IOP Conference Series: Materials Science and Engineering

Computational Analysis on Stent Geometries in Carotid Artery: A Review

Computational Analysis on Stent Geometries in Carotid Artery: A Review

Muhammad Sufyan Amir Paisal[1], Ishkrizat Taib[2], Al Emran Ismail[3]

Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, Parit Raja, 86400 Batu Pahat, Johor, Malaysia.

[1]muhammadsufyanamir@gmail.com, [2]iszat@uthm.edu.my, [3]emran@uthm.edu.my

Abstract. This paper reviews the work done by previous researchers in order to gather the information for the current study which about the computational analysis on stent geometry in carotid artery. The implantation of stent in carotid artery has become popular treatment for arterial diseases of hypertension such as stenosis, thrombosis, atherosclerosis and embolization, in reducing the rate of mortality and morbidity. For the stenting of an artery, the previous researchers did many type of mathematical models in which, the physiological variables of artery is analogized to electrical variables. Thus, the computational fluid dynamics (CFD) of artery could be done, which this method is also did by previous researchers. It lead to the current study in finding the hemodynamic characteristics due to artery stenting such as wall shear stress (WSS) and wall shear stress gradient (WSSG). Another objective of this study is to evaluate the nowadays stent configuration for full optimization in reducing the arterial side effect such as restenosis rate after a few weeks of stenting. The evaluation of stent is based on the decrease of strut-strut intersection, decrease of strut width and increase of the strut-strut spacing. The existing configuration of stents are actually good enough in widening the narrowed arterial wall but the disease such as thrombosis still occurs in early and late stage after the stent implantation. Thus, the outcome of this study is the prediction for the reduction of restenosis rate and the WSS distribution is predicted to be able in classifying which stent configuration is the best.

1. Introduction

Carotid artery is a blood vessel from aorta that circulates blood from neck to the brain. It divides into two which are internal carotid artery and external carotid artery. The abnormality of hemodynamics in carotid artery caused by high blood pressure leads to the implantation of stent. A stent is a device with circular section used to reinforce the internal wall of the artery [1]. However, there are still a few complications that occur after the implantation which are restenosis of blood vessel, thrombosis and embolization. These complications give high mortality and morbidity [2, 3 and 4]. Figure 1 shows the basic anatomy of carotid artery in human body [5].

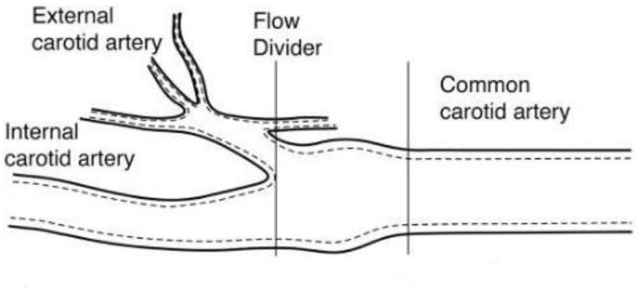

Figure 1. Basic anatomy of carotid artery [5].

The criteria in choosing the right configuration of stent also need to be focused on, because each type of stent has its advantages and disadvantages. There are two type of stent which are opened and closed type. Opened type stent is chosen because the closed type is not suitable to be used in bendable muscular with torsional effect. Opened type stent is then categorized into two which are self-expendable and balloon expendable. Self-expendable is not chosen due to sedative medications that lead into over-sedation, drug reaction and aspiration. Balloon expendable type is selected although it may cause cell proliferation [6].

Stent geometry and its strut configuration also play the main role in maintaining the efficiency of the blood flow in the artery. This is because the flexibility and stiffness are controlled by the parameters which are the material and geometry of the stent. The geometry of the stent has the structure which having a repetitive number of cell or geometrical pattern. Usually, the diameter of stent is two or four times larger of the original one after the implantation [1]. Besides that, the stent strut position also influences the stress distribution and the maximum compressive stress which increase by 10 percent due to changes in the final struts configuration alone when the stent strut is very distant from its neighbor [7].

The development of Computational Fluid Dynamics (CFD) nowadays made it easier to predict the blood flow through the stent. The inlet of this flow is the common carotid artery and the outlets of this flow are internal carotid artery and external carotid artery. However, the CFD analysis considers the outlets as free flow that lead to inaccurate result. The outlets have its own blood pressure accordingly to the cardiac cycle of the heartbeat. The blood pressure in the carotid artery is calculated by using lumped parameter mathematical model. This mathematical model is common in use nowadays for studying the factors that affect pressure and flow waveforms [8].

2. Patient Condition

The condition of patient is important in determining the pressure which to be used in the CFD computation. For this research, the considered four conditions of patient are normal, prehypertension, stage 1 hypertension and stage 2 hypertension. Hypertension is a disease of medical term for high blood pressure [9].

For normotensive condition, the mean pressure in left carotid artery is 100 mmHg and its pulse pressure is 48 mmHg [10, 11]. To get the hypertensive blood pressure in the carotid artery, following formula is used by using the aortic pulse pressure [11].

$$PP_{car} = (0.98 \pm 0.11) \times PP_{ao} + (0.13 \pm 8.14) \quad (1)$$

Where PP_{car} is a carotid pulse pressure and PP_{ao} is a pulse pressure for aortic artery. Since pulse pressure is difference between systolic and diastolic blood pressure, these pressures could be get from the Table 1 [12]. Systolic blood pressure means the highest pressure amount of the heart beats while diastolic blood pressure is the lowest pressure amount of the beating heart. Table 1 shows the classification of normotensive and hypertensive blood pressure in adult patient [12].

