Applied Mechanics and Materials Vols. 465-466 (2014) pp 789-795
© (2014) Trans Tech Publications, Switzerland
doi:10.4028/www.scientific.net/AMM.465-466.789

Numerical Simulation to Investigate the Effect of Non Newtonian Properties of Blood on Wall Shear Stress in Diseased Artery

Muhamad Yunus[1, a], Anis Suhaila Shuib[2,b], Hasan Fawad[3,c]

[1]Mechanical Engineering Department, Universiti Teknologi PETRONAS Malaysia

[2]Chemical Engineering Department, Center for Intelligent Signal & Imaging Research (CISIR), Universiti Teknologi PETRONAS Malaysia

[3]Mechanical Engineering Department, Center for Intelligent Signal & Imaging Research (CISIR), Universiti Teknologi PETRONAS Malaysia

[a]yunus_g02031@utp.edu.my, [b]anisuha@petronas.com.my, [c]hasan.fawad@petronas.com.my

Keywords: Aneurysm, Wall Shear Stress, Newtonian, Power Law.

Abstract. Wall Shear Stress (WSS) in the artery is one of the indicators for brain artery disease progression. WSS is proportional to the viscosity and shear rate of the flowing fluid. In this study, WSS of cerebral artery with aneurysm was predicted using Computational Fluid Dynamics (CFD). The effect of non-Newtonian properties of blood will be studied by comparing Power law model with Newtonian model. Based on the results, maximum value of WSS is 150 Pa for Newtonian model and for Power Law model is 24 Pa. Newtonian model was found overpredicted the WSS resulted from Power Law.

Introduction

Aneurysm is one of the cerebrovascular disease which related to disorder in blood vessels of brain. The implication could leads include to stroke and ischaemic attack. Stroke caused by destruction of brain cells due to blood supply reduction. Impairment of sight as well as inability to speak, taste and move is a typical ischaemic attack symptoms. An aneurysm is formed when a blood vessel becomes dilated or distorted causing the vessel to expand to a size greater than its original diameter. Aneurysms can occur in a variety of blood vessels though they are most commonly found in the intracranial arteries. An aneurysm is a localized, blood-filled balloon-like bulge in the wall of a blood vessels. When the size of an aneurysm increases, there is a significant risk of rupture, resulting in severe bleeding, other complications or death. The mortality rate is almost 57%[1] for rupture occurs at a medical facility. Aneurysms can be hereditary or caused by disease, both of which cause the wall of the blood vessel to weaken[2][3].

When heart is pumping the blood to the vascular network, the artery wall is subjected to hemodynamic forces. The perpendicular forces resulting from the pressure pulse is responsible for arterial wall distension. The tangential stress exerted by the blood flow is the frictional force known as wall shear stress (WSS). Wall shear stress has been proposed as a key parameter to characterize aneurysm[4]. Measurement of wall shear stress can help predict the areas at risk where aneurysms can be rupture and this result useful for clinical diagnosis data. This information will assist medical practitioners to make clinical decision on the appropriate treatment for aneurysm. Wall shear stress is a function of the fluid mechanics of blood, and therefore the understanding of the development of aneurysms requires knowledge from the blood flow dynamics. WSS is a function of viscosity. Singh et al.[5] investigated the effect of smoking and hypertension conditions in aneurysmal artery. Hypertension and smoking correspond to high blood viscosity. They observed that aneurysm site increase the area if subjected to high WSS.

In recent years, many computational fluid dynamics (CFD) models have been constructed for cerebral aneurysms[6]. CFD has the potential to be a useful clinical tool in observing vascular flow and disease pathology. In CFD, hemodynamic studies employed Newtonian[3,7,8,9] and non-Newtonian models[10]. For studies which assume blood is a Newtonian fluid, the viscosity is taken as a constant value, thus ignoring the shear-thinning behavior of blood.

