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Comparative Blood Flow Velocity investigations in the Patient-Specific Circle of Willis with Aneurysm: Transcranial Doppler, Computational Fluid Dynamic

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Abstract: *The main center of the brain blood distribution is the Circle of Willis (COW). Obtaining information of hemodynamic parameters is very important for diagnosing of cardiovascular diseases, such as aneurysm in cerebral arteries. Non-invasive or semi-invasive Clinical methods for diagnosing any vascular diseases in this area can only measure blood velocity. One of them is Transcranial Doppler. Several factors influence the accuracy of TCD such as arteries wall motion, probe positions and angle and even mistake of operator. The existence of these errors can lead to wrong estimations and affect the treatment planning. Computational fluid dynamic is one of the most important approaches for obtaining exact hemodynamic information. In this study, realistic three-dimensional models have been produced from angiography images. A domain of the blood flow has been simulated by the ANSYS.CFX software. The velocity in the Circle of Willis has been calculated and compared with the velocity obtained from Transcranial Doppler, and the accuracy of the measured parameters has been considered. Results showed that the correspondence between computational fluid dynamics (CFD) and Doppler test (TCD) in different vessels of the circle of Willis are different, and in some arteries it increases. Maximum differences in the arteries are achieved to 80 cm/s and on the opposite side 40 cm/s. Comparison of the results shows that in arteries which are near the surface of the skull and slight inflexion, the accordance between the TCD and the CFD data is appropriate.*

1 INTRODUCTION

The main center of the brain blood distribution is the Circle of Willis (COW). Circle of Willis is a network of cerebral arteries in the base of the brain that blood flow is entered into the skull by Common Carotid Arteries (CCA) from anterior and Vertebral Arteries (VA) from posterior (Figure 1). The importance of understanding the sensitivity of cerebral perfusion in COW is for preventing stroke as the third frequent cause of death [1]. Development of any disturbance in the circle and exit of their natural conditions can change the hemodynamic of the blood flow and result in damage of the vascular system. One of these damages is known as brain aneurysm that occurs in 3-6% of people with 75% mortality rate [2-5].

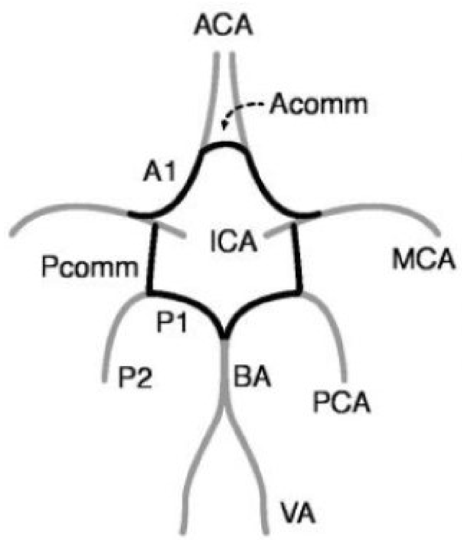


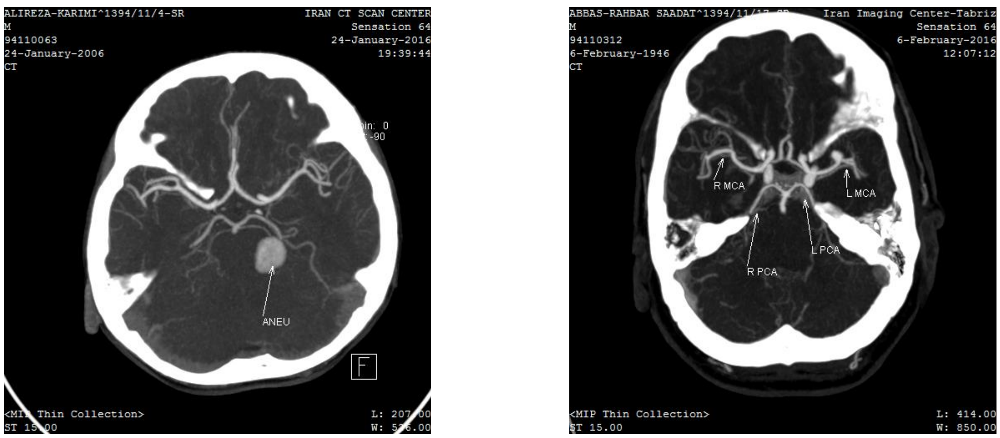
Figure 1: Schematic diagram of the Circle of Willis arteries; ACA: Anterior Cerebral Artery, AComm: Anterior Communication Artery, MCA: Middle Cerebral Artery, PComm: Posterior Communication Artery, PCA: Posterior Cerebral Artery, BA: Basilar Artery, VA: Vertebral Artery.