Table 1. Classification of normotensive and hypertensive blood pressure [12].

Condition	Systolic Blood Pressure (mmHg)	Diastolic Blood Pressure (mmHg)
Normal	90-119	60-79
Prehypertension	120-139	80-89
Hypertension (Stage 1)	140-159	90-99
Hypertension (Stage 2)	160-179	100-109

The high blood pressure in the artery could cause blocking effect of embolism which the blood flow becomes narrow gradually [2]. Embolism is the effect of embolus formation where the blood clots due to irregular linings of artery. The hardening of arterial walls which called as atherosclerosis is also occurred due to inflammation of inner lining of arteries and deposition of fatty material as plaques as shown in Figure 2 [3]. The rupture of atherosclerotic plaque triggers the formation of blood clot which could also be called as thrombosis that blocks the normal hemodynamics of blood flow in artery [4].

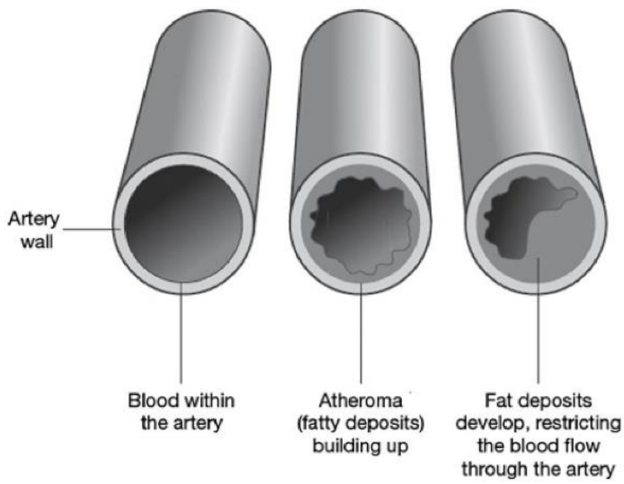

Figure 2. The narrowing blood vessel due to atherosclerosis [3].

3. Artery Stenting

The following topics explain the effects of stent design to the hemodynamic and its arterial diseases, by relating to the previous research that has been done.

3.1. Effect of Stent Configuration to the Artery

Uncontrollable of hypertensive blood pressure could lead to arterial disease which is stroke due to damaged and weakened blood vessel [13]. Stenting of carotid artery in this research could treat the re-stenosis, embolization and thrombosis that occurred.

For this research, balloon expandable of opened type stent is suitable to be applied in the carotid artery. This is due to its good properties in the fully annealed, well adapted mechanical properties, biocompatibility and resistance to the corrosion as well as fatigue performances [14].

Since this research has four conditions, five different designs of stent for each condition are studied. Thus, the blood flow performance of each design is predicted by using CFD method. Figure 3 shows some example of different commercial design of stents.

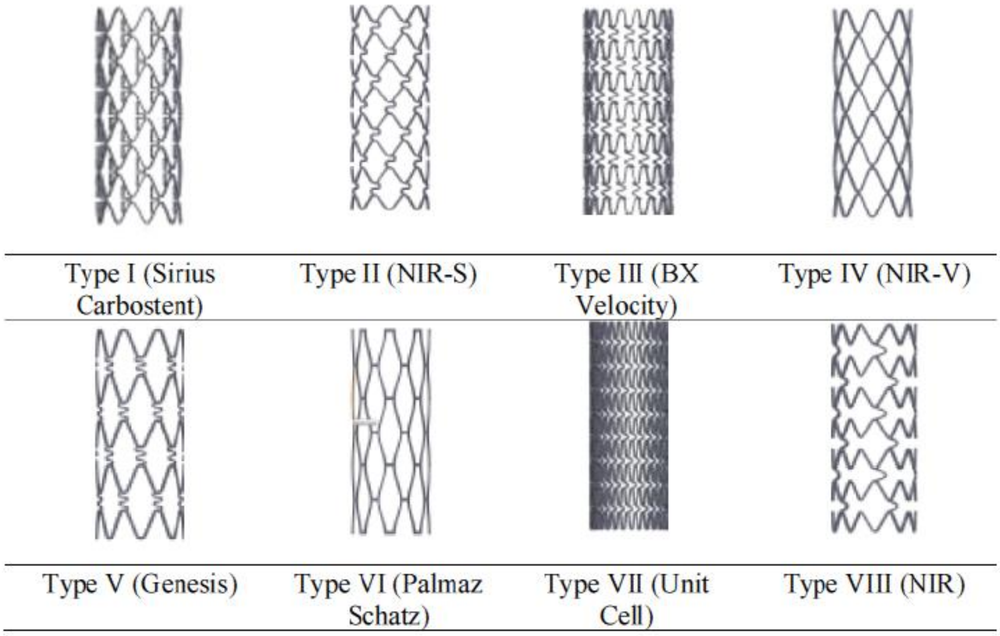

Figure 3. Examples of commercial stent design [15].

In the implantation of stent, each artery has different condition that need to be considered. Thus, there are many designs of stent implemented according to its desired configurations. However, there are still a few complications occurred although a lot of stentings are improved as shown in the Table 2.

Table 2. Significance along with the complications of the previous study.