The objectives of this study is to fundamentally investigate the effect of shear-thinning behavior of blood WSS of cerebral artery with aneurysm. The flow of blood in aneurysm geometry is simulated using CFD approach. The 3D geometry dimensions are construction according to the average size of middle cerebral artery. Power law model is used to represent shear thinning behavior. The interest of the study is to compare the WSS resulted from Power law model and Newtonian model.

Methodology

Aneurysm Geometry

In this study, idealized model is constructed and meshing it using Design Modeller in ANSYS 14.0 software. Idealized model construct 3mm for diameter *d* with length *L* and maximum diameter *D*, 3 and 2 times the diameter[6]. Idealized model shown in Fig.1. Relative to a cylindrical *(z-r)* coordinates system centered at the middle of the bulge, the bulge and tube wall are defined by the function :

$$r'(z') = \begin{cases} 1/2 & \text{if} \quad |z'| > \mathrm{LR}/2 \\ \dfrac{DR+1}{4} + \dfrac{DR-1}{4}\cos\dfrac{2\pi z'}{LR} & \text{if} \quad |z'| \leq \mathrm{LR}/2, \end{cases}$$

where primes denote non-dimensionalisation by *d*, and a diameter ratio DR = *D/d* and length ratio LR = *L/d*.

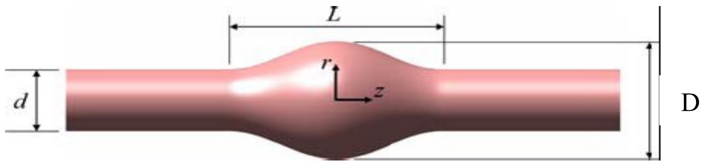


Fig. 1 Schematic idealized model under investigation, showing key dimensions and the cylindrical *(z-r)* coordinates. Fluid flows through the interior of the model.

Simulation model

The governing Navier-Stokes equation can be expressed in a vector form[11]:

$$\rho \frac{DV}{Dt} = -\Delta p + \mu \nabla^2 V + \rho S \tag{1}$$

where V is velocity magnitude, μ is viscocity of the fluid, ρ is density of the fluid, and S is body acting forces. The aneurysm diameter size 3mm is much larger than the size of blood cells ~5µm, hence, the blood can be modeled as a continuum.

Blood is generally accepted as a incompressible fluid with the density, ρ = 1080 kg/m^3[12]. The vascular wall treated as rigid. Newtonian blood viscosity is taken as, μ = 0.0041 kg/m-s[13].

Shear stress for Power Law model can be calculated from equation[13]:

$$\tau = \tau_0 + K(\gamma)n \tag{2}$$

For Power law, where K = consistency index, n = power law index, T = reference temperature. The parameters for simulation is summerised in Table 1. In order to calculate the WSS, the following relationship is used[14][15]:

$$\tau_w = -\mu\gamma = -\mu\frac{\partial v}{\partial r} \tag{3}$$

where τ_w is wall shear stress, μ is viscocity of blood, and γ is shear rate.

Table 1 Boundary conditions for Power Law model[16]

Power Law Index (n)	Reference Temperature (K)	Minimum Viscosity Limit (kg/m-s)	Yielding Viscosity (kg/m-s)	Consistency Index (kg-s ^n-2/m)
0.4851	310	0.00125	0.003	0.2073

Inlet velocity which is in the form of pulse flow is shown in Fig. 2. The inlet flow is the average of velocity in middle cerebral artery of 355 patients[17]. The pulse was set to 1s and the results are captured at 0.25s interval.

