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Evaluation of Blood Hemodynamics in Patients with Cerebral Aneurysm

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ABSTRACT

Background: Aneurysm is a blood-filled bulge in the wall of vessels that occurred in abdominal aortic and cerebral vessels. The dilation of artery leads to aneurysm.
Methods: Three dimensional modelling was utilized for a patient with cerebral aneurysm and a normal subject, and additional fluid-structural interaction simulation was performed. We consider pulsatile blood velocity as inlet, and blood pressure as outlet of flow.
Results: The main results including blood velocity, wall shear stress (WSS) of vessel and displacement of wall of vessel. The maximum velocity in normal subject has been 0.2 m/s, that this value in a patient has increased into 0.27 m/s. Blood flow in normal subject and patient remained in limitation of laminar flow and occurrence of aneurysm, has not lead into the turbulent flow. The results showed, WSS in the of vessel after occurrence of aneurysm has increased into 6.3 times greater than normal, which this difference revealed that this parameter was proper index for evaluation of aneurysm. Also, the phase lag of WSS between the normal subject and patient has been 98º that this phase lag was significant in two cases. Due to occurrence of aneurysm, the thickness of the wall decreased during the disease by up to 10% which the continuation of disease progress result in rupture of vessel.
Conclusion: To help the physician, besides analysing hemodynamic parameters of blood flow through non-invasive method, the effective numerical indices (WSS magnitude and WSS phase lag between patient and normal subject) introduced in order to evaluation cerebral aneurysm conditions.

Keywords: Fluid-structural interaction; Wall shear stress; Numerical index; Blood velocity; Displacement of vessel

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INTRODUCTION

Aneurysm is a local dilation of an artery wall, in most cases aneurysms happen in abdominal aortic and cerebral vessels. Subarachnoid hemorrhage is a kind of brain hemorrhage which is caused by ruptured of aneurysm and leads to many casualties. According to statistics data this happen occurs nearly 12% before receiving medical attention and 40% after being hospitalized. In less than one month and more than one third of survived patients mostly ends up with neurological deficits [1]. Cerebral aneurysms usually happened in vessels that are curved form and in bifurcating arteries of Willis circle [1].

In previous studies analysed that the geometry of aneurysm is an effective parameter for evaluation of the intensity of aneurysm and rupturing of vessels [2-5]. Based on these findings, some researchers investigated the effect of size of formed aneurysm dome and revealed that this size has considerable effect on growth of aneurysm and risk of rupture [6-9].

Other studies assessed hemodynamics parameter of blood flow in patients with cerebral aneurysm by computational fluid dynamics (CFD) [10-12]. Valencia et al. analysed particular effects of non-Newtonian blood, through CFD in patients with cerebral aneurysm in carotid [10]. They revealed that the study of blood as non-Newtonian fluid in evaluation of wall shear stress (WSS), is significant important in some parts of vessels that has high gradient velocity [10].

Steinman et al. by CFD method, compared the effect of change of vortices in input parts of aneurysm, between normal subject and patient [11]. They follow-up a patient in 6 month for evaluation of the blood vortex. They found that the blood flow pulsatility has significant effect in aneurysm studies.

Shojima et al. investigated and compared WSS between the aneurysm dome and parent artery [12]. The results showed that low WSS may due to growth aneurysm if we have high degenerative changes in the wall of cerebral aneurysm.

Although, aforementioned studies have been computed through CFD, the displacement of vessel wall in the aneurysm dome has not been considered.

In other studies about hemodynamic parameter of blood flow, they used fluid-structure interaction (FSI) method for analysis of cerebral aneurysm [13,14].

Baek et al. examined the effect of size and the direction of vector of WSS and the effect of unstable flow in aneurysm region, through FSI method [13]. Their results showed that WSS vectors near the aneurysm's region display significant spatio-temporal changes in direction.

Valencia et al. examined the effect of hemodynamic parameters of blood flow in bifurcation location of vessels through FSI method [14].