Researcher	Stent Configuration	Significance	Complication
[16,17]	Bare Metal Stent	Allow shorter dual-antiplatelet therapy duration for high bleeding risk or need of immediate surgery.	High rate of restenosis.
[18]	Drug-Eluting Stent (First Generation)	Risk of Stenosis after percutaneous coronary intervention is reduced.	High risk of late stent thrombosis.
[19]	Drug-Eluting Stent (Second Generation)	More safety and efficiency than the first generation of drug-eluting stent.	Stent thrombosis still occurs.
[20]	Biodegradable Polymer Stent	High efficiency in reducing very late stent thrombosis.	Not reducing the risk of mortality.
[21]	Balloon Expandable Stent	Immediate substantial improvement in lumen diameter after implantation and low rate of re-stenosis.	High potential of early thrombosis and relatively high rate of peripheral vascular complications.
[22]	Self-Expandable Stent	Lower the occlusion rate, less therapeutic failure, less need of re-intervention and lower cholangitis incidence.	Mortality within 30 days.

3.2. Thrombosis Versus Stent Strut Geometry

Different design of stent strut geometry alters different early thrombosis rate. Early thrombosis is a stage which is within 30 days after the stent implantation. Different geometry shape gives different rate of early thrombosis.

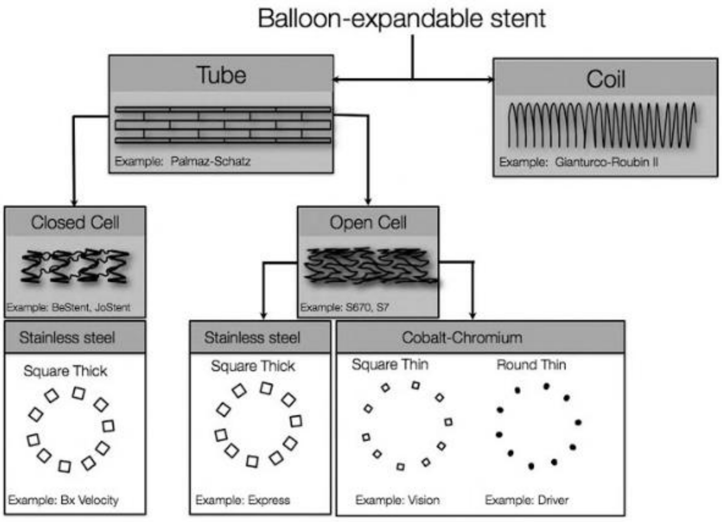

Figure 4. Basic Strut Geometry of Balloon-Expandable Stent [23].

For self-expandable with mesh type stent, the early stent thrombosis is very high which is almost 5 percent. Since the early thrombosis rate is very high, the usage of stent is move onto the balloon-expandable type stent. As shown in Figure 4, the balloon-expandable type stent have two which are tube and coil. The coil type stent has also high early thrombosis rate which is almost 4 percent. For the tube stent type, the early thrombosis is low which is 2 percent and below [23].

If Drug-Eluting Stent (DES) and Bare Metal Stent (BMS) are to be compared, the long-term rate of stent thrombosis for DES is lower than BMS. This is based on the patients treated with DES have a difference about 1.1 percent of weighted risk from the patients treated with BMS through 33 months [24].

3.3. The Hemodynamic Effect of Stent Strut Geometry

The changes of parameters for stent design such as decreasing the strut width, increasing the strut-strut spacing and decreasing the strut-strut intersection, are proved to be in the reduction of restenosis rate. This is due to the mechanical properties of fluid dynamics near to the wall such as intrastrut flow patterns and Wall Shear Stress (WSS) [25].

A higher normalized Wall Shear Stress enhances the hemodynamic performance of the stent. Furthermore, the most optimum stent design is defined which have the most minimum area of low intrastrut time averaged WSS [26].

Wall Shear Stress Gradient (WSSG) is a parameter to represent the non-uniformity in the flow patterns. WSSG that having the value of 20 dynes/cm^3 and above is likely to have a cellular proliferation and Neointimal Hyperplasia (NIH) in the artery. The value of WSSG is high near the strut and remains distinctly non-zero for most of the region between the struts of the stent.

The previous study that has been done by Ladisa et al. [27] shows that WSS is lower at the stented region for all simulation and the stagnation zones occurred around stent strut. The maximum value of WSSG is occurred at four-strut polygonal which it is higher than 20 dynes/cm^3. However, the maximum WSSG did not occur in the eight-strut polygonal stent. This can be seen in Figure 5 that investigating the value of WSS and WSSG which affected by different design of stent configuration.

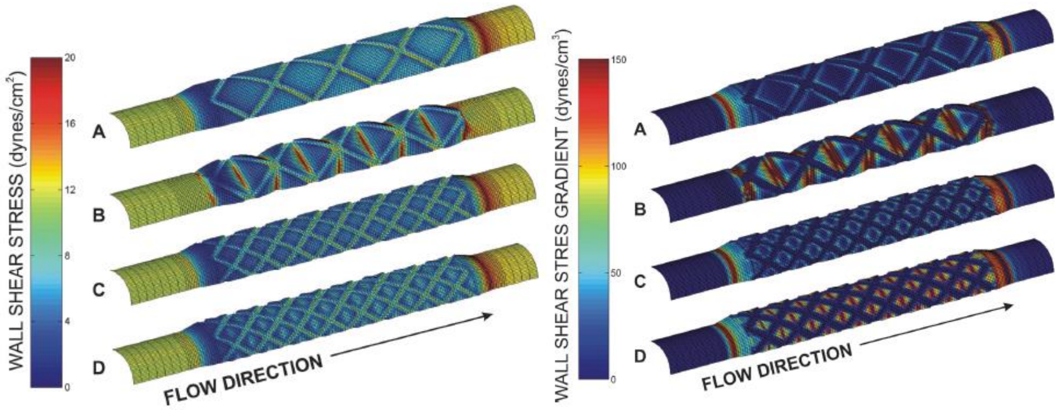

Figure 5. CFD analysis of WSS (left) and WSSG (right) for four different design of stent configuration [27].

