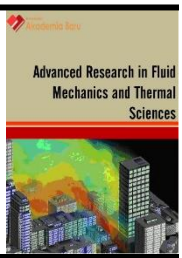
Penerbit Akademia Baru

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage: www.akademiabaru.com/arfmts.html
ISSN: 2289-7879



Qualitative and Quantitative Comparison of Hemodynamics Between MRI Measurement and CFD Simulation on Patient-specific Cerebral Aneurysm – A Review

Open Access

Lim Sheh Hong[1,*], Mohd Azrul Hisham Mohd Adib[1], Mohd Shafie Abdullah[2], Radhiana Hassan[3]

[1] Medical Engineering & Health Intervention Team (MedEHiT), Human Engineering Group, Faculty of Mechanical & Automotive Technology Engineering, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia
[2] Department of Radiology, School of Medical Sciences, Health Campus, Universiti Sains Malaysia, 16150 Kubang Kerian, Kelantan, Malaysia
[3] Department of Radiology, Kulliyyah of Medicine, International Islamic University Malaysia, 25200 Kuantan, Pahang, Malaysia

ARTICLE INFO

Article history:
Received 19 December 2019
Received in revised form 26 January 2020
Accepted 26 January 2020
Available online 30 March 2020

Keywords:
Aneurysm; Hemodynamics; Magnetic Resonance Imaging; Computational Fluids Dynamics

ABSTRACT

The significant progress in computer innovation technique, computational fluid dynamics (CFD) has been applied for real applications on patient-specific hemodynamics and extensively used to study cerebral aneurysm rupture. In addition, the computational study with representative blood vessel configuration has become a great tool in providing comprehensive information on geometry, the flow field of blood and wall shear stress (WSS). Generally, the numerical simulations have an expected problem on the specification of the exact boundary conditions which leads to unphysical numerical solutions. Therefore, this paper tends to find out whether CFD simulation manages to obtain precise and better predictions of hemodynamics patterns at present time especially for phase-contrast magnetic resonance imaging (PC-MRI) in terms of the velocity flow field and WSS distribution. Several research articles are included and their qualitative and quantitative results on hemodynamics have been compared. Both MRI measurement and CFD simulation have reasonably good agreement on velocity flow fields and a detailed spiral recirculating flow pattern can be observed in CFD simulation as compared to MRI measurement instead. However, CFD simulation has overestimated the WSS, especially at the maximum WSS location. The CFD simulation is capable to achieve good agreement on velocity flow fields with MRI measurement, yet the result for WSS distribution has to be further improved and justified with consistent assumptions and techniques.

1. Introduction

The consideration of hemodynamics is crucial for a comprehensive understanding and diagnosis of biological responses towards the cerebrovascular system of humans [1-4]. One of the pronounced

* *Corresponding author.*
E-mail address: shehhong.lim@gmail.com (Lim Sheh Hong)

https://doi.org/10.37934/arfmts.68.2.112123

biological responses, particularly subarachnoid hemorrhage (SAH) is typically initiated due to cerebral aneurysm rupture [5]. The yearly reported case of a cerebral aneurysm in Malaysia is up to 1.1–1.7 percent of 100,000 population while the rupture of cerebral aneurysms is supplementary to notable morbidity and a monthly mortality rate of up to 35 percent [6–8]. Therefore, clinicians and researchers in the medical industry nowadays are striving for a better diagnosis or interpretation method to determine the hemodynamics of cerebral aneurysms.

The current available approaches are phase-contrast magnetic resonance imaging (PC-MRI) [9–19] and model-based computational fluid dynamics (CFD) simulations [9,10,13–18]. PC-MRI has been widely used in modern years due to its hustle-free operation and unrestricted 3D anatomical coverage image. The flow velocity and magnitude images are able to be extracted from PC-MRI images. The measurement is taken into account for qualitative interpretation to reveal the presence, magnitude, and direction of blood flow. Plus, flow velocity, volume flow rate and displaced volumes can be acquired through the quantitative interpretation from the measurement [20–22]. The only limitation of PC-MRI is because of the inadequate spatial and temporal resolutions which subsequently affect the exactitude of hemodynamics approximations [23]. Therefore, CFD simulation is further used as a substitute to predict behavior or blood flow patterns in various vascular geometries, namely cerebral aneurysms [1,9,13], cerebral arteries [17], thoracic aorta [24] and carotid bifurcation [9,15,18].

The CFD simulation performs fluid flow numerical analysis through the constructed three-dimensional (3D) models which are replicated from radiography and medical imaging sources to visualize the flow fields of blood and dictate hemodynamics using Navier-Stokes equations. With regard to the parameters involving geometry and physiology, the CFD simulation is known to be time-consuming for solving the governing equations. During the simulation, users are required to define boundary conditions, but there is no unified rule to define the boundary conditions. Therefore, the validation of the results is unreliable due to human error which depends on one's particular assumption [25].

However, there are researches concluded that CFD simulation can be reliable and achieves good agreement with PC-MRI measurement [15,17,18]. Therefore, this review paper is to find out whether CFD simulation manages to attain accurate, close and better approximations of patient-specific hemodynamics as PC-MRI measurement at present. The qualitative determination of the velocity flow field and quantitative determination of relative WSS distribution between PC-MRI measurement and CFD simulation are the principal and secondary outcomes in this paper, respectively.