Intracranial aneurysms are difficult to treat and often do not reveal symptoms before the rupture. Nowadays, only morphological properties of aneurysm are evaluated pretreatment, without reference to hemodynamic abnormalities. At the moment, *in-vivo* clinical methods used for measurement of hemodynamic parameters especially blood velocity, are Transcranial Doppler (TCD) and Phase Contrast Magnetic Resonance Imaging (PC-MRI). TCD is a common, noninvasive and cost-effective method providing information regarding velocity [6, 7]. However, it has some faults. Its accuracy depends on the correct localization of vessels, angle of probe, operator [8]. Therefore, the important point is that whether clinical methods used for diagnosis of brain lesions can be reliable for determining the risk factors. Studies have been conducted to investigate the reliability of clinical methods and comparing hemodynamic parameters with numerical methods or other clinical method in the carotid artery [6, 9] and cerebral arteries [2, 8, 10-13]. The concordance between Computational Fluid Dynamic (CFD) and clinical methods showed that it was qualitatively appropriate, but there were quantitative differences.

Until now, limited studies have been done on the entire Circle of Willis or Circle of Willis with aneurysm, and their accuracy and reliability has been rarely investigated by clinical methods. Thus in this paper, realistic model of the entire COW with aneurysm was simulated and patient-specific boundary conditions were imposed. Also the velocity in all of the cerebral arteries of each case was measured by TCD. Then the correspondence between CFD and TCD was accomplished for investigating the accuracy of the clinical method (TCD) in different vessels of the Circle of Willis.

2 METHOD

One of the most important factors in determining blood flow parameters through COW and intra-aneurysm is exerted realistic and patient-specific geometry. In this study, patient-specific geometries of COW with aneurysm were studied for two cases. CT scan data in DICOM format was prepared from Iran Imaging Center, Tabriz, Iran. Images of head and neck were generated by a Siemens/Sensation 64 CT Scanner. Thick slices and resolution of images are 1 mm and 512×512 pixels. Geometries of COW and site of aneurysm in these circles are different. Case A is a 10 years-old male without Posterior Communicating Arteries (PComm) on both sides in the COW and with aneurysm sized 29×30 mm located in the Basilar artery. Case B is a 70 years-old male with a 7×6.9 mm size aneurysm located in the left Middle Cerebral Artery (MCA) as shown in Figure 2.



(a) (b)

Figure 2: Angiography images of Circle of Willis for, a) case A, b) case B.

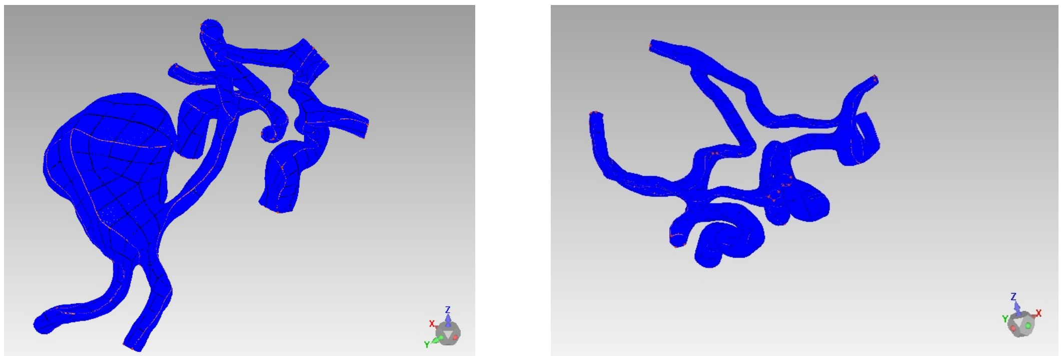
The CT images of each patient were imported to the Mimics software (Materialise). There, threshold of vascular tissue was identified and cerebral arteries were separated from other tissues and other arteries. Finally, for each case 3D model of geometry of COW, as cloud points, was created. The process of converting cloud points to exact surface was performed by the GEOMAGIC-STUDIO software (3D system) as shown in Figure 3. Then models with IGES format were transferred to the ANSYS.CFX. The purpose of this research is to study the correspondence between CFD and TCD. Therefore, the Transcranial Doppler test was done to obtain pulsatile velocity profile in the cerebral arteries of COW. These velocities were measured in Imam Reza Hospital, Tabriz, Iran for each patient.