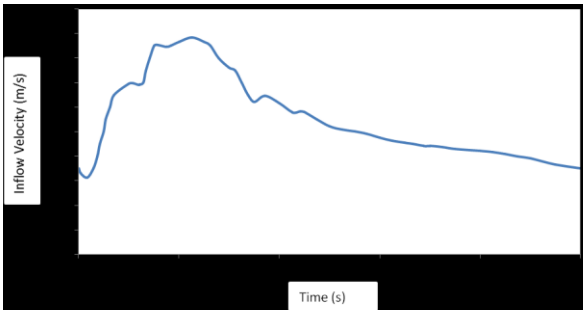


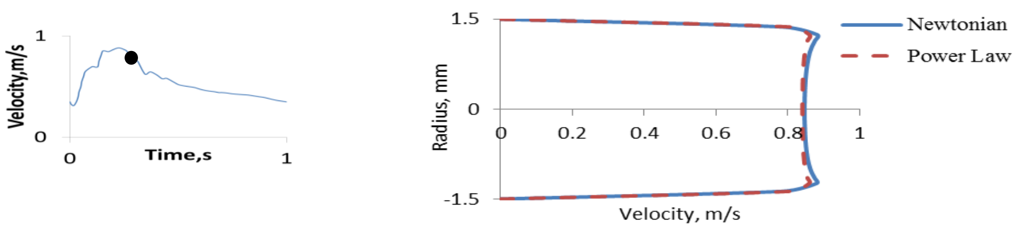
Fig. 2 The figure shows the inflow velocity profile with the time[17]

Results and Discussion

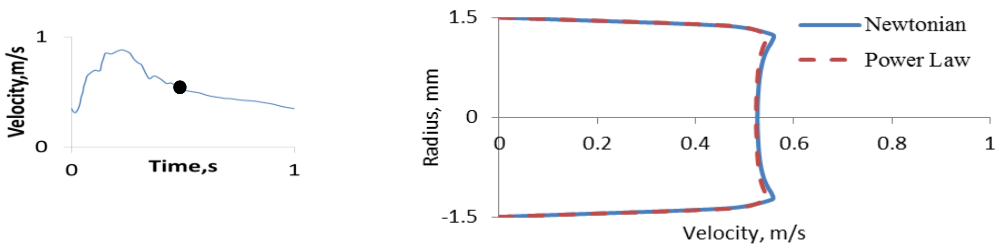
The results of velocity and WSS is analyzed at time t=0.25s, 0.5s, 0.75s and 1s. The pulse is maximum at t=0.20s.

Velocity Plot

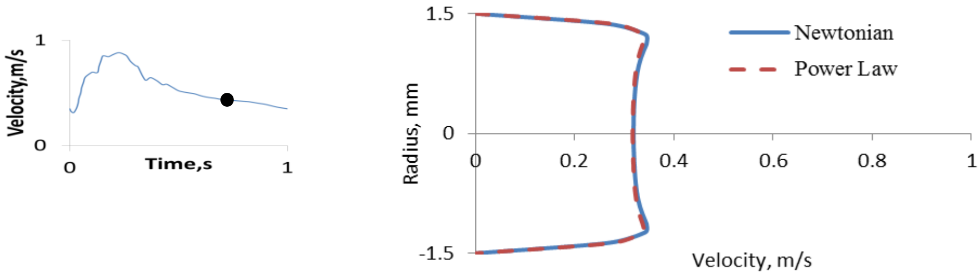
As shown in equation 3, velocity as an important parameter to obtain the WSS. The velocity resulted from Newtonian and Power law model for each time interval is plotted in Fig. 3.



