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Effect of Single and Double Stenosed on Renal Arteries of Abdominal Aorta: A Computational Fluid Dynamics

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ABSTRACT

This study investigated the impact of single stenosed (SS) and double stenosed (DS) of renal artery branches using the Computational Fluid Dynamics (CFD) approach. A 3D abdominal aorta with renal artery branches model was constructed using MIMICS software. Some modification of SS and DS are applied at right and left renal artery branches, respectively. Numerical analysis of both stenosed cases with the condition of normal blood pressure (NBP) and high blood pressure (HBP) are performed using CFD solver in software ANSYS-18. The results of velocity, pressure and wall shear stress of SS and DS renal artery branches with the condition of NBP and HBP are compared with respect to the blood flow behavior. The results concluded that DS-NBP showed the highest value for velocity magnitude. Meanwhile for pressure and wall shear stress value, DS-HBP showed the highest value for both results, respectively. The present study demonstrates the fundamental aspects of haemodynamics of blood flow behavior in idealized abdominal aorta with stenosed renal branches subjected to the normal and high pressure conditions of DS and SS cases of renal artery branches.

Keywords:
Renal Artery; Renal Artery Stenosed; Atherosclerosis; Computational Fluid Dynamics; Hemodynamics

1. Introduction

Renal artery stenosis is widely known as the principal cause of kidney failure. The stenosis restrains the blood supply and obstruct blood flows through the blood vessel towards kidney and narrowing arteries size. This lead to the reduction of oxygenated blood volume to kidney and may cause to the failure of kidney. Hence, stenosis in renal artery branch is a crucial issue as it linked with secondary hypertension [1]. Renal artery stenosis has also lead to the augmented of the blood flow pressure and velocity but reduced the mass flow rate [2,3]. Meanwhile, the investigation by

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Mortazavinia *et al.,* [4] has proven the angulation of stenosed at renal artery subjected to the changes of velocity and mass flow of blood flow, which lead to hypertension. Similar, Kagadis *et al.,* [5] also has investigated the clinical effects of renal artery stenosis on flow dynamics and vessel wall based on patient specific data.

Furthermore, the emerging of today's technology specifically on coupling technique of clinical imaging such as Magnetic Resonance Imaging (MRI), Computed Tomography (CT) and Ultrasound Doppler Imaging with numerical simulation helps researchers to understand detailed of blood flow behaviour especially on the mechanism of stenosis development in patient [6,7]. Moreover, this technique helps researchers to developed invasive studies of blood flow in recent years [5,8,9].

Recently, there are several researches investigating the blood flow behavior of cardiovascular disease using the aid of numerical simulation such as Computational Fluid Dynamics (CFD) and Fluid Structure Interaction (FSI) techniques. Hussain *et. al.,* [10], conducted a numerical CFD studies of blood flow system of aorta coronary sinus conduit using simulation in ANSYS. A different model of conduit, which differs in the inlet diameter, was investigated based on the pressure drop from 80 mmHg to 15 mmHg. The comparison chart was produced to compare the pattern of pressure reduction as well as velocity distribution in each model. Basri *et al.,* [11] has conducted a CFD study to investigate the effects of severe aortic stenosis (AS) disease on the blood flow behavior. The results clearly showed that the severity of AS disturbs the natural flow of blood into the carotid branches, hence it leading to unequal distribution of blood supply into the important organs of the body [12]. In another study, Basri *et al.,* [13] carried out the FSI simulation of Transcatheter Aortic Valve Implantation (TAVI) valve to investigate the occurrence of paravalvular leakage (PVL) issue, at different percentage of valve opening. Zakaria *et al.,* [14–17] conducted a Cartesian non-boundary fitted grid method of blood flow in the aorta using OpenFOAM and developed new NBF-VOF to solve the problem of the flow on the stationary body on a fixed grid.Second paragraph starts here. A nanofluid can be produced by dispersing metallic or non-metallic nanoparticles or nanofibers with a typical size of less than 100 nm in a base liquid.

On the other hand, there are also other numerical studies on haemodynamics behavior of stenosed renal artery condition using CFD and FSI approaches for critical understanding on the blood flow behavior impact due to the stenosed of the vessel [4,18–20]. Khader *et al.,* [18] conducted a comparison study of haemodynamic behavior of normal, single stenosed and double stenosed of renal artery for condition resting and exercise cases using CFD approach. The results showed that high flow velocity is relatively low in rest and more intense during exercise condition. WSS occurred at the throat of the stenosis either in single or double stenosed compared to normal model, where maximum WSS occurred at the distal wall side of renal branches. Basri *et al.,* [21] further this study with FSI approach of normal and single stenosed renal artery with normal blood (NBP) pressure and high blood pressure (HBP) conditions. The results concluded that stenosed condition showed higher reduction of blood flow distribution compared to normal case due to the acute luminal diameter of blood vessel. Meanwhile, Stenosed-HBP indicated as the highest maximum value of velocity, WSS arterial, pressure von-Mises stress distribution and wall deformation compared to Stenosed-NBP, Normal-HBP and Normal-NBP.