In this study we investigate hemodynamics parameters of blood flow in the cerebral aneurysm with curved vessels through FSI method. After evaluation effect of these parameters, we introduce the numerical indices for analysing the intensity of aneurysm, in order to help the physicians to diagnosis and predict the risk of rupture and to select a proper treatment option for patients with cerebral aneurysm.

METHODS

It first, after extracting the dimensional and modelling data in Solid-Work Software 2012 (Figures. 1 a and b), these data were transferred to ABAQUS Software 6.14. Model 1 is patient with cerebral aneurysm which the type of neck aneurysm is circular neck and model 2 is related to normal subject. The dimensional data of models 1 and 2 is showed in Table 1 [15]. Numerical analysis of models have been done through FSI and using the formalization of arbitrary Lagrangian-Eulerian (ALE). Blood has considered as fluid domain and the wall of vessel as solid domain. The blood considered Newtonian and non-compressible fluid and the wall of vessel considered linear elastic.

Computational Analysis

Regarding the use of FSI method and ALE equations for numerical simulation of equations governing the wall of vessel and blood flow model, Mass and momentum conservation equations which is applied for analyzing fluid domain (blood) in Eulerian approach, is according

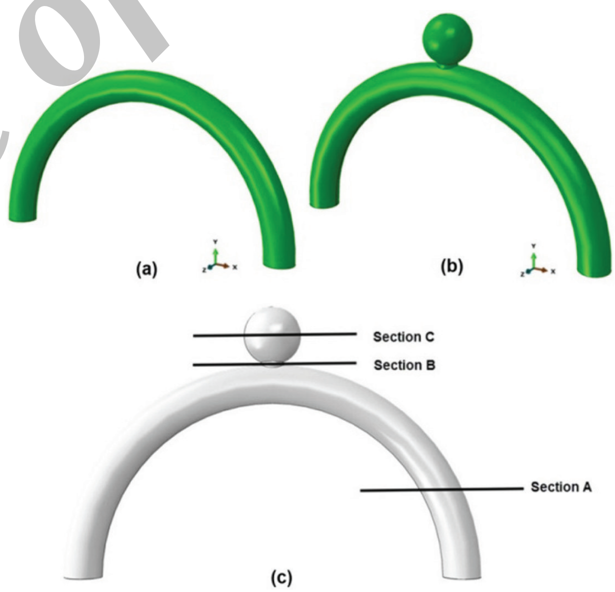

Figure 1. Panel a and b show 3D models of normal subject vessel and the vessel of patient with aneurysm, respectively. Panel c shows three sections of vessel and aneurysm region.

Table 1. Geometrical information of the normal subject's vessel and patient's aneurysm.

Normal subject diameter (mm)	Patient diameter (mm)	Vessel's wall thickness in cases (mm)	Parts of vessel and aneurysm
4	4	0.6	Parent artery
---	6	0.38	Aneurysm dome
---	2.5	0.38	Neck aneurysm

Equations (1 and 2):

$$\nabla \cdot u = 0 \quad (1)$$

$$\rho_f \left(\frac{\partial u}{\partial t} + \left(\left(u - u_g\right).\nabla\right)u = -\nabla_P + \nabla_\tau\right) \quad (2)$$

where ρ_f, u, u_g, (u-u_g) are blood density, blood velocity vector, velocity in moving coordinate and relative velocity of the blood with respect to the moving coordinate velocity, respectively [16].

The equation of Cauchy stress tensor (τ) as follows:

$$\tau_{ij}^{f} = -p\delta_{ij} + 2\mu e_{ij} \quad (3)$$

where μ is blood viscosity and δij is Kronecker Delta [17]. Strain tensor (e_{ij}) is defined by Equation (4):

$$e_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \quad (4)$$

where u_i and u_j are fluid velocity vector in the direction of i and j, respectively [18].