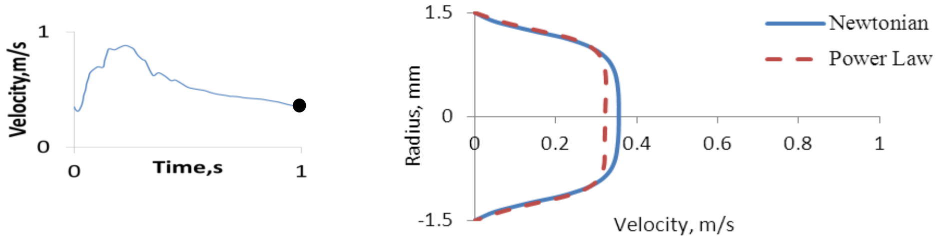
a. t= 0.25s



b. t= 0.50s



c. t= 0.75s



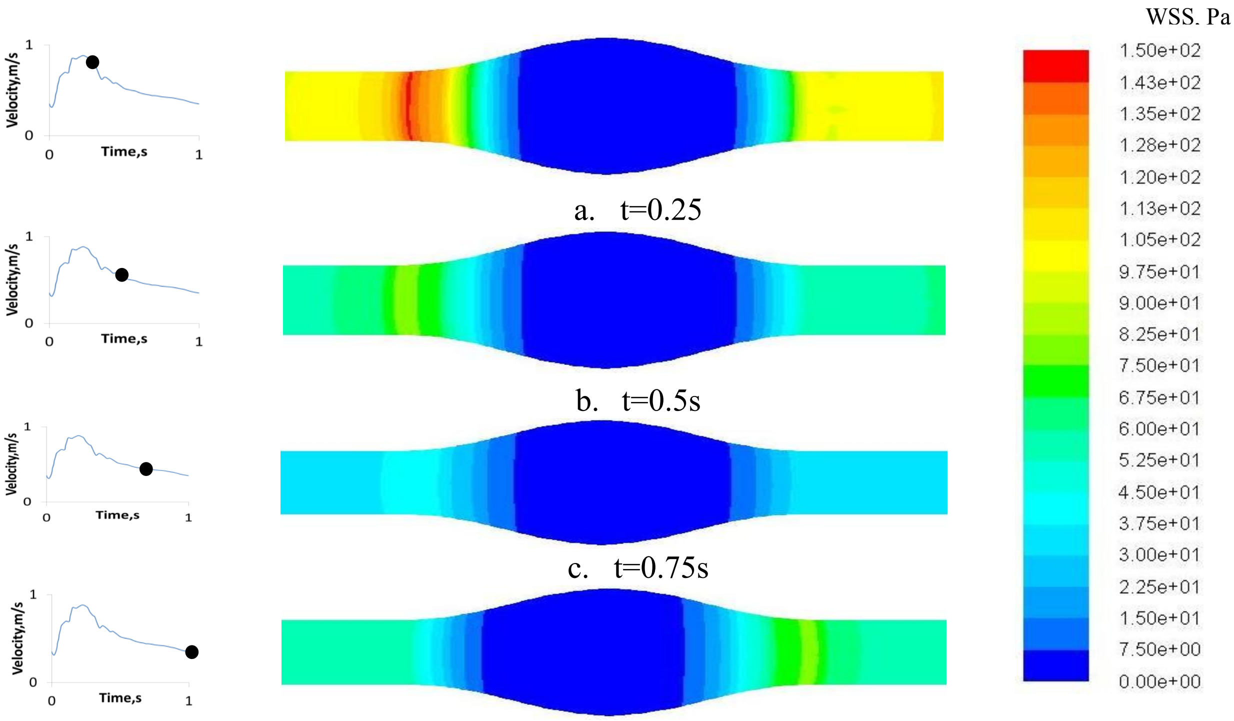
d. t= 1.0s

Fig. 3 Velocity profile along the anuerysm radius for Newtonian and Power Law model

As indicated in Fig. 3a, the velocity at t=0.25s is at around the peak of pulse flow with velocity of 0.85m/s. There is negative shear gradient in the region after the boundary layer at the artery wall which due to drag force. Similar velocity profile was observed at t=0.5s and t=0.75s. The magnitude of maximum velocity is 0.55m/s and 0.32m/s, respectively. The velocity magnitude for Newtonian and Power law is almost similar. At t=1s, the face of velocity profile is blunted with positive shear gradient. The maximum velocity for Newtonian model is 0.35m/s and 0.32m/s for Power Law. Power law predicted maximum velocity of 8.6% lower that Newtonian at this time instant.