In the present work, CFD simulation was carried out to investigate the inter-relationship between single stenosed (SS) and double stenosed (DS) cases of renal artery during normal blood pressure (NBP) and high blood pressure (HBP) conditions. A 3D models of abdominal aorta with renal branches is constructed from a single mid-slice of CT image using MIMICS software and CFD simulation was conducted using ANSYS 18. The simulation provides advantages for the medical expertise to understand blood flow's behavior in term of velocity, pressure and wall shear stress (WSS) due to aggravated of stenosis at the blood vessel.

2. Methodology
2.1 Patient Specific Aorta Model

In this simulation, the details construction of 3D geometry of idealistic abdominal with the renal branch with SS and DS cases is explained in [18,21,22].

2.2 Mesh Study

The grid dependency study was carried out by comparing the mesh elements with the results of maximum velocity (refer Figure 1). The best selection of mesh for fluid domain can be concluded to be approximately to 385000 and 394500 structured and unstructured elements of single and double stenosed models, respectively.

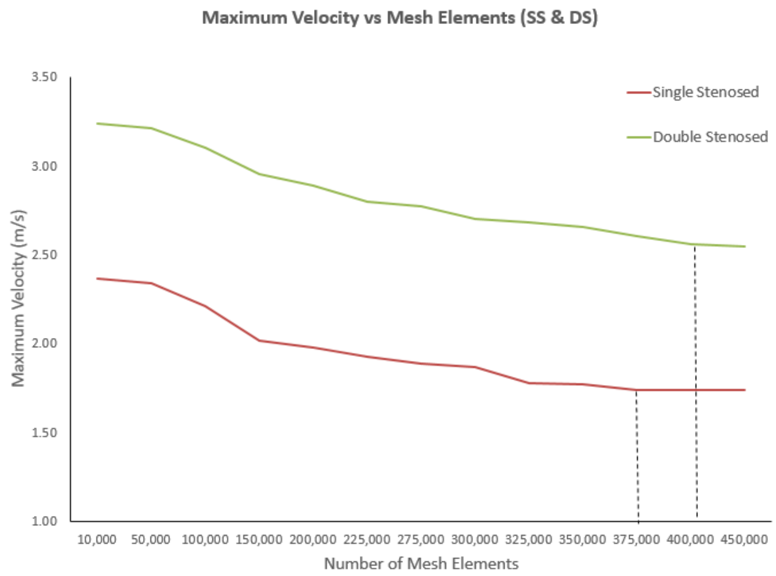


Fig. 1. Mesh Dependency for SS and DS

2.3 Boundary Condition
2.3.1 Fluid model

The CFD solved the governing Navier Stokes equation of fluid motion. The governing equations of flow that were considered in this study are as follows

Continuity

$$\nabla \cdot \vec{V} = 0 \tag{1}$$

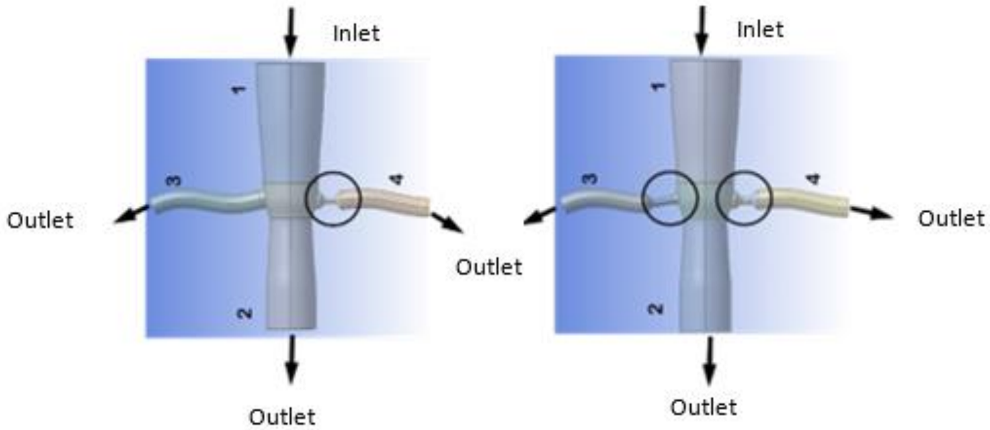
Momentum

$$\frac{\alpha^2}{Re}\iiint_v \frac{\partial \vec{V}}{\partial t} d\vec{V} + \iiint_v (\vec{V} \cdot \nabla)\vec{V} d\vec{V} = -\iint_s p.dA + \frac{1}{Re}\iint_s \tau \cdot dA \tag{2}$$

Where, τ is the viscous stress tensor; p is the pressure; Re =$\nabla \cdot \vec{V} = 0$ is the Reynolds number; α = (ω/v) is the Womersley parameter; U is the maximum inlet velocity; R is the aorta inlet radius; v is the kinematic viscosity; ω is the inlet pulse frequency (ω=2πf ; f is the heart rate).