3.4. Flow Characteristic on Single Strut and Complete Pattern Strut

The following topics explain the hemodynamic characteristic based on single strut stent and complete pattern strut.

3.4.1. Single Strut

A study on a single strut is a concern because it affects the spatial distribution of WSS. The change in spatial WSS distribution is also a change to the progression of endothelialization, neointimal hyperplasia, and restenosis.

The stent design with intrastrut of approximate 40 degree angle minimize the area of low time-averaged WSS regardless of intrastrut area or vessel size since the design of stent that have minimum area of low time-averaged WSS is considered as optimum stent design. Figure 6 shows the parameters that affecting the WSS [26].

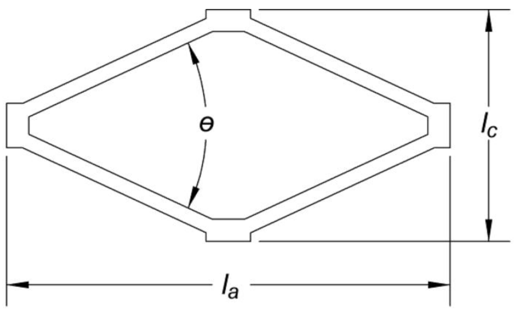

Figure 6. Parameter on single strut which Θ is angle, l_a is length and l_c is width [26].

3.4.2. Complete Pattern Strut

Compared to the study of single strut, the analysis of complete pattern strut plays the main role of restenosis by using CFD method. The hemodynamic behavior and WSS distribution could be obtained in overall.

Based on the study that has been done by Hsiao et al. [28], the simulated result shows the minimum WSS occurs at the circulation zones located at the downstream or backside of each stent struts. At the regions near the backside of each stent strut, the flow velocity and shear rate are fairly low, but a large disparity in viscosity is exist in Newtonian and non-Newtonian flow models. As shown in Figure 7, the WSS value is investigated in two models which are Newtonian and Non-Newtonian flow.

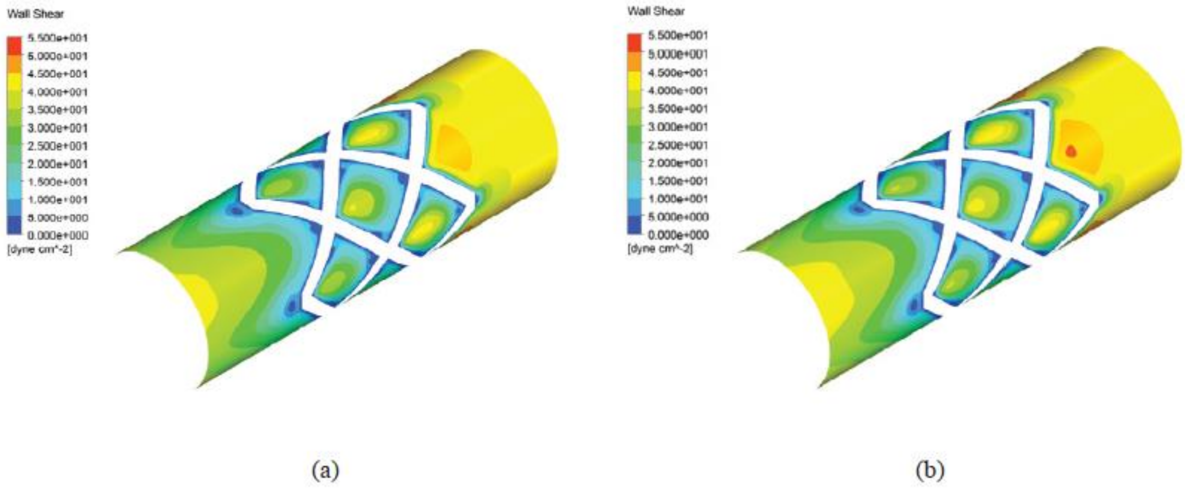

Figure 7. WSS contours for (a) Newtonian flow and (b) non-Newtonian flow model [28].

3.5. Different Shape of Stent Geometry

Shape of stent geometry is commonly dictated by manufacturing limitations but it can play a fundamental role in the improvement of hemodynamic performance [29].

Circular shape stent is the most commonly used in the artery. However, Kim et al. [30] states that the efficiency of stent is related to several parameters including porosity and stent strut shapes. Thus, the concept of flow reduction is used in characterizing the flow efficiency in rectangular shape stent. The rectangular shape stent is observed to be optimal and to decrease the magnitude of the velocity by 53.92% in the 3D model and 89.25% in the 2D model in the aneurysm sac.