Wall Shear Stress

WSS is calculated according to equation 3. The contour of wall shear stress for Newtonian and Power Law model are shown in Fig. 4 and Fig. 5, respectively.



a. t=0.25

b. t=0.5s

c. t=0.75s

d. t=1.0s

Fig. 4 Wall Shear Stress Contour for Newtonian model

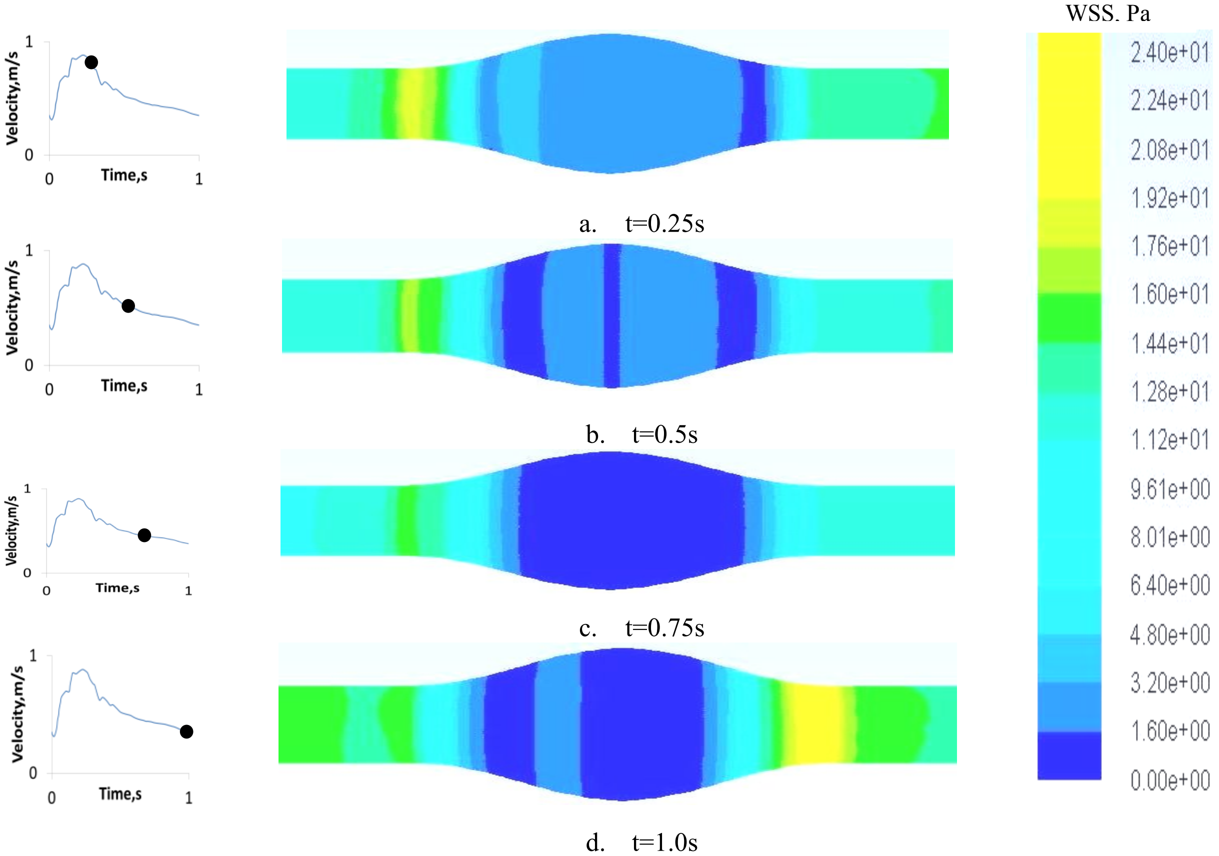
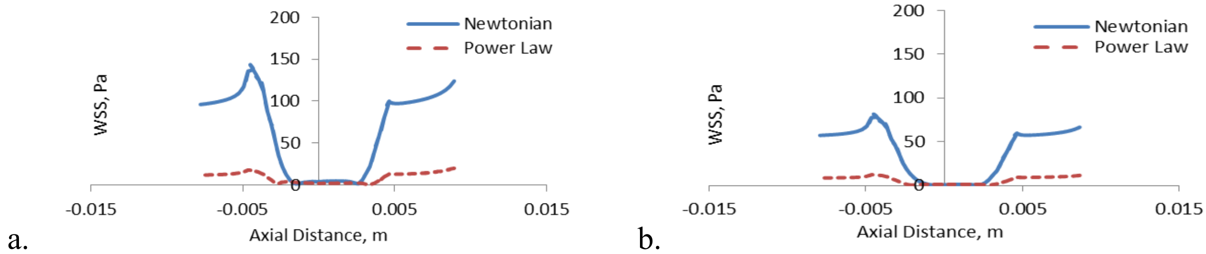