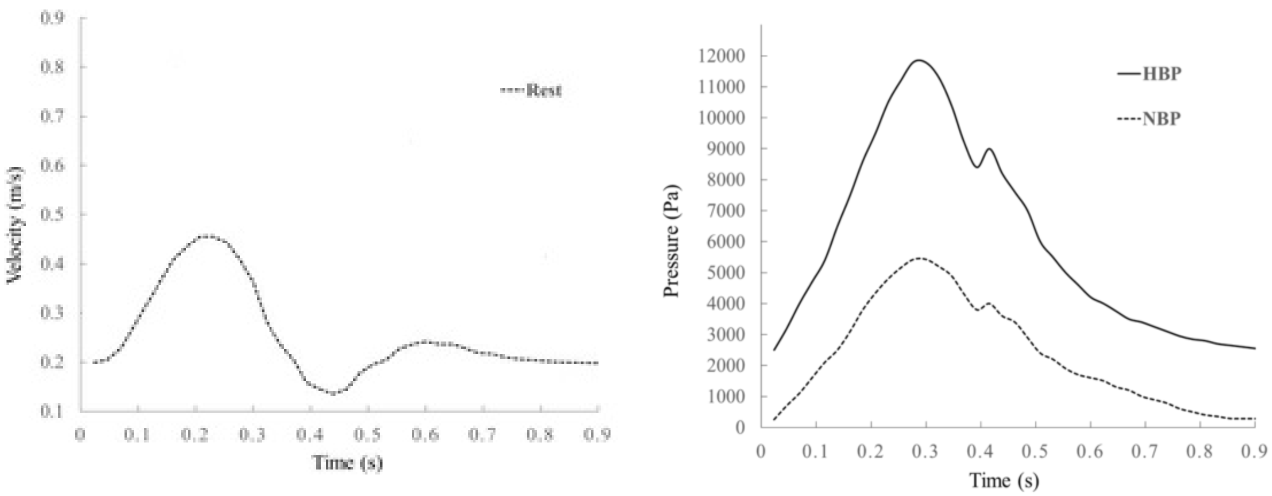
The velocity and pressure were indicated as the respective inlet and outlet with the condition of pulsatile blood flow (Figure 2), as referring to Basri *et al.,* [21]. The inlet flow was assumed to be Newtonian and incompressible due to the higher relative shear rate ratio above 100 s^{-1} [13]. The value of blood density and dynamic viscosity were 1050 kg/m^3 and 0.004 Pa/s, respectively [18,22]. For the turbulent model selection, k-ω Shear Stress Transport (SST) was additionally used, referring to Basri *et al.,* [11,13,21].

The pulsatile time varying velocity profile as shown in the Figure 3a is applied at the inlet. Meanwhile, two different outlet pulsatile pressure are carried out separately under NBP and HBP condition (Figure 3b). The total simulation time was 3s for three complete cardiac cycles with 0.05s time step and the solution converged at 10-6. It took about 48 hours to complete the simulation using the system with the configuration of Intel® Core ™ i7-3520M CPU @ 2.90 GHz and 32GRAM. Hence, four time points of pulsatile flow was taken as the reference point in this study which are early systole (ES), peak systole (PS), early diastole (ED) and late diastole (LD) for the result observation.



(a) (b)

Fig. 2. Geometric description of SS and DS(a) Single stenosed (b) Double stenosed



(a) (b)

Fig. 3. (a) Pulsatile velocity applied at inlet (b) Pulsatile pressure applied at outlet

3. Results and Discussion

Numerical simulation of single stenosed (SS) and double stenosed (DS) models with normal blood pressure (NBP) and high blood pressure (HBP) of renal artery were carried out for three pulse cycle.

The last cycle was considered and results obtained was taken for further investigation. The hemodynamics parameters such as velocity, pressure, and WSS are studied at specific instants of pulse cycle like ES, PS, ED and LD. These parameters vary with time due to the pulsatility of the flow waveform and the maximum value generally occurred at the peak systole when the inflow is maximum.