The boundary between blood and vessel in all interfaces has been considered as boundary FSI. The boundary conditions are according Equations (5-7):

$$d_s = d_f \quad (5)$$

$$\sigma_s.\widehat{n_f} = \sigma_f.\widehat{n_f} \quad (6)$$

$$u_s = u_f \quad (7)$$

where d_s, d_f, σ_f, σ_s, and n̂ are displacement of solid domain, displacement of fluid domain, stress tensor in the blood in the FSI boundary, stress tensor in the wall of vessel in the FSI boundary and the normal vector in the FSI boundary, respectively. Equation 6 shows the dynamic boundary conditions which are indicating the conformity of stress from blood and vessel in normal plane on FSI interface. Equation 7 indicates the velocity of blood and the wall of vessel in FSI interface is the same, that this condition also called kinematic boundary conditions [19].

Material properties and boundary conditions

The biological-fluid properties of fluid (blood) and biomechanical characters of solid (wall of vessel) domains are showed in Tables 2 and 3 [20-22]. Internal wall of vessel in all parts which are contacted by blood, considers as FSI boundaries.

Blood pulsatile flow at the entrance of vessel consider as inlet flow. The inlet amplitude of velocity function

Table 2. The assumptions for the fluid model (blood)

Dynamic viscosity (Pa.s)	Density (kg/m^3)
0.004	1050

Table 3. The assumptions for the solid model (wall of vessel)

Density (kg/m^3)	Young's modulus (MPa)	Poisson ratio
2300	3	0.49

and its frequency were imposed as 0.21 m/s and 1.61, respectively [14]. However, outlet pressure considered zero [17]. Figure 2a, shows the diagram of inlet flow. The place of inlet and outlet of blood flow illustrate in Figure 2b. The entrance and exit of vessel in which portrayed by red color (Figure 2b), were constrained in three directions. It is worth noting that the place and diagram of inlet and outlet flow, has been the same for both normal subject and patient.

Grid independence study

The type of elements applied in modelling fluid and solid are tetrahedral and triangular, respectively. In order

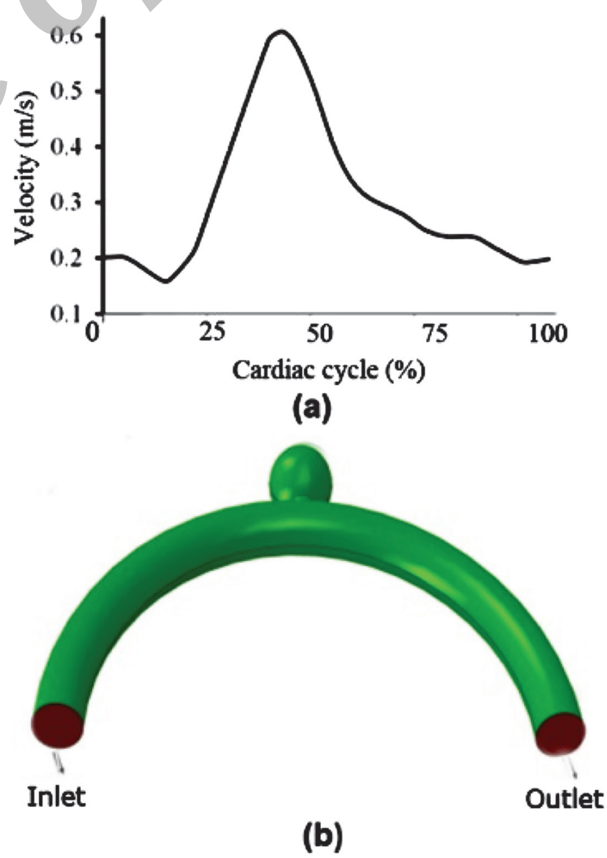

Figure 2. Panel a shows the inlet velocity diagram of blood flow. Panel b shows the place of inlet and outlet of blood flow.

to investigate of grid independence and convergence of numerical model, we have been compared blood velocity in aneurysm. According to Figure 3, there is a little different between medium and fine element. It indicates that convergence conditions and grid independence is acceptable.