The Finite Volume Method (FVM) was used for the fluid governing equations. In cerebral arteries the fluid was considered incompressible, and the flow was considered laminar as described as:

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

$$\rho\left(\frac{\partial \vec{V}}{\partial t} + \vec{V}.\nabla\vec{V}\right) = -\nabla P + \nabla \cdot \tau_{ij} \tag{2}$$

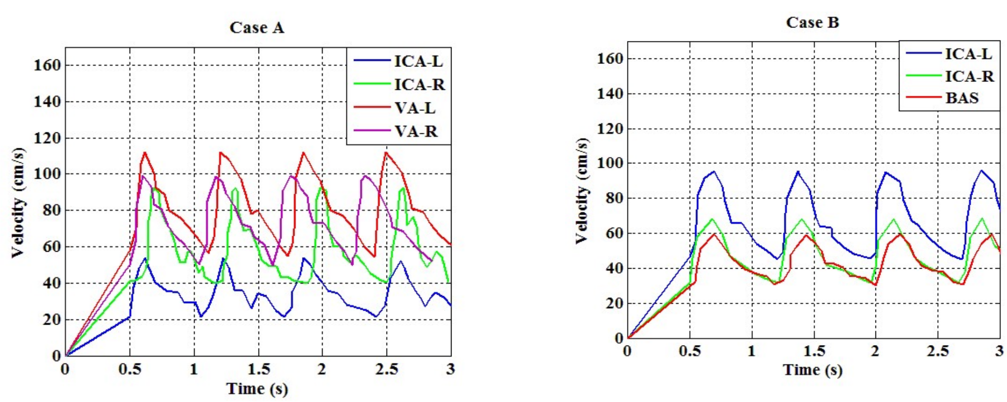
Where $\bar{V}$ is the fluid velocity vector, ρ=1050 kg/m^3 is fluid density, t is time, P is pressure and τ_{ij} is viscous stress tensor. The average shear rate in the cerebral arteries is more than 100 s^{-1} [14-16]. Therefore, Newtonian model with μ= 0.00339 Pa.s was used.



(a) (b)

Figure 3: 3D structure of Circle of Willis for: a) case A, b) case B.

It is important to investigate hemodynamic parameters with conditions based on physiological data. Thus, patient-specific boundary conditions were used. COW of Case A has four inlets and six outlets and case B has three inlets and seven outlets. For inlet boundaries, patient-specific pulsatile velocity was applied. These blood velocities were measured by Transcranial Doppler (Figure 4). due to limitation of blood pressure measurement and with regard to the transfer of blood flow from the circle of Willis arteries to the capillary, Outlet boundaries (long outlet branches were included in the computational model to minimize the effect of boundary conditions on hemodynamic parameters) were imposed by capillary pressure of 17 mmHg [17]. Initial condition for parameters was zero.



(a) (b)

Figure 4: pulsatile velocity profile obtained from TCD at the inlets of a) case A, b) case B.

Unstructured grids with 3D tetrahedral elements and 10 nodes were imposed for domain. Also, prismatic elements were used in boundary layer with 0.2mm thickness and 5 layers. Computational quality of mesh and skewness were appropriate and approximately 0.81 and

0.27, respectively. For integration of this time-depended problem the implicit Euler method was used with a time step of 0.01 s (The time step independence test was done for 0.04s, 0.01s and 0.005s). Four cycles of time were simulated and the result was extracted from the third cycle.

The grid independence test was done for two cases and was solved and velocity were compared with different size of elements. Eventually, Number of element for case A was 1652731 and for case B is 2903597.