3.1 Velocity Contour

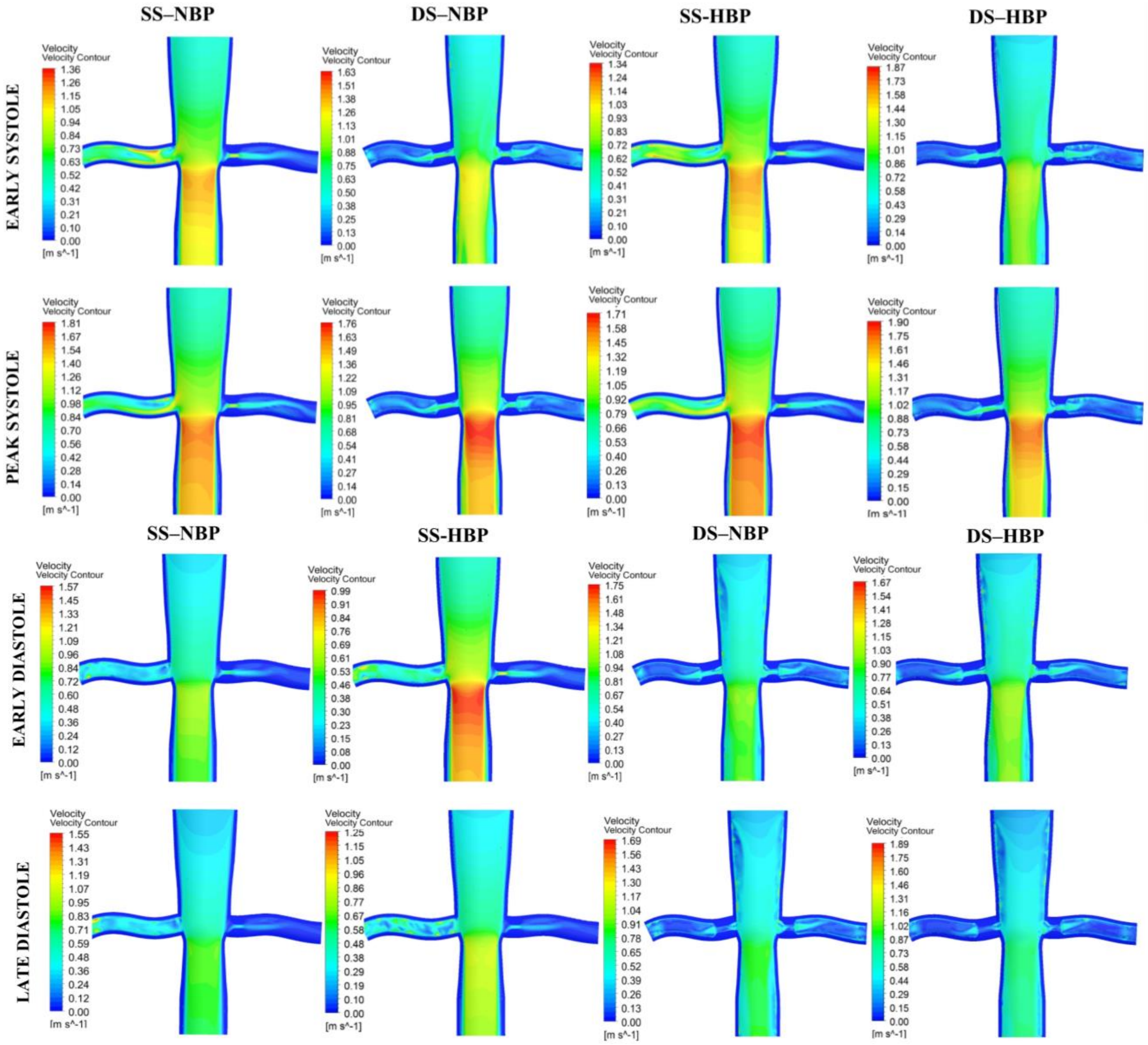
Figure 4(a) shows the comparison of velocity contour of blood flow in abdominal aorta and renal branches of SS-NBP, SS-HBP, DS-NBP and DS-HBP at ES, PS, ED and LD. It described the flow separation such that the flow divides into two streams with maximum velocity at the distal wall of the renal bifurcation and slower moving fluid on the proximal wall [21,22]. The qualitative results showed significant difference of velocity contour at the left and right renal arteries between the SS and DS cases. It can be observed that the DS produced lower velocity contour at left and right renal artery compared to SS, which showed a lower velocity contour only at the right renal artery. This is due to the effect of stenosed at the renal artery vein which obstruct the blood flow passing through the acute diameter of stenosed. Hence, the balance of the blood flow supplied at the downward of the abdominal aorta. Indeed, the highest magnitude of velocity contour occurs at PS state compared to the other states. Meanwhile, Figure 4(b) represents the quantitative data of maximum velocity of the abdominal with stenosed renal artery at 4 different states. It can be observed that the DS produced a wide range of maximum velocity difference compared to SS condition with twofold of the value for the whole pulsatile cycle. The DS-NBP showed the highest maximum value of velocity contour, followed by the DS-HBP, SS-LBP and SS-HBP at each of state condition. At PS state, the highest value of maximum velocity is stated to be 2.56 m/s, followed by 2.13 m/s, 1.74 m/s and 1.71 m/s for DS-NBP, DS-HBP, SS-NBP and SS-HBP, respectively.

3.*2 Pressure Contour*

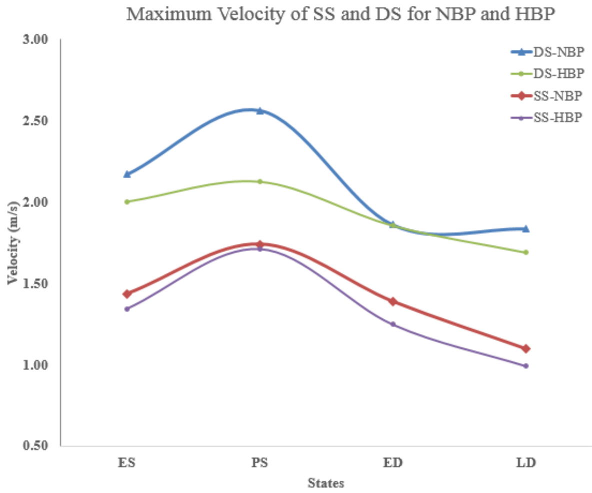
Meanwhile, Figure 5(a) showed the pressure contour of abdominal aorta with stenosed renal artery for ES, PS, ED and LD states. It was observed that the HBP of SS and DS performed twice maximum pressure contour compared to the NBP of SS and DS cases. The details observation showed that high pressure contour occurred at upwards of abdominal aorta compared to the downwards, where SS produced higher value than DS for NBP and HBP conditions, respectively. Meanwhile, at renal artery location of SS case, the right renal artery with stenosed vessel showed lower pressure contour compared to left artery of normal vessel condition. Hence, for DS cases, the right artery stenosed performed higher pressure contour compared to the left artery stenosed. On the other hand, Figure 5(b) showed the graph of maximum pressure value versus states of SS-NBP, SS-HBP, DS-NBP and DS-HBP. The quantitative results revealed that the DS-HBP indicated as the highest value of maximum pressure with 18674 Pa, followed by SS-HBP, SS-NBP and SS-HBP with 18407 Pa, 9144 Pa and 8992 Pa, respectively.

