston, P. R., Corney, S., & Kilpatrick, D. (2004). Non-Newtonian blood flow in human right coronary arteries: steady state simulations. *Journal of biomechanics*, *37*(5), pp. 709-720.
87. Oberkampf, W. L., & Trucano, T. G. (2002). Verification and validation in computational fluid dynamics. *Progress in aerospace sciences*, *38*(3), pp. 209-272.
88. Giurgea, C., Bode, F., Budiu, O. I., Nascutiu, L., Banyai, D., & Damian, M. (2014). Experimental investigations of the steady flow through an idealized model of a femoral artery bypass. *EPJ Web of Conferences*, EDP Sciences, pp. 02031.
89. Sadrehaghighi, I. (2017). Mesh generation in CFD. *CFD Open Ser*, *151*.
90. Salim, S. M., & Cheah, S. (2009). Wall Y strategy for dealing with wall-bounded turbulent flows. *Proceedings of the international multiconference of engineers and computer scientists*, pp. 2165-2170.
91. Nagaraj, H. M., Pednekar, A., Corros, C., Gupta, H., & Lloyd, S. G. (2008). Determining exercise-induced blood flow reserve in lower extremities using phase contrast MRI. *Journal of Magnetic Resonance Imaging: An Official Journal of the International Society for Magnetic Resonance in Medicine*, *27*(5), pp. 1096-1102.

92. Mut, F., Löhner, R., Chien, A., Tateshima, S., Viñuela, F., Putman, C., & Cebral, J. R. (2011). Computational hemodynamics framework for the analysis of cerebral aneurysms. International journal for numerical methods in biomedical engineering, 27(6), pp. 822-839.
93. Ku, D. N., Giddens, D. P., Zarins, C. K. and Glagov, S. (1985). Pulsatile Flow and Atherosclerosis in the Human Carotid Bifurcation Positive Correlation between Plaque Location and Low Oscillating Shear Stress. *Arter. Thromb Vasc Biol*, 5(3), pp. 293–302.
94. Taib, I. (2016). *Improvement of Haemodynamic Stent Strut Configuration for Patent Ductus Arteriosus Through Computational Modelling*, Universiti Teknologi Malaysia: Doctoral dissertation.
95. Darlis, N. (2016). *Improvement of spiral flow aortic cannula for cardiopulmonary bypass operation*. Universiti Teknologi Malaysia: Ph.D thesis.
96. Beier, S., Ormiston, J., Webster, M., Cater, J., Norris, S., Medrano-Gracia, P., & Cowan, B. (2016). Hemodynamics in idealized stented coronary arteries: important stent design considerations. *Annals of biomedical engineering*, *44*(2), pp. 315-329.
97. Casa, L. D., Deaton, D. H., & Ku, D. N. (2015). Role of high shear rate in thrombosis. *Journal of vascular surgery*, *61*(4), pp. 1068-1080.
98. Rana, A., Westein, E., Niego, B. E., & Hagemeyer, C. E. (2019). Sheardependent platelet aggregation: mechanisms and therapeutic opportunities. *Frontiers in cardiovascular medicine*, *141*.
99. Soga, Y., Yokoi, H., Ando, K., Shirai, S., Sakai, K., Kondo, K., & Nobuyoshi, M. (2010). Safety of early exercise training after elective coronary stenting in patients with stable coronary artery disease. *European Journal of Preventive Cardiology*, *17*(2), pp. 230-234.
100. LaDisa Jr, J. F., Olson, L. E., Guler, I., Hettrick, D. A., Audi, S. H., Kersten, J. R., & Pagel, P. S. (2004). Stent design properties and deployment ratio influence indexes of wall shear stress: a three-dimensional computational fluid dynamics investigation within a normal artery. *Journal of applied physiology*, *97*(1), pp. 424-430.

101. Winzer, E. B., Woitek, F., & Linke, A. (2018). Physical activity in the prevention and treatment of coronary artery disease. *Journal of the American Heart Association*, *7*(4), pp. e007725.

102. Chen, Y. W., Apostolakis, S., & Lip, G. Y. (2014). Exercise-induced changes in inflammatory processes: Implications for thrombogenesis in cardiovascular disease. *Annals of medicine*, *46*(7), pp. 439-455.

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