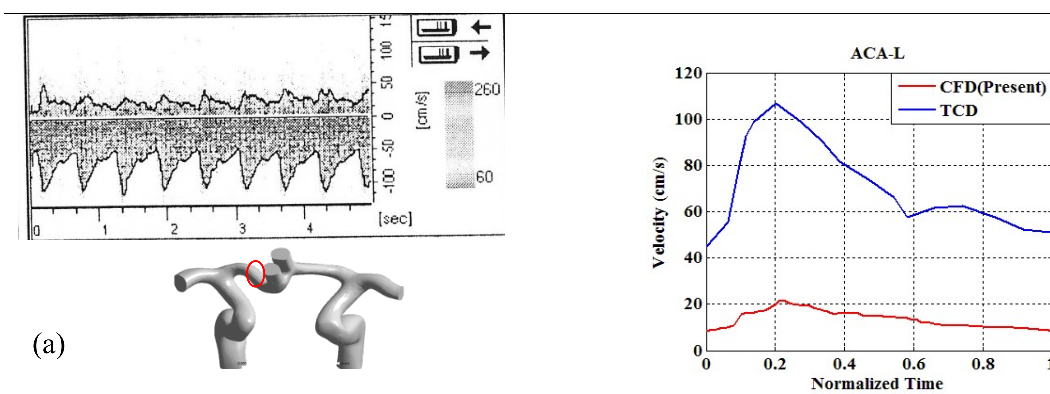
3 RESULT

For case A, the Doppler test was done after treatment. This aneurysm was treated with endovascular coiling method. In this COW, there was no communication between the anterior and posterior region, therefore the hemodynamic of anterior should not change before and after the treatment (aneurysm is located in the posterior of circle). Computational fluid dynamic was solved for COW with aneurysm which was done before the treatment.

In the numerical method, cross section of vessels used for gaining average velocity in one cycle was approximately near to the positions accomplished by the TCD test.

As shown in Figure 5 blood velocity of one cycle in the Anterior region of COW for case A was compared for two methods. As seen here, accordance for different arteries is different. In the middle cerebral arteries (MCA) at the both sides, velocity profiles are match qualitatively. Differences in the left Anterior Cerebral Artery (ACA-L) in the peak of the diagram (maximum velocity) is more than 80 cm/s. Also it observed on the opposite side (ACA-R) is 40 cm/s. Since ACA is located in the middle part of the skull and away from the surface of skull, the possibility of errors increases; for MCA arteries are located near by the surface, so it is expected that it is detected less error.

In Figure 6 comparison of blood velocity between the two methods are shown for case B. Different accordance is noticed for various vessels. Difference of velocity between them is about 10 cm/s for the anterior region and MCA-L; it is about 20 cm/s for PCA-R and about 30 cm/s for PCA-L. The peak of the velocity of TCD method is more than CFD for the right Middle Cerebral Artery (MCA-R). Its difference is about 40 cm/s.



(a)