3.3 Wall Shear Stress

The WSS contour of SS-NBP, SS-HBP, DS-NBP and DS-HBP at ES, PS, ED and LD state, as in Figure 6 (a). The maximum value of legend limit is fixed to be 150 Pa for a better visualization of contour comparisons. It can be observed that high WSS contour occurred at the downward of the abdominal aorta and both renal artery stenosed location for DS cases. The result showed a significant high WSS value for DS-HBP followed by DS-NBP, SS-HBP and SS-NBP especially at PS state. For SS cases, the right renal artery with stenosed revealed higher WSS value compared to the left renal artery, while for DS cases, both location of renal artery with stenosed show high value of WSS contour. This happen due to effect of acute diameter of vessel stenosed, which higher WSS value was produced due to the impact of high velocity flows occurred at wall of the stenosed region. This qualitative results are supported quantitatively on maximum WSS value, as in Figure 6 (b). At PS state, the results indicated the highest value of maximum WSS, which DS-HBP produced highest WSS, and followed by DS-NBP, SS-NBP and SS-HBP with 124.45 Pa, 114.83 Pa, 113.99 Pa, and 104.47 Pa, respectively.

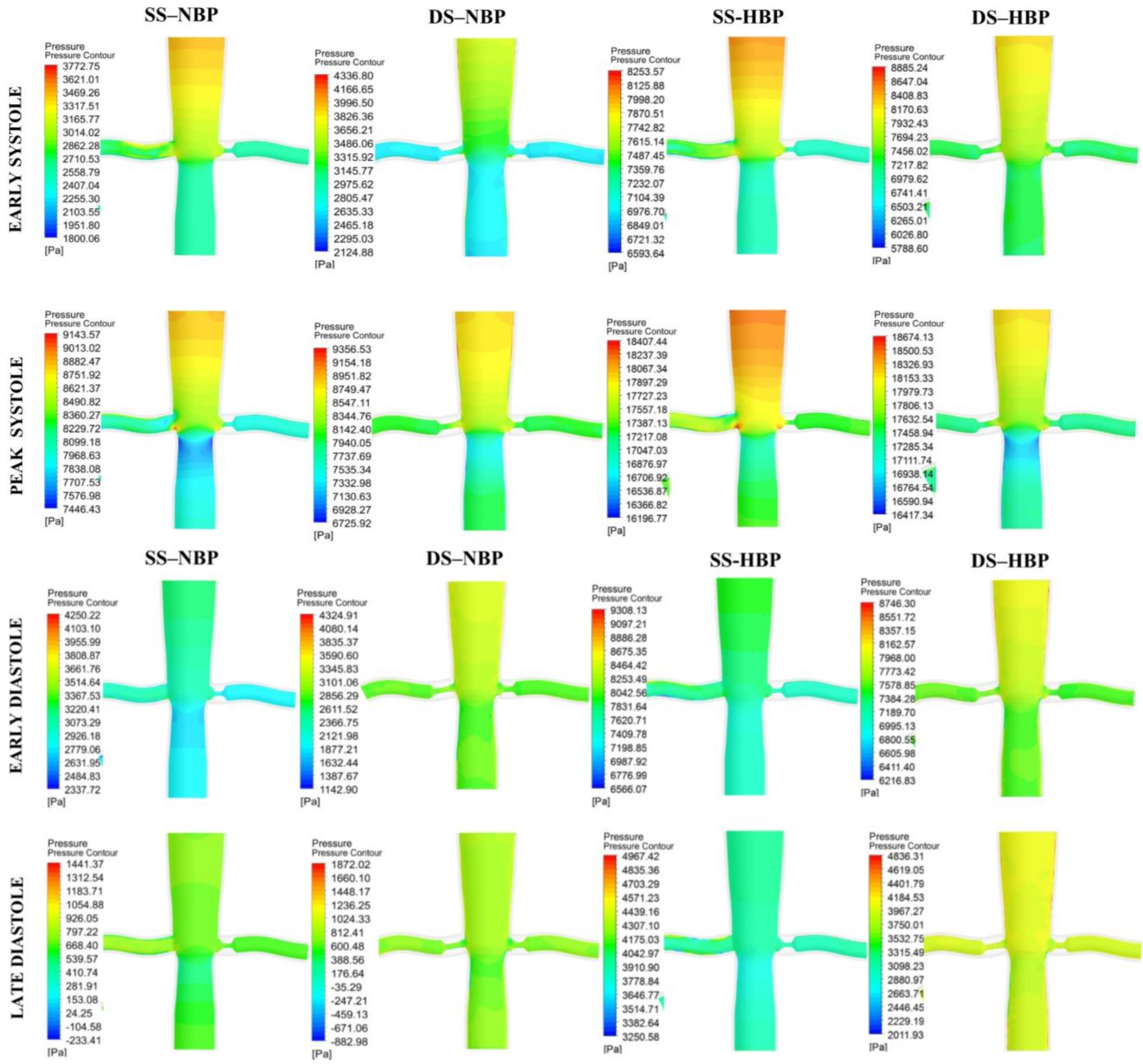


(a)