RESULTS

Evaluation of blood velocity

After ensuring of grid independence, the results computed periodically through FSI method. In order to analyze the flow, it is necessary to measure and compare the velocity of blood in the patient and normal subject.

According to Figure 4, maximum velocity of blood is in parent artery (it is not in aneurysm region) and its maximum magnitude for patient is equal 0.268 m/s. This value in Zhang et al.'s and Shishir et al.'s studies are 0.208 and 0.230 m/s, respectively [15,22]. The error between velocity data of this study and previous studies has been equaled 22% and 30%, respectively. The reason of this difference is the solution method utilized in this study. In those studies the boundary between blood and wall of vessel in the aneurysm, has been limited by the conditions of No-Slip and that solution method were CFD. But in this study fluid-solid interface is movable and the solution method is FSI. Therefore, in this study, the condition of blood flow is considered near to its in vivo conditions. Therefore the outcomes are more desirable and more reliable.

According to Figure 4 and Table 4, the maximum velocity in normal subject and patient are 0.20 m/s and 0.29 m/s, respectively. This means that, after occurrence of disease, the blood velocity in aneurysm dome has been reduced. But the magnitude of maximum velocity that showed in section A (referred Figure 1c), has increased up to 35%. Considering this description, the blood velocity in patient with cerebral aneurysm could be a weak index for evaluation of aneurysm conditions.

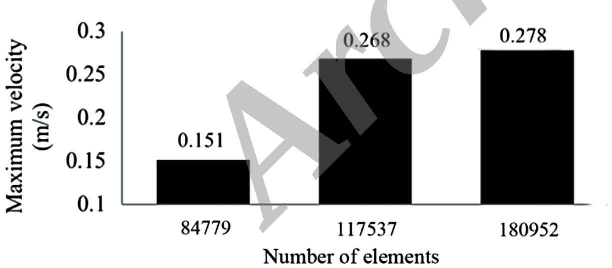

Figure 3. The diagram of maximum blood in terms of element numbers. The convergence of results and their grid independence conditions can be seen.

Table 4. The comparison of blood velocities between normal subject and patient

Blood velocity in normal subject (m/s)	Blood velocity in patient (m/s)	
0.199	0.268	Section A
-	0.176	Section B
-	0.032	Section C

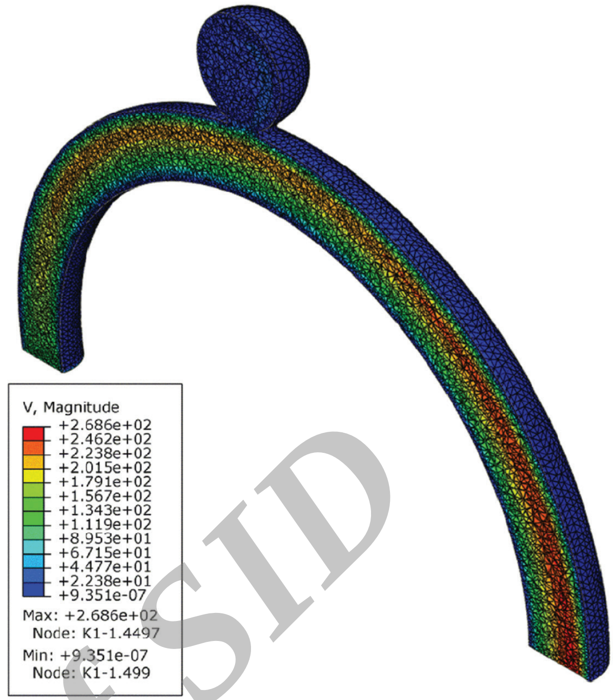

Figure 4. The distribution of blood velocity in vessel and aneurysm region for patient.

According to Table 4, the maximum blood velocity of patient has occurred in section A (parent artery), and also, the minimum velocity was in section C (aneurysm dome). The reason of such phenomenon is the continuity law. Considering the continuity law and the fact that parent artery has a smaller cross-sectional area than the aneurysm dome, therefore the blood velocity in this cross section should be max and consequently, the velocity magnitude should decrease with the increase in cross-sectional area. This trend of velocity reduction for patients is completely visible in Figure 4.