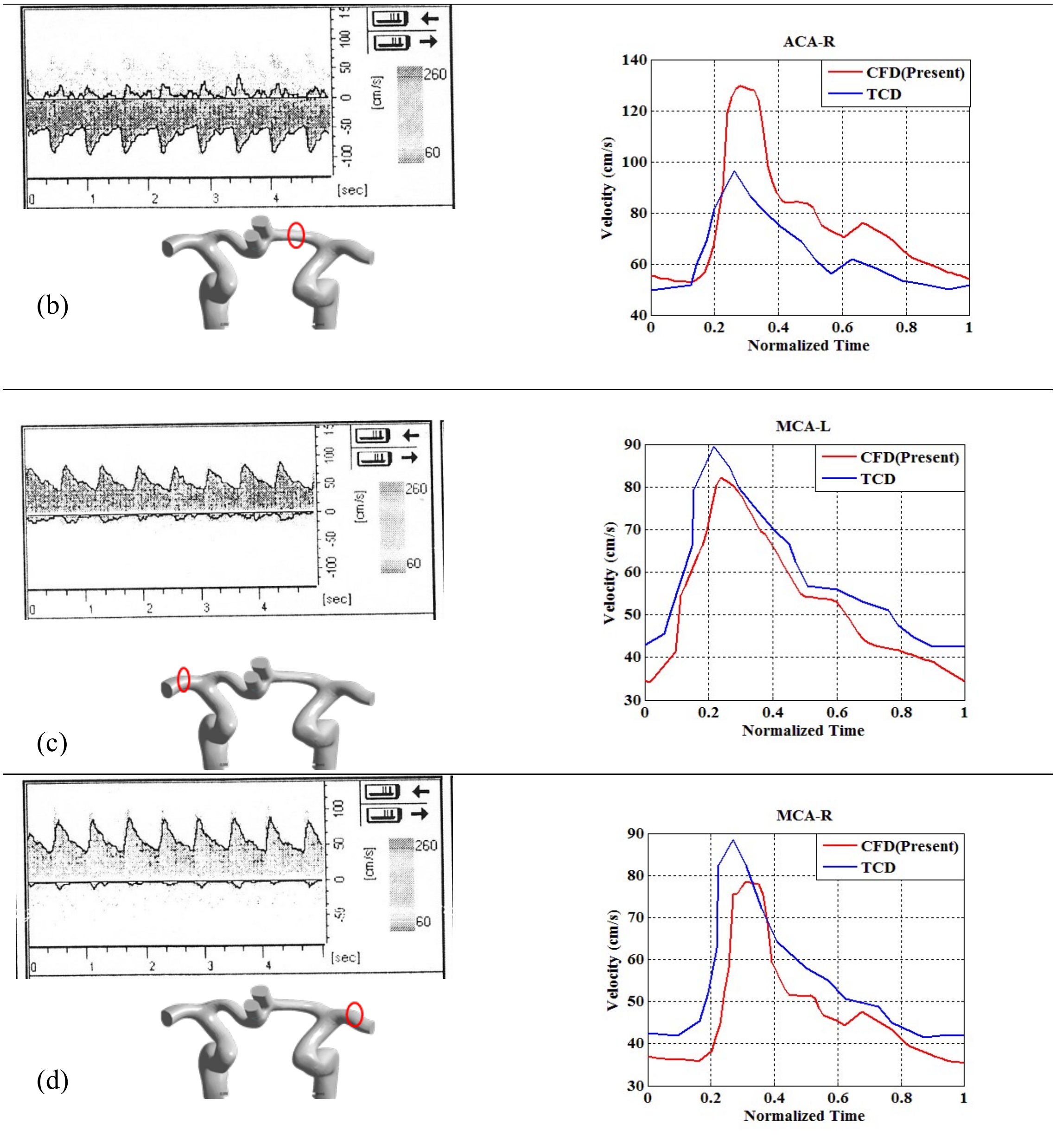
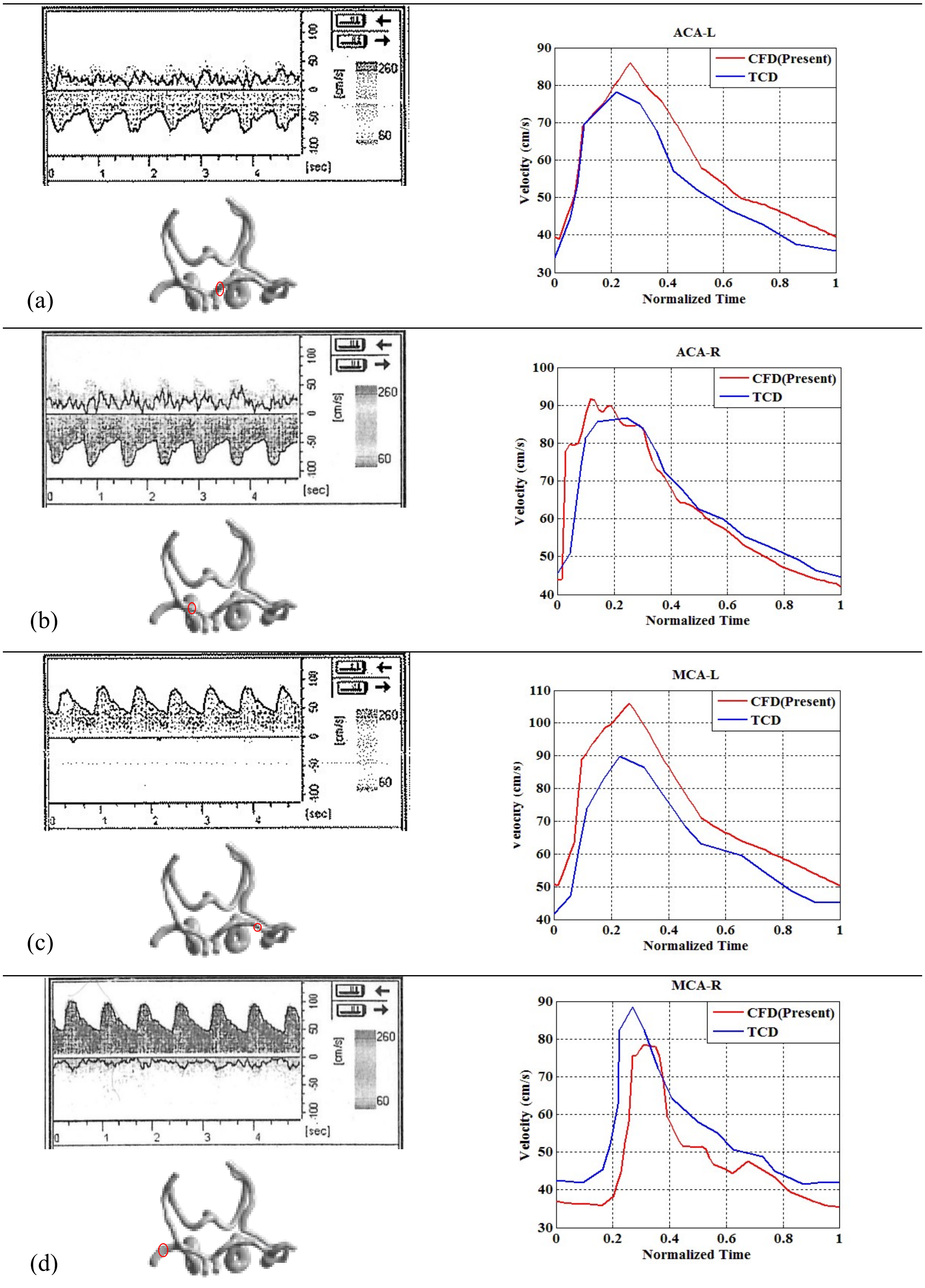