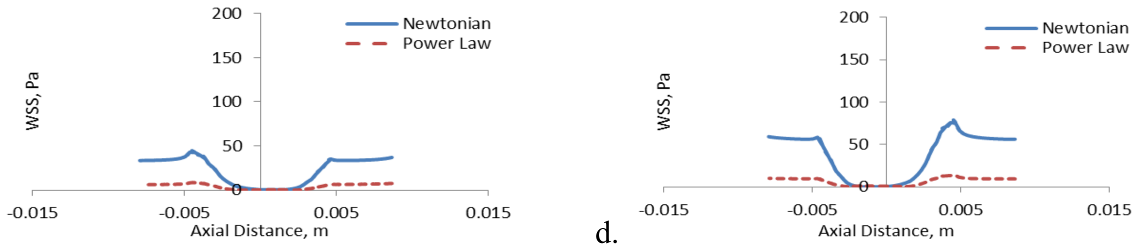
Fig. 5 Wall Shear Stress Contour for Power Law model

Newtonian model has a peak value of WSS is 150 Pa at t=0.25s which can be observed in Fig. 3a. The location of peak WSS is found prior to aneurysm bulge. The WSS decrease as the velocity decrease from peak pulse to t=1s. As shown in Fig. 5a, Power Law model has a peak value of WSS at 24 Pa. The WSS is decrease as the flow is decreased.

The comparison of WSS in axial direction is compared in Fig. 6. In general, high WSS occured prior entering the anuerysm site. High levels of wall shear stress encourages endhotelial and smooth muscle cell development in aneurysms, which may enhance the integrity of the wall tissue [12]. The WSS in anuerysm bulge is the lowest due the sudden increase in area and reduce in velocity. Low wall shear stress aneurysms exhibited significantly more growth, suggesting that the wall tissue in the center of the bulge is most susceptible to aneurysm disease progression [12].

In general power law predicted lower WSS value compared to Newtonian model. The highest difference occured at peak pulse of t=0.25s where WSS for Newtonian model is 6.25 times higher that Power law model.





c. d.

Fig. 6 WSS in axial z-direction at time interval, a. t=0.25s, b. t=0.50s, c. t=0.75s, d. t=1.0s

Conclusion

Blood flow in artery with anuerysm was simulated by considering Newtonian and Power Law rheological models. Power Law take in to accound the shear thinning property of blood. The velocity for both results was almost identical, hence it could be concluded that the shear thinning property is not affecting the magnitude of velocity. However, the peak WSS predicted by Newtonian model was 150 Pa which is 6.25 times higher than Power law. The results suggest that the non Newtonian property of blood is important and sensitive to WSS value.

Acknowledgement

The main author would like to express gratitude to Universiti Teknologi PETRONAS for supporting and sponsoring the research.

References

[1] M. J. Brown, A. J. Sutton, P. R. Bell, R. D. Sayers., A *Meta Analysis of 50 Years of Ruptured Abdominal Aortic Aneurysm Repair.* Br J Surg (2002). **89**. p: 714-730.

[2] C. Basciano, C. Kleinstreuer, S. Hyun, and E. A. Finol., *A Relation Between Near-Wall Particle-Hemodynamics and Onset of Thrombus Formation in Abdominal Aortic Aneurysms.* Annals of Biomedics Engineering, 2011. **39**(7): p. 2010-2026.

[3] Liang-Der Jou and Michel E. Mawad., *Hemodynamic effect of Neuroform stent on intimal hyperplasia and thrombus formation in a carotid aneurysm.* Elsevier-Science Direct, 2011. **33**: p.573-580.