In other hand, Mejia et al. [29] also did a study on the evaluation of stent strut profile on shear stress distribution using statistical moments. The result shows that, the streamlined profile exhibits better hemodynamic performance than the standard circular and rectangular profile. For tear drop profile, up to 96% of the area between strut is exposed to the wall shear stress levels above the critical value for the onset of restenosis while for the square profile, the analogous value is 19.4%. Figure 8 shows the investigated stent strut profile that affecting shear stress distribution.

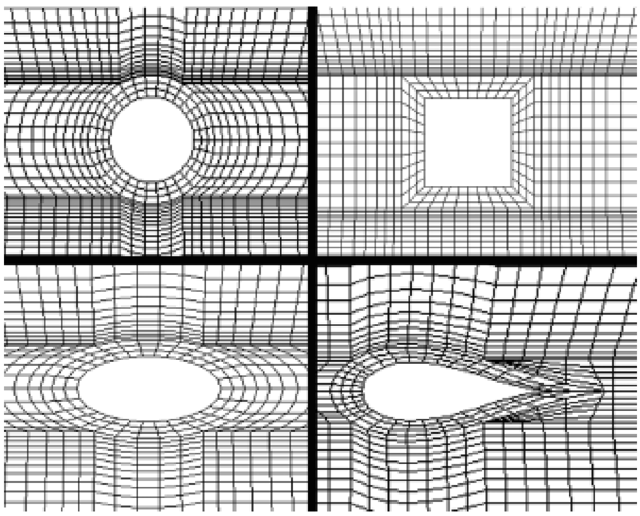

Figure 8. Stent strut profile of circular (top-left), square (top-right), elliptical (bottom-left) and tear-drop (bottom-right) [29].

Dumoulin et al. [31] who studied the mechanical behavior modeling of balloon-expandable stents states that the lowest value of critical pressure by the radial compression or geometric nonlinearity influence is important to maintain the long-term usage. The geometry mode of stents being studied are elliptical, triangle and rectangular. As shown in the figure below, the elliptical mode has the lowest critical pressure which is 0.116 MPa among the three modes to withstand the radial compression. Figure 9 shows the obtained critical pressure according to the shape of stent geometry.

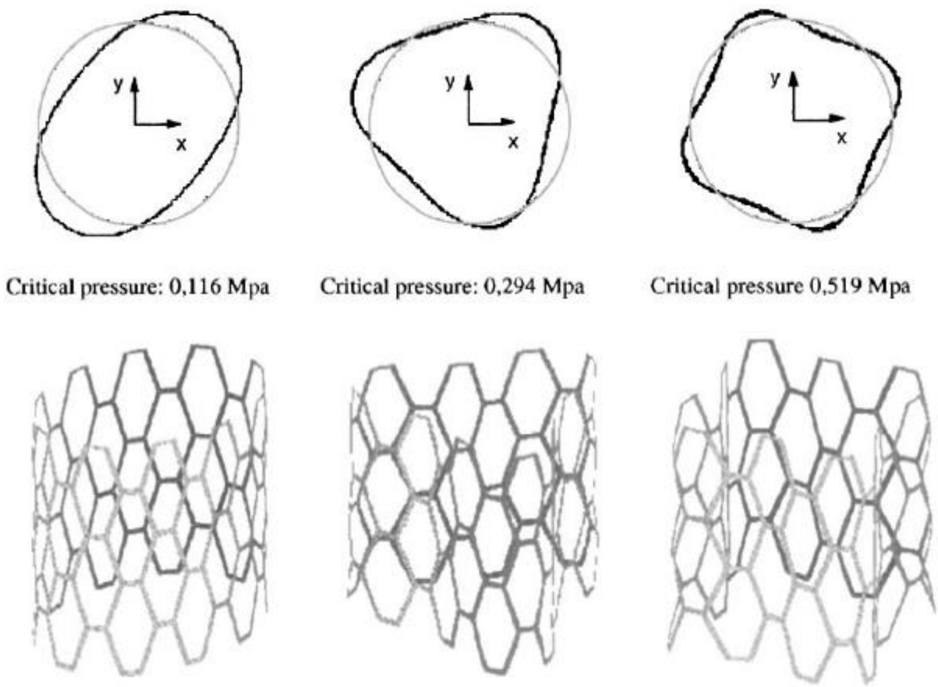

Figure 9. Critical pressure according to the shape of stent geometry [31].

4. Influence of Lumped Parameter Mathematical Modelling to the Artery

The first step in doing the CFD is to have all the required parameters. To do so, mathematical model of a carotid artery need to be done. The use of this mathematical model is to simplified the uneven and complexity of biological condition into computable data [32]. Most of the mathematical model of an artery use electrical schematic model as an analogy for the flow in a tube.

To be in detail, Table 3 shows the physiological parameters of artery which respectively describe the parameters of fluid dynamic as electrical analogue [33].

Table 3. The quantities of fluid dynamics and their analogues [33].

Fluid dynamics	Physiological variables	Electrical analogue
Pressure P [Pa=J/m^3]	Blood pressure [mmHg]	Voltage U [V=J/C]
Flow rate Q [m^3/s]	Blood flow rate [L/s]	Current I [A=C/s]
Volume V [m^3]	Blood volume [V]	Charge q[C]
Viscosity η	Blood resistance $\square = \frac{8\eta Nl}{\pi r^4}$	Electrical resistance R
Elastic coefficient	Vessel's wall compliance	Capacitor's capacitance C
Inertance	Blood Inertia	Inductor's inertance L
Poiseuille's law:	$Q = \frac{\Delta P}{\square} = \frac{\Delta P \pi r^4}{8\eta\ell}$	Ohm's law: $I = \frac{\Delta U}{\square}$

In this research, the mathematical model used is lumped parameter. This model describes the physics of the problem in an easier way and changing the model parameters give insight to the behavior of the carotid artery [34].