Figure 5: Comparison of velocity profile obtained from TCD and CFD at the, a) ACA-L, b) ACA-R, c) MCA-L, d) MCA-R, for case A.

The differences between the velocity values based on two methods at a normalized time and at the maximum value are reported by error relative percentages. These errors were calculated using the following equation and are shown in Table 1:

$$error\% = \frac{V_{TCD} - V_{CFD}}{V_{CFD}} \times 100 \tag{3}$$


(a)
ACA-L
CFD(Present)
TCD
Velocity (cm/s)
Normalized Time
(b)
ACA-R
CFD(Present)
TCD
Velocity (cm/s)
Normalized Time
(c)
MCA-L
CFD(Present)
TCD
velocity (cm/s)
Normalized Time
(d)
MCA-R
CFD(Present)
TCD
Velocity (cm/s)
Normalized Time
[cm/s]
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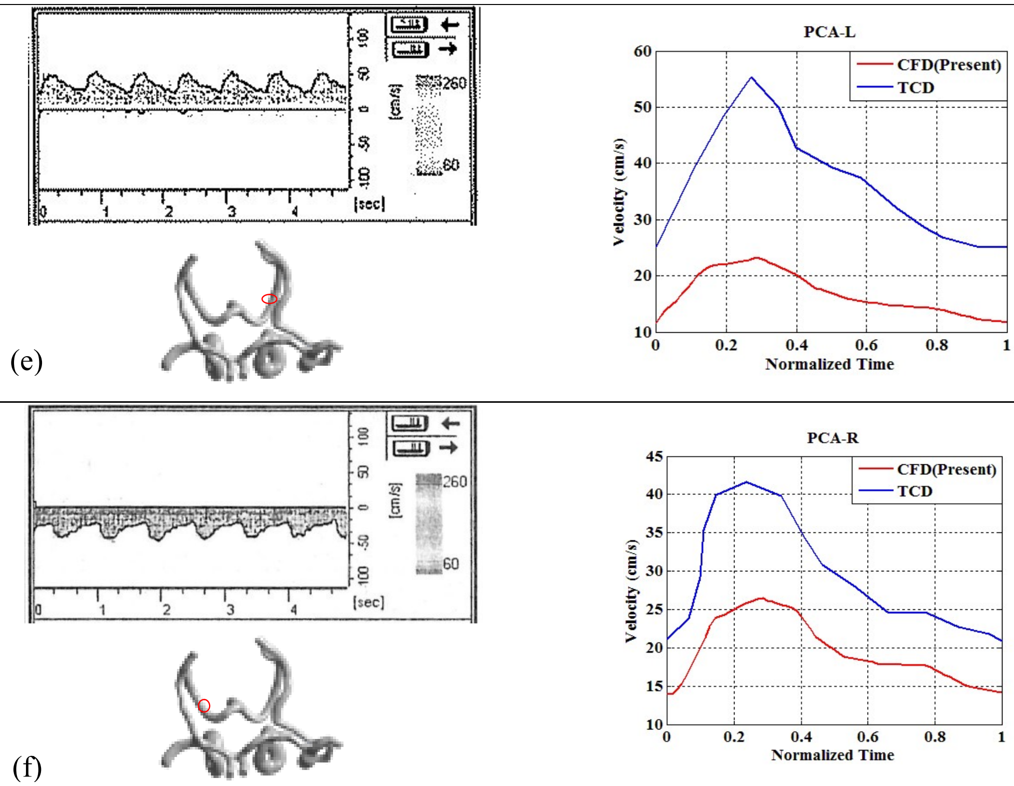