Evaluation of wall shear stress

Figure 5 illustrates the distribution of WSS in vessel and aneurysm region for patient. According to this figure, in the patient with cerebral aneurysm, the maximum magnitude of WSS has occurred in the neck aneurysm and this value is equal to 28.5 Pascal (Table 5).

According to Table 5, the maximum WSS in patient and normal subject are 28.5 Pascal and 4.5 Pascal,

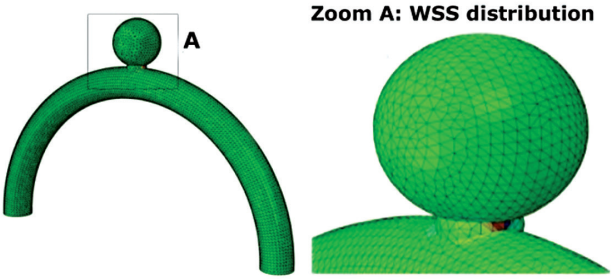

Figure 5. The distribution of WSS in vessel and aneurysm region for patient.

Table 5. The comparison of WSS between normal subject and patient

WSS in normal subject (Pa)	WSS in Patient (Pa)	
4.5	6.5	Section A
-	28.5	Section B
-	8.4	Section C

respectively. After occurrence of aneurysm, the value of WSS in all places (sections A, B and C) has increased severely. The maximum WSS in patient were about 6.3 times greater than those in normal subject.

DISCUSSION

Figure 6 has compared blood velocity diagrams in three sections (referred sections A, B and C in Figure 1c) for patient and in one section (sections A) for normal subject. According to Figure 5, there is less than 9° phase lag between blood velocity function in three sections for normal subject. It is noteworthy that the maximum velocity is occurred in the time of 13% of cardiac cycle for both patient and normal subject.

According to Table 4, the difference between the velocities in patient and normal subject is about 35%. For the functional usage of this result, physicians with head Cine PC magnetic resonance imaging (Cine PC-MRI) of patient can measure and compare the velocity diagram in the neck aneurysm and parent artery.

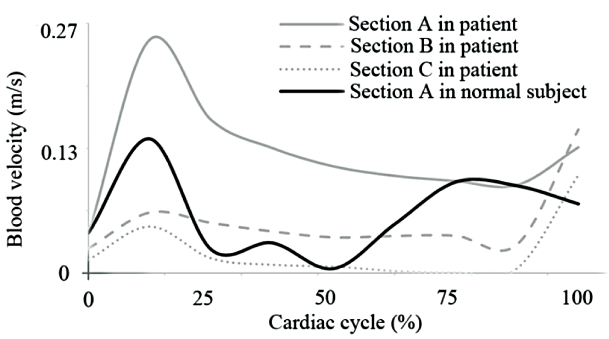

Figure 6. The comparison of blood velocity diagrams between normal subject and patient.

According to Figure 7, the WSS diagrams have been shown according to cardiac cycle of normal subject and patient. The maximum WSS in patient were 6.3 times greater than those in normal subject while this value for blood velocity is only 1.3, also, the phase lag of WSS functions between the patient and normal subject was equal 98º (Figure 7), but this

value for the blood velocity was 9º (Figure 6). Therefore, we can conclude that maximum WSS and phase lag of its diagram between patient and normal subject have significant changes. Finally these parameters are proper indices for evaluation of aneurysm conditions.

The Reynolds number is the best index to determine if the blood flow is laminar or turbulent and is calculated by the following equation (8):

$$Re = \frac{\rho^f \boldsymbol{u}\,\boldsymbol{D}}{\mu} \tag{8}$$

where Re is the Reynolds number and D is the diameter of the section of vessel or aneurysm. In biofluid studies, Reynolds number less than 1, means diffusive flow and also Reynolds number less than 1000, indicates the laminar flow. Reynolds number in normal subject and patient are 215.3 and 290.7, respectively.