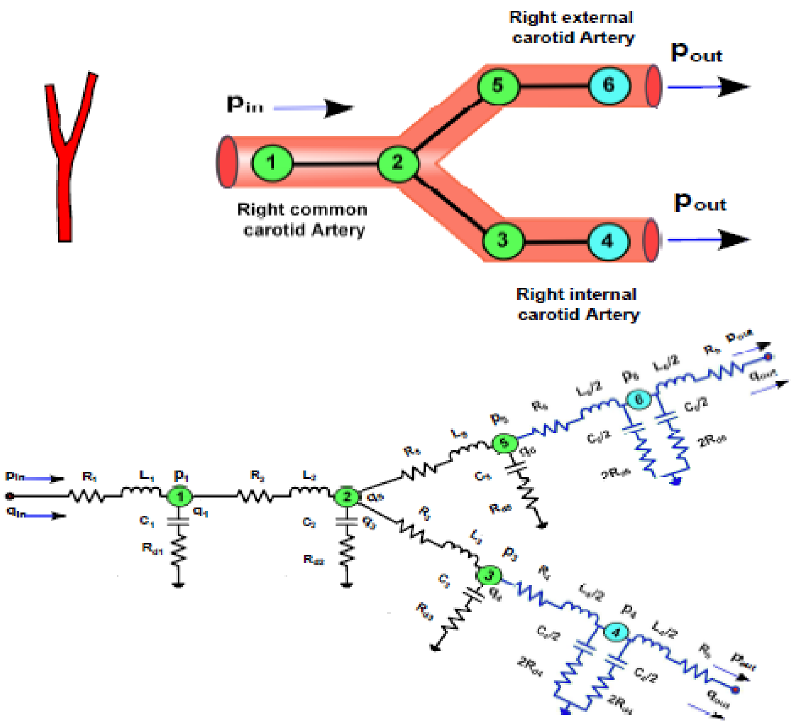

Figure 10. Simplified anatomy (top) and electrical schematic diagram (bottom) of a right carotid artery [34].

Figure 10 illustrates on how the anatomy of a right carotid artery is changed into electrical schematic diagram. To find the pressure at each node, following equations are used [8]:

$$P_{(i-1)} - P = q_i R_i + L_{V_i} \frac{dq_i}{dt} \quad (2)$$

$$q_{C_i} = C_{V_i} \frac{dP_i}{dt} \quad (3)$$

Table 4 shows the findings by the previous researchers [34, 35, 36, 37, 38] on how they modeled the artery into computable form.

Table 4. Type of mathematical model used for artery by previous researchers.

Researcher	Type of mathematical model used	Findings
[34]	Lumped parameter mathematical model on human cardiovascular system.	Able to measure pressure and flow of the hemodynamics.
[35]	Finite difference method with the governing equations of motion of incompressible steady couple stress fluids in the absence of body force and body moment.	It leads the shear stress, flow rate and impedance to be changed suddenly with all the parameters of both sides of apex in the artery.
[36]	One dimensional wave propagation theory and assumes the pressure waveform is a superposition of forward propagating wave and backward waves from many reflection sites.	This model shows the age-related changes in blood pressure waveform. If the pressure wave form is impossible to be obtained due to moving subject, this model is suitable to be used.
[37]	A stenosed artery could be obtained by using Herschel-Bulkley fluid which the blood flow is considered axially symmetric, laminar, pulsatile, fully developed flow and assumed incompressible.	The variation of pressure gradient corresponding to the axial distance is obtained.
[38]	A Windkessel model which the small blood vessels or capillaries are considered as resistance R and the large blood vessels are considered as compliance C.	This method able to estimate the blood pressure in the artery because of its simplest form using 2 element equations but conflicts with other modern methods in terms of wave propagation and reflection.

5. CFD of Blood Flow

Next step is doing the CFD method for the blood flow through stented carotid artery. Computational Fluid Dynamics (CFD) nowadays could be applied to simulate and analyze the flow pattern of hemodynamic in artery. Thus, there a few assumptions made to simplify the computation.

Uemiya et al. [39] did a study on analysis of restenosis after carotid artery stenting. In the work that has been made, the blood is assumed to be Newtonian, incompressible and laminar flow with a constant dynamic viscosity of 0.0035 Pa s and density of 1050 kg/m^3. Besides that, the wall of the patient is considered as rigid. The inflow of blood is ranged from 250 ml/minute to 380 ml/minute.

Conti et al. [40] also did a study on carotid artery hemodynamics of before and after stenting. For the CFD analysis, the outflow sections consisting external and internal carotid artery, are prescribed by using Windkessel model. The peripheral impedance for both outflows is represented by two resistances R_1, R_2 and one compliance C.

6. Validation and Verification

The computation of lumped parameter mathematical model needs a validation by referring to the previous researcher in order to know whether the method is correct or not with the percentage of accuracy. If the method is accurate enough, the work can be proceed to the CFD of carotid artery stenting.