Figure 6: Comparison of velocity profile obtained from TCD and CFD at the a) ACA-L, B) ACA-R, c) MCA-L, d) MCA-R, e) PCA-L, and f) PCA-R for case B.

		Normalized Time				
		0.2s	**0.4s**	**0.6s**	**0.8s**	**Max velocity**
Error% (Case A)	**ACA-L**	438%	404.3%	338.1%	464.7%	397.3%
	ACA-R	24.6%	12.5%	12.2%	16.1%	25.7%
	MCA-L	19.6%	6.5%	8.1%	9.0%	8.9%
	MCA-R	51.8%	11.7%	13.5%	5%	12.8%
Error% (Case B)	**ACA-L**	1.2%	16.8%	9.8%	15.4%	8.9%
	ACA-R	3.4%	10.8%	1.7%	8.0%	5.6%
	MCA-L	15.3%	12.9%	7.5%	14.2%	15.6%
	MCA-R	28.2%	29.6%	29.8%	35.1%	29.3%
	PCA-L	121.7%	101.9%	135.2%	85.7%	139.3%
	PCA-R	60%	43.3%	42.8%	34.5%	57.4%

Table 1: The relative errors between the computed and measured velocity in Cerebral arteries.

4 DISCUSSION

Simulation of two different geometries of cerebral arteries with aneurysm were performed to assess the correspondence between numerical method result and the experimental data of TCD. Computational fluid dynamic does not give complete and accurate information from *in-vivo* conditions but it is possible with correct and close to *in-vivo* conditions simulating, to obtain reliable information. Also, Transcranial Doppler test is a common method for measuring velocity in vessels [6,7]. Based on clinical observation, the result of this method is often contradicted with *in-vivo* results. So, it is not justified because of critical situation, especially in the Circle of Willis.

In this paper, by creating patient-specific model based on real physiological data, blood velocity in all the vessels of Circle of Willis were compared with velocity acquired by TCD.
Comparison of the results of the two cases shows that in arteries which are near the surface of the skull with slight inflexion, amount of error of the TCD method is minimal. Actually, the accordance between the clinical method and the numerical method is appropriate. But in the vessels which place in middle region of the skull the difference increases. The errors of TCD method that was noted, may be the cause of these differences. The existence of these errors can lead to wrong estimations and affect the treatment planning and it can endanger patient's life.

It should be considered, in this study, wall of vessels has not been assumed. Whenever, movement of wall could be one of the effective factors on blood flow and other hemodynamic parameters. So, for the modeling to be realistic FSI modeling with appropriate mechanical properties of arterial wall should be employed.
Further, investigations and comparison of hemodynamic parameters between two methods should involve study for more patient-specific cases to obtain more data for reliable and comprehensive processing.

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