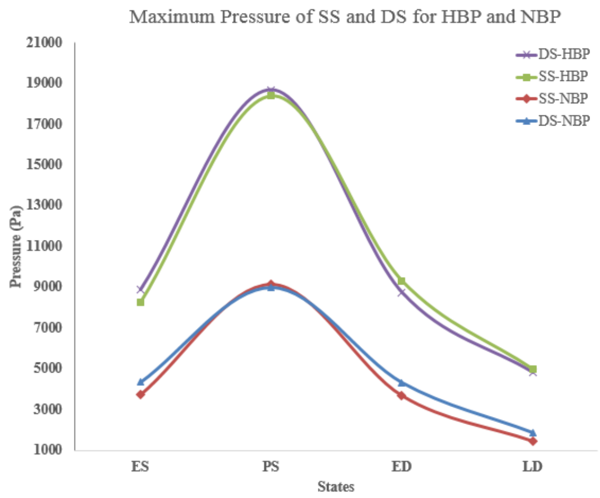


(b)

Fig. 4. (a) Velocity contour throughout renal artery of SS and DS for NBP and HBP condition (b). Maximum velocity of SS and DS for NBP and HBP condition

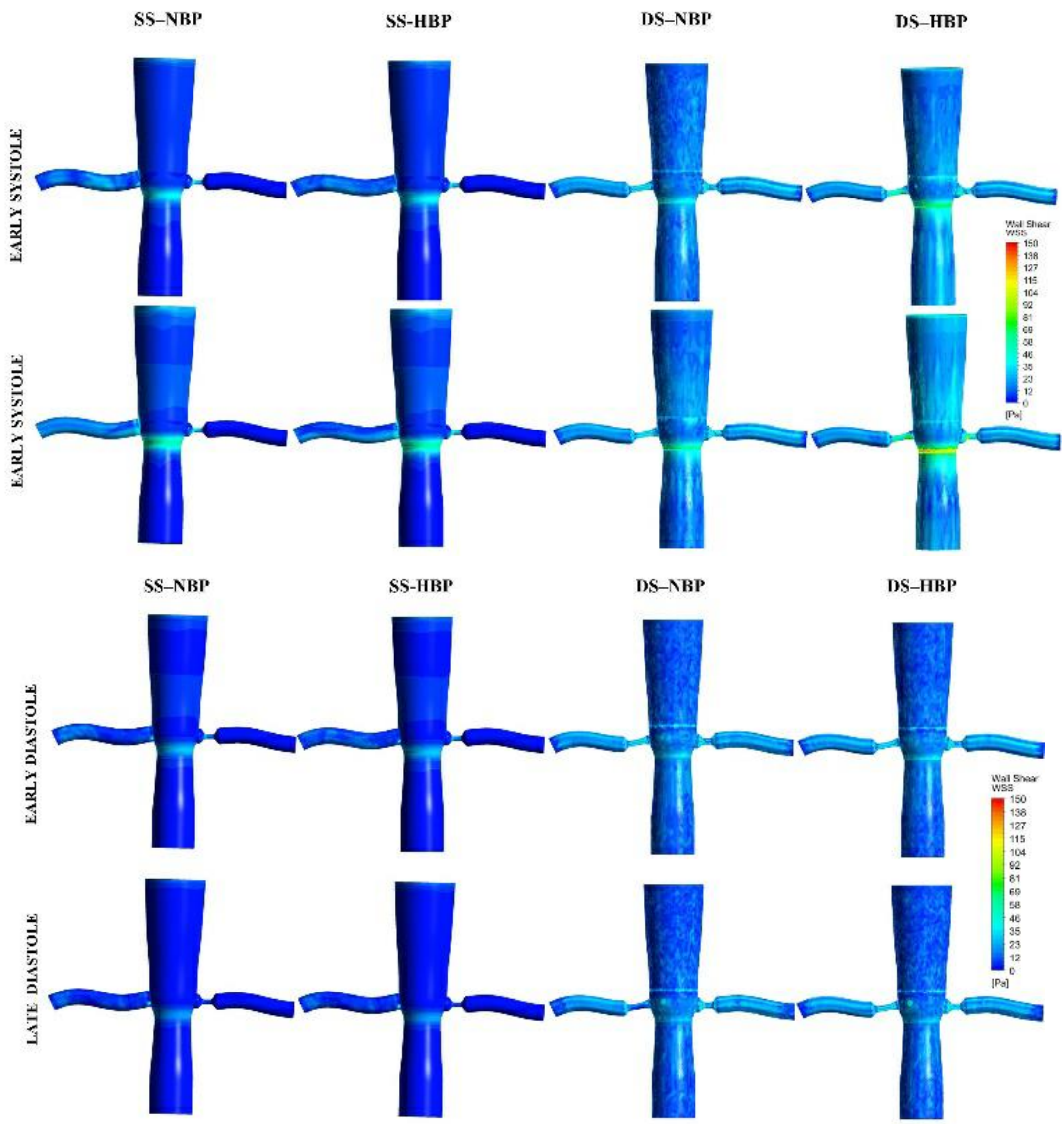


(a)