The involved case for the validation is the pressure waveform of healthy patient condition in carotid artery. Figure 10 below shows the pressure waveform of carotid artery which to study about the validation of carotid artery as a means of estimating augmentation index of ascending aortic pressure by Chen et al. [41]. Solid curve is carotid AI (AI_t) while dotted curves is aortic AI (AI_m). Figure 10(a) shows carotid waveform has a clear inflection point on the upstroke, but no inflection point could be found on the aortic pressure curve. Figure 10(b) shows no inflection point could be found on either waveform. For Figure 10(c), the inflection points were on the upstrokes of both waveforms while for Figure 10(d), the inflection points were on the downstrokes of both waveforms. In Figure 10(e), the inflection points were on the downstroke of carotid and on the upstroke of aortic waveforms. Lastly for Figure 10(f), the inflection points were on the upstrokes of both waveforms, but AI_t was greater than AI_m [41].

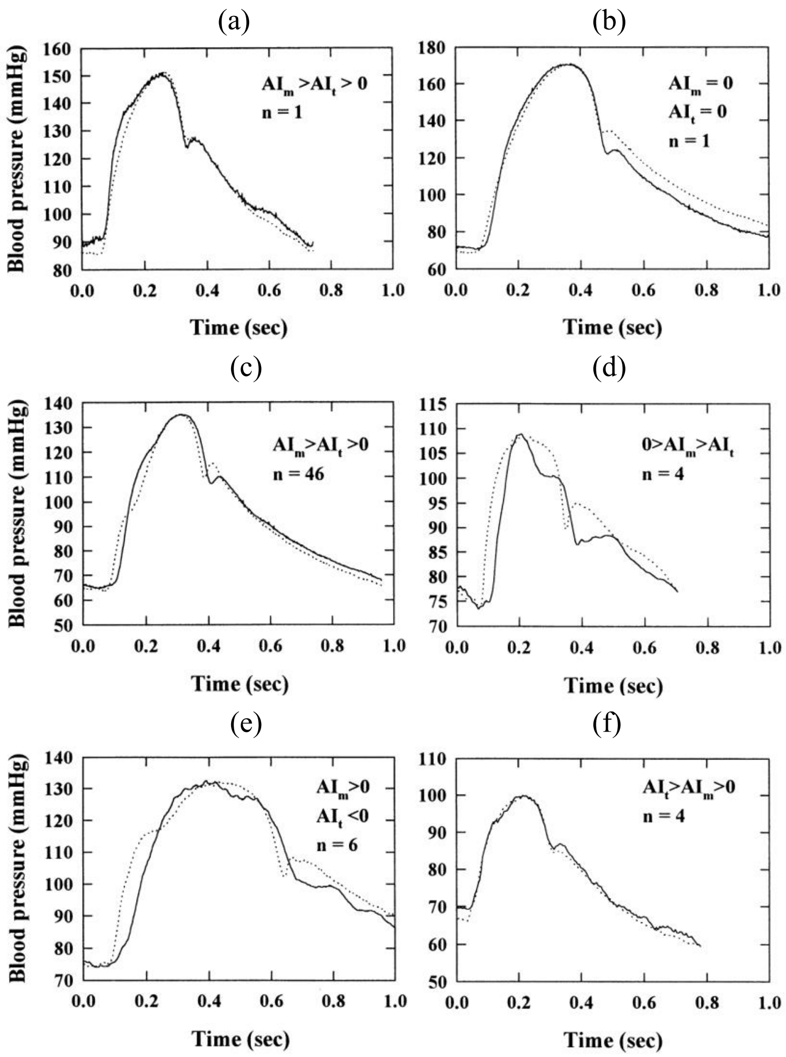

Figure 11. Summary comparisons of waveforms and augmentation indexes (AIs) at baseline in adult patient [41].

7. Conclusion and Future Direction

Over the years, the CFD of hemodynamic in artery stenting become more relevance in predicting the mechanical properties and performance of blood. However, this work requires a high level of understanding of bio-fluid mechanism in relating to the schematic diagram of lumped parameter circuit.

At the end of this study, the resulting of WSS distribution is predicted to be able in classifying which stent design is the best in overcoming the arterial disease of hypertension such as restenosis, thrombosis and embolization. Thus, the rate of failure in the carotid artery could be reduced. The calculated WSS distribution could also reduce the try-and-error method which has been done by previous clinicians.

In the new paradigm of surgical field, the community is hoped to have a better healthcare with the use of today's computational and evaluation method along with the stent technologies.