[4] J. R. Blake, W. J. Easson, and P. R. Hoskins., *A Dual Phantom System for Validation of Velocity Measurements in Stenosis Models Under Steady Flow*. Elsevier Journal Ultrasound in Medical and Biology. 2009. **35**(9): p. 1510-1524.

[5] P. K. Singh, A. Marzo and B. Howard., *Effects of Smoking and Hypertension on Wall Shear Stress and Oscillatory Shear Index at The Site of Intracranial Aneurysm Formation*. Clinical Nuerology and Neurosurgery. 2010. **112**:p. 306-313.

[6] Harvey Ho, Jian Wu and P. Hunter., *Blood Flow Simulation in a Giant Intracranial Aneurysm and Its Validation by Digital Subtraction Angiography*. Springer science. 2011.

[7] B. Luo, X. Yang, S. Wang, H. Li, J. Chen, H. Yu, Y. Zhang, Y. Zhang, S. Mu, Z. Liu and G. Ding., *High Shear Stress and Flow Velocity in Partially Occluded Aneurysms Prone to Recanalization* . Journal of American Heart Association, 2011. **42**: p. 745-753.

[8] G. J. Isaksen, Y. Bazilevs, T. Kvamsdal, Y. Zhang, J. H. Kaspersen, K. Waterloo, B. Romner and T. Ingebrigtsen., *Determination of Wall Tension in Cerberal Artery Aneurysms by Numerical Simulation.* Journal of American Heart Association, 2008. **39**: p. 3172-3178.

[9] A. G. Radaelli, L. Augsburger, J. R. Cebral, M. Ohta, D. A. Rufenacht, R. Balossino, G. Benndorf, D. R. Hose, A. Marzo, R. Metcalfe, P. Mortier, F. Mut, P. Reymond, L. Socci, B. Verhegghe and A. F. Frangi., *Reprodicibility of Haemodynamical Simulations in a Subject-Spesific Stented Aneurysm Model* . Journal of Biomechanics Elsevier, 2008. **41**: p. 2069-2081.

[10] V. L. Rayz, L. Boussel, M. T. Lawton, G. Acevedo-Bolton, L. Ge, W. L. Young, R. T. Higashida and D. Saloner., *Numerical Modelling of the Flow in Intracranial Aneurysms : Prediction of Regions Prone to Thrombus Formation* . Journal of Biomedical Engineering, 2008. **36**: p. 1793-1804.
[11] G. J. Sheard., Flow *Dynamics and Wall Shear Stress Variation in a Fusiform Aneurysm.* Journal Eng Math (2009). **64**. p: 379-390.
[12] J. P. McGarry, B. P. O'Donnell, P. E. McHugh and J. G. McGarry., *Analysis of the Mechanical Performance of a Cardiovascular Stent Design Based on Micromechanical Modelling*. Computational Materials Science Elsevier, 2004. **31**: p. 421-438.
[13] S. O' Callaghan, M. Walsh and T. McGloughlin., *Numerical modelling of Newtonian and non-Newtonian representation of blood in a distal end-to-side vascular bypass graft anastomosis.* science direct elsevier 2006. **28**: p. 70-74.
[14] P. R. Hoskins and D. Hardman., *three-dimensional imaging and computational modelling for estimation of wall stresses in arteries.* British Journal of Radiology, 2009. **82**: p. S3-S17.
[15] D. Elad and S. Einav., *Physical and Flow Properties of Blood*. 2004, Tel Aviv.
[16] S. Petkova, A. Hossain, J. Naser and E. Palombo., *CFD Modelling of Blood Flow in Portal Vein Hypertension With and Without Thrombosis.* Conference on CFD in the Minerals and Process Industries. 2003.
[17] K. V. Sendstad, K. A. Mardal, M. Mortensen, B. A. P. Reif and H. P. Langtangen., *Direct Numerical Simulation of Transitional Flow in a Patient-Spesific Intracranial Aneurysm.* Journal of Biomechanics Elsevier, 2011. **44**: p. 2826-2832.