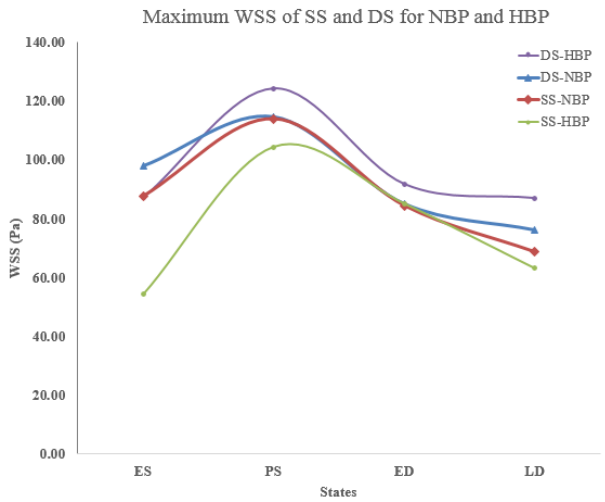


(b)

Fig. 5. (a) Pressure contour throughout renal artery of SS and DS of NBP and HBP conditions (b). Maximum pressure of SS and DS of NBP and HBP conditions



(a)



(b)

Fig. 6. (a) Wall shear stress contour throughout renal artery of SS and DS (b) Maximum WSS magnitude of SS and DS of NBP and HBP condition

4. Conclusions

Computational Fluid Dynamics (CFD) simulation of abdominal aorta branching into renal artery under normal pressure (NBP) and high pressure (HBP) were carried out for single (SS) and double stenosed (DS) models in this present study. The changes of pressure outlet for NBP and HBP showed major effects on pressure contour compared to velocity and WSS contours. For pressure contour, the DS-HBP shows the highest value of maximum pressure, and followed by SS-HBP, SS-NBP and DS-HBP.

Meanwhile, for velocity contour, the effects of stenosed condition (SS and DS) showed a great significant effect compared to pressure outlet changes, whereby DS-NBP and DS-HBP produced higher value than SS-NBP and SS-HBP. On the other hand, for the WSS contour, the effects of stenosed condition and pressure outlet changes showed minimal different with DS-HBP with the highest value, then followed by DS-NBP, SS-NBP and SS-HBP. The present study demonstrates the fundamental aspects of haemodynamics of blood flow behavior in idealized abdominal aorta with stenosed renal branches subjected to normal and high pressure conditions. The potential of significant results of this research due to the effects of high pressure condition may lead to other major vascular complications, stroke, endocarditis, and coronary artery occlusion.

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References

[1] Albert, Scott, Robert S. Balaban, Edward B. Neufeld, and Jenn Stroud Rossmann. "Influence of the renal artery ostium flow diverter on hemodynamics and atherogenesis." *Journal of biomechanics* 47, no. 7 (2014): 1594-1602.

[2] Moore Jr, James E., Chengpei Xu, Seymour Glagov, Christopher K. Zarins, and David N. Ku. "Fluid wall shear stress measurements in a model of the human abdominal aorta: oscillatory behavior and relationship to atherosclerosis." *Atherosclerosis* 110, no. 2 (1994): 225-240.

[3] Zhang, Weisheng, Yi Qian, Jiang Lin, Peng Lv, Kaavya Karunanithi, and Mengsu Zeng. "Hemodynamic analysis of renal artery stenosis using computational fluid dynamics technology based on unenhanced steady-state free precession magnetic resonance angiography: preliminary results." *The international journal of cardiovascular imaging* 30, no. 2 (2014): 367-375.

[4] Mortazavinia, Z., A. Zare, and A. Mehdizadeh. "Effects of renal artery stenosis on realistic model of abdominal aorta

and renal arteries incorporating fluid-structure interaction and pulsatile non-Newtonian blood flow." *Applied Mathematics and Mechanics* 33, no. 2 (2012): 165-176.

[5] Kagadis, George C., Eugene D. Skouras, George C. Bourantas, Christakis A. Paraskeva, Konstantinos Katsanos, Dimitris Karnabatidis, and George C. Nikiforidis." Computational representation and hemodynamic characterization of in vivo acquired severe stenotic renal artery geometries using turbulence modeling." *Medical engineering & physics* 30, no. 5 (2008): 647-660.

[6] Suh, Ga-Young, Andrea S. Les, Adam S. Tenforde, Shawn C. Shadden, Ryan L. Spilker, Janice J. Yeung, Christopher P. Cheng, Robert J. Herfkens, Ronald L. Dalman, and Charles A. Taylor. "Hemodynamic changes quantified in abdominal aortic aneurysms with increasing exercise intensity using MR exercise imaging and image-based computational fluid dynamics." *Annals of biomedical engineering* 39, no. 8 (2011): 2186-2202.

[7] Suh, Ga-Young, Andrea S. Les, Adam S. Tenforde, Shawn C. Shadden, Ryan L. Spilker, Janice J. Yeung, Christopher P. Cheng, Robert J. Herfkens, Ronald L. Dalman, and Charles A. Taylor. "Quantification of particle residence time in abdominal aortic aneurysms using magnetic resonance imaging and computational fluid dynamics." *Annals of biomedical engineering* 39, no. 2 (2011): 864-883.

[8] Marshall, Ian, Shunzhi Zhao, Panorea Papathanasopoulou, Peter Hoskins, and X. Yun Xu. "MRI and CFD studies of pulsatile flow in healthy and stenosed carotid bifurcation models." *Journal of biomechanics* 37, no. 5 (2004): 679-687.