References

[1] Guimaraes T A, Duarte M A V and Oliveira S A G 2005 Topology Optimization of the Stents Cells Plane Model with Maximum Hardening and Flexibility *Proceedings of the Inverse Problems, Design and Optimization (IPDO - 2004) Symposium, Rio de Janeiro, Brazil, March 17-19, 2004* ed Colaço M J et al (Rio de Janeiro: E-papers Pub. House) p 192.
[2] Ramdass and Shivakumar A 2005 *A Guide to High Blood Pressure* (New Delhi: Lotus Press).
[3] Aziz S and Aziz Z 2015 *Understanding High Blood Pressure* (London: SPCK).
[4] Sanders T and Emery P 2003 *Molecular Basis Of Human Nutrition*. (London: Taylor & Francis).
[5] Polak J F, Pencina M J, Meisner A, Pencina K M, Brown L S, Wolf P A and D'Agostino R B 2010 *Journal of Ultrasound in Medicine: Official Journal of the American Institute of Ultrasound in Medicine* **29**(12) 1759-1768.
[6] Casserly I P, Sachar R and Yadav J S 2011 *Practical Peripheral Vascular Intervention* (Market Street: Lippincott Williams & Wilkins).
[7] Amatruda C M, Hose D R, Lawford P and Narracott A 2012 *Journal of Biomechanics* **45** S25.
[8] Waite L and Fine J M 2007 *Applied Biofluid Mechanics* (New York: McGraw-Hill).
[9] Brewer S 2014 *Overcoming High Blood Pressure: The Complete Complementary Health Program* (Oxford: Duncan Baird Publishers).
[10] Khamdaeng T, Luo J, Vappou J, Terdtoon P and Konofagou E 2012 *Ultrasonics* **52**(3) 402-411.
[11] Boutouyrie P, Bussy C, Lacolley P, Girerd X, Laloux B and Laurent S 1999 *Circulation* **100**(13) 1387-1393.
[12] Chobanian A V, Bakris G L, Black H R, Cushman W C, Green L A, Izzo J L and Jones D W 2003 *Hypertension* **42** 1206-1252.
[13] Siddiqui A, Morr S and Lin N 2014 *Medical Device: Evidence and Research* **7** 343-355.
[14] Auricchio F, Constantinescu A, Conti M and Scalet G 2015 *International Journal of Fatigue* **75** 69-79.
[15] Taib I 2016 *Improvement of Haemodynamic Stent Strut Configuration for Patent Ductus Arteriosus Through Computational Modelling* (Johor: Universiti Teknologi Malaysia).
[16] Wiebe J, Colleran R and Kastrati A 2016 *JACC: Cardiovascular Interventions* **9**(12) 1256-1258.
[17] Mauri L, Silbaugh T S, Garg P, Wolf R E, Zelevinsky K, Lovett A and Varma M R 2009 *New England Journal of Medicine* **360**(3) 300-302.
[18] Kaiser C, Galatius S, Erne P, Eberli F, Alber H, Rickli H and Pedrazzini G 2011 *New England Journal of Medicine* **364**(12) 1178-1180.
[19] Shi H, Chu H, Gu W, Cai X, Guo J, Ding Z and Wen S 2016 *International Journal of*

Cardiology **214** 393-397.
[20] Yang Y, Lei J, Huang W, and Lei H 2016 *International Journal of Cardiology* **222** 486-493.
[21] Savage M P, Fischman D L, Schatz R A, Teirstein P S, Leon M B, Baim D and Goldberg S 1994 *Journal of the American College of Cardiology* **24**(5) 1207-1212.
[22] Sawas T, Al-Halabi S, Parsi M A and Vargo J J 2015 *Gastrointestinal Endoscopy* **82**(2) 256-267.
[23] Mukherjee D 2010 *Cardiovascular Catheterization and Intervention: A Textbook of Coronary, Peripheral, and Structural Heart Disease* (New York: Informa Healthcare).
[24] Kereiakes D J, Yeh R W, Massaro J M, Driscoll-Shempp P, Cutlip D E, Steg P G and Mauri L 2015 *JACC: Cardiovascular Interventions* **8**(12) 1552-1562.
[25] Duraiswamy N, Schoephoerster R T and Moore J E 2009 *Journal of Biomechanical Engineering* **131**(6) 061006.
[26] Gundert T J, Marsden A L, Yang W and LaDisa J F 2012 *Journal of Biomechanical Engineering* **134**(1) 011002.
[27] LaDisa J F 2004 *Journal of Applied Physiology* **98**(3) 947-957.
[28] Hsiao H, Lee K, Liao Y and Cheng Y 2012 *Procedia Engineering* **36** 128-136.
[29] Mejia J, Ruzzeh B, Mongrain R, Leask R and Bertrand O F 2009 *BioMedical Engineering OnLine* **8**(1) 8.
[30] Kim Y H, Xu X and Lee J S 2010 *Annals of Biomedical Engineering* **38**(7) 2274-2292.
[31] Dumoulin C and Cochelin B 2000 *Journal of Biomechanics* **33**(11) 1461-1470.
[32] Abdi M, Navidbakhsh M and Razmkon A 2016 *J Biomed Phys Eng* **6**(1) 33-40.
[33] Kokalari I, Karaja T and Guerrisi M 2013 *Journal of Biomedical Science and Engineering* **6**(1) 92-99.
[34] Raheem G 2016 *Mathematical Modelling and Sensitivity Analysis of Lumped-Parameter Model of the Human Cardiovascular System* (Abbottabad: Freien Universitat Berlin).
[35] Srinivasacharya D and Rao G M 2016 *Mathematical Biosciences* **278** 37-47.
[36] Lazović B, Mazić S, Zikich D and Žikić D 2015 *Wave Motion* **56** 14-21.
[37] Sankar D and Hemalatha K 2006 *International Journal of Non-Linear Mechanics* **41**(8) 979-990.
[38] Tsanas A, Goulermas J Y, Vartela V, Tsiapras D, Theodorakis G, Fisher A C and Sfirakis P 2009 *Medical Engineering & Physics* **31**(5) 581-588.
[39] Uemiya N, Lee C, Ishihara S, Yamane F, Zhang Y and Qian Y 2013 *Journal of Clinical Neuroscience* **20**(11) 1582-1587.
[40] Conti M, Long C, Marconi M, Berchiolli R, Bazilevs Y and Reali A 2016 *Computers & Fluids* **000** 1-13.
[41] Chen C, Ting C, Nussbacher A, Nevo E, Kass D A, Pak P and Yin F C 1996 *Hypertension* **27**(2) 168-175.