Therefore, despite increasing of Reynolds number after occurrence of disease into 35%, the low Reynolds number indicates a relatively laminar flow in patient and normal subject.

Therefore, WSS is better index than velocity and Reynolds number for evaluation of the condition of the patient with cerebral aneurysm, because both velocity and Reynolds number in patient was 35% more than normal subject, while, WSS of patient was 3.4 times greater than normal.

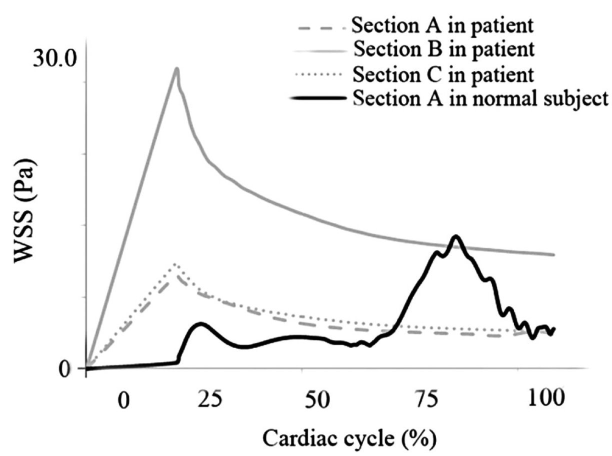

Figure 7. The comparison of WSS diagrams between normal subject and patient.

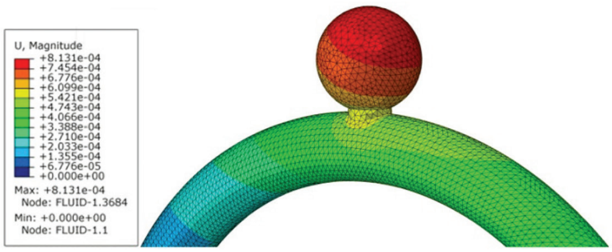

Figure 8. Panel shows the displacement of aneurysm region in patient.

Investigating of thickness of vessel

Aneurysm is change geometry in vessel. The physician observes the images of head MRI and clinical symptoms of patient for understanding of intensity of aneurysm and selects a suitable treatment option of patient. For this reason, in this section, we analyze the displacement of wall of vessel after occurrence of aneurysm.

Figure 8 shows that maximum displacement is occurred in the aneurysm dome. According to this figure, the thickness of vessel has decreased during disease up to 10%. After occurrence of aneurysm, shear stress of blood towards wall of vessel is increased and thickness of wall of vessel is decreased. Consequently, if this trend continues, rupture of vessel would occur. This phenomenon causes cerebral hemorrhage and finally leads to patient's death.

The limitation of this study was assumptions of blood flow. As we know, blood is a non-Newtonian fluid with a lot of particles but in this study we considered blood as Newtonian fluid. Because of low velocity of blood in aneurysm, probably the assumption of Newtonian could be regarded as a suitable approach for analyzing of the blood flow in this study.

CONCLUSIONS

Our research compared the three-dimensional blood flow model in a patient with cerebral aneurysm and a normal subject. The results reflected the manner of blood hemodynamic parameters changes in the patient and normal subject. Results showed that after occurrence of cerebral aneurysm, the maximum blood velocity and maximum WSS were 1.3 and 6.3 times greater than normal subject, respectively. Additionally, the thickness of vessel after occurrence of aneurysm decrease and the continuous of this reduction would due to rupture of vessel. The maximum and phase lag of WSS in patients with cerebral aneurysm has been introduced as proper indices in order to evaluation of the conditions of disease and the physicians can used these indices as effective parameters for understanding of intensity of disease. In this study, we investigated the biomechanism of changes in blood hemodynamic after occurrence of aneurysm and introduced the indices for evaluation of disease. This can significantly help physicians in selection of a proper and reliably effective treatment strategy.

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