[9] Wong, K. K., Jingliang Dong, and Jiyuan Tu. "Numerical Study of Stenosed Carotid Bifurcation Models Based on Wall Shear Stress Distribution." *International proceedings of chemical, biological and enviornmental engineering (IPCBEE)* 34 (2012): 40-44.

[10] Hussain, Siti Aslina, Tan Hong Tat, Mohd Ismail Abdul Hamid, Norhafizah Abdullah, and Azni Idris. "Pressure Reduction on Blood flow in Aorta Coronary Sinus Conduit." *Editorial Board* (2012): 347.

[11] Basri, Adi Azriff, Muhammad Zuber, Mohamad Shukri Zakaria, Ernnie Illyani, and Arifin Ahmad. "The Effects of Aortic Stenosis on the Hemodynamic Flow Properties using Computational Fluid Dynamics." In *Proc. Int. Conf. Comput. Methods Eng. Heal. Sci.(ICCMEH), December*, pp. 17-19. 2016.

[12] Basri, Adi A., Mohamed Zubair, Ahmad FA Aziz, Rosli M. Ali, Masaaki Tamagawa, and Kamarul A. Ahmad. "Computational fluid dynamics study of the aortic valve opening on hemodynamics characteristics." In *2014 IEEE Conference on Biomedical Engineering and Sciences (IECBES)*, pp. 99-102. IEEE, 2014.

[13] Basri, Adi Azriff, Muhammad Zuber, Mohamad Shukri Zakaria, Ernnie Illyani Basri, Ahmad Fazli Abdul Aziz, Rosli Mohd Ali, Masaaki Tamagawa, and Kamarul Ariffin Ahmad. "The hemodynamic effects of paravalvular leakage using fluid structure interaction; Transcatheter aortic valve implantation patient." *Journal of Medical Imaging and Health Informatics* 6, no. 6 (2016): 1513-1518.

[14] Zakaria, Mohamad Shukri, Farzad Ismail, Masaaki Tamagawa, Ahmad Fazli Abdul Aziz, Surjatin Wiriadidjaja, Adi Azrif Basri, and Kamarul Arifin Ahmad. "A Cartesian non-boundary fitted grid method on complex geometries and its application to the blood flow in the aorta using OpenFOAM." *Mathematics and Computers in Simulation* 159 (2019): 220-250.

[15] Zakaria, Mohamad Shukri, Farzad Ismail, Masaaki Tamagawa, Ahmad Fazli Abdul Aziz, Surjatin Wiriadidjaya, Adi Azrif Basri, and Kamarul Arifin Ahmad. "Numerical analysis using a fixed grid method for cardiovascular flow application." *Journal of Medical Imaging and Health Informatics* 6, no. 6 (2016): 1483-1488.

[16] Zakaria, Mohamad Shukri, Farzad Ismail, Masaaki Tamagawa, Ahmad Fazli Abdul Aziz, Surjatin Wiriadidjaja, Adi Azrif Basri, and Kamarul Arifin Ahmad. "Review of numerical methods for simulation of mechanical heart valves and the potential for blood clotting." *Medical & biological engineering & computing* 55, no. 9 (2017): 1519-1548.

[17] Zakaria, Mohamad Shukri, Farzad Ismail, Masaaki Tamagawa, Ahmad Fazli Abdul Azi, Surjatin Wiriadidjaya, Adi Azrif Basri, and Kamarul Arifin Ahmad. "Computational Fluid Dynamics Study of Blood Flow in Aorta using OpenFOAM." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 43, no. 1 (2018): 81-89.

[18] Khader, Shah Mohammed Abdul, Adi Azriff, Raghuvir Pai, Mohammed Zubair, Kamarul Arifin, Zanuldin Ahmad Ahmad, and Koteshwara Prakashini. "Haemodynamics Study in Subject-Specific Abdominal Aorta with Renal Bifurcation using CFD-A Case Study." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 50, no. 2 (2018): 118-121.

[19] Taylor, Charles A., Thomas JR Hughes, and Christopher K. Zarins. "Finite element modeling of three-dimensional pulsatile flow in the abdominal aorta: relevance to atherosclerosis." *Annals of biomedical engineering* 26, no. 6 (1998): 975-987.

[20] LIANG, Fuyou, Ryuhei YAMAGUCHI, and Hao LIU. "Fluid dynamics in normal and stenosed human renal arteries: an experimental and computational study." *Journal of Biomechanical Science and Engineering* 1, no. 1 (2006): 171-182.

[21] Basri, Adi Azriff, Shah Mohammed Abdul Khader, Cherian Johny, Raghuvir Pai, Muhammad Zuber, Kamarul Arifin Ahmad, and Zanuldin Ahmad. "Numerical Study of Haemodynamics Behaviour in Normal and Single Stenosed Renal

Artery using Fluid–Structure Interaction." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 51, no. 1 (2018): 91-98.

[22] Khader, Shah Mohammed Abdul, Adi Azriff, Cherian Johny, Raghuvir Pai, Mohammad Zuber, Kamarul Arifin Ahmad, and Zanuldin Ahmad. "Haemodynamics Behaviour in Normal and Stenosed Renal Artery using Computational Fluid Dynamics." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 51, no. 1 (2018): 80-90.