2. Methodology
2.1 Article Preference

Original research articles involving the studies and comparisons of hemodynamics effects such as velocity flow field and WSS distribution by showing the level of agreement in terms of PC-MRI measurement and CFD simulation specifically in the patient-specific cerebral aneurysm are preferred. Most of the selected articles must have involved both PC-MRI measurement and CFD simulation for comparison. Other research articles involving animal-specific cerebral aneurysm are excluded from the analysis. The research articles which involve the study of both patient-specific cerebral aneurysm and blood vessel or artery are taken into consideration and being reviewed by focusing on the aneurysm measurement only.

2.2 Data Extraction and Analysis

Several data had been extracted from each research article to facilitate analysis or comparison. The extracted data includes the author, patient age, aneurysm location, aneurysm diameter (if available), PC-MRI acquisition technique, CFD simulation acquisition technique, parameter assumption (primary viscosity, density, velocity and pressure if available) for CFD simulation, level of velocity flow field agreement and level of WSS distribution agreement. For the qualitative determination of the velocity flow field between PC-MRI measurement and CFD simulation, specific images were extracted from the articles and compared at respective orientation or direction qualitatively. For the quantitative determination of relative WSS distribution between PC-MRI measurement and CFD simulation, the quantitative measurements from the articles were extracted and then compared the relative values of WSS distribution in terms of percentage between PC-MRI measurement and CFD simulation.

2.3 Material Specifications

The research conducted by Rispoli *et al.,* [10] demonstrated the use of CFD–MRI combined solver. The authors conducted simulations using the approach of the finite volume method. Also, idealistic assumptions such as rigid walls and Newtonian viscosity were imported to the SIMPLER algorithm in Cartesian grids in Matlab for simulations. In their work, combined solver simulations assumed density, viscosity and flow velocity of blood to be 1,100 kg/m^3, 0.005 Pa.s and 8 cm/s, respectively. In vitro and in vivo analyses were conducted by Van Ooij *et al.,* [11] on WSS estimations on the patient-specific cerebral aneurysm. For in vitro analysis, a replicated artificial glass model of a 9 mm diameter aneurysm of an anterior communicating artery (AcomA) was used. However, for the vitro model, it was then scanned with a 3.0 Tesla MR scanner. The 3D model was processed using VTMK and FLIRT. The CFD simulations were performed using FLUENT by applying constant and pulsatile flow. The density, viscosity and flow velocity of blood used in their analysis have a slight difference from Rispoli *et al.,* [10] which were 1,060 kg/m^3, 0.004 Pa.s and 15 cm/s, respectively. Naito *et al.,* [12] performed flow dynamics analysis on patient-specific cerebral aneurysms using magnetic resonance fluid dynamics (MRFD). The authors determined the differences in both the velocity flow field and hemodynamics between MRFD and CFD simulation. A total of 15 elderly people were investigated. The aneurysms were scanned with a 3.0 Tesla MR scanner with a resolution of 1 × 1 × 0.8 mm. For the CFD simulation, three-dimensional (3D) models were constructed by using Aquilium64 through CT measurement. The velocity fields and WSS were computed using FLOVA by using DICOM data from the PC-MRI image. The non-Newtonian fluid property for blood was assumed. The simulations were performed using density, dynamics viscosity and flow velocity of the blood of 1,055 kg/m^3, 0.0049 Pa.s and 10 cm/s, respectively.

Isoda *et al.,* [13] also conducted a comparison on the hemodynamics of patient-specific cerebral aneurysms between PC-MRI measurement and CFD simulation on five patients of 51 to 71 years old. The diameters of the aneurysm from the patients were within 3 to 8 mm. The PC-MRI imaging on the aneurysms was performed by using a 1.5 Tesla MR scanner with the same resolution used by Naito *et al.,* [12]. The aneurysm models used for CFD simulation were built using Amira software. Image smoothing and segmentation were also conducted using the same software. The CFD simulation for the aneurysm models was then performed by using ACUSIM software to acquire 3D velocity vector fields. The fluid conditions were Newtonian and incompressible with a specific density and viscosity of 1,054 kg/m^3 and 0.0038 Pa.s, respectively. The vessel wall conditions used were rigid with no-slip conditions. A research article published by Boussel *et al.,* [1] concerning the exactitude of PC-MRI measurement implemented in vivo in three patients ranged from 44 to 68 years old. The studied subjects, referring to the cerebral aneurysms with a diameter of 12 to 18.2 mm were found at the basilar trunk. The aneurysms were scanned with a 1.5 Tesla MR scanner with a resolution of 1 × 1 × 1.2 mm. For the CFD simulation, 3D models were constructed by using Rapid form through contrast-enhanced magnetic resonance angiography (CE-MRA) measurement. The background noise together with the non-participated smaller vessels was removed and the surface was smoothened. The velocity flow fields and WSS were figured using FLUENT. The flow conditions used were laminar and Newtonian while the rigid arterial walls were considered as the lack elastin aneurysmal blood vessels. The viscosity of blood used was 0.035 Pa.s.

The simulation work by Mohd Adib *et al.,* [26] was conducted based on three approaches on ten patients diagnosed with aneurysms with diameter ranging from 1.81 to 9.13 mm at peak systole condition at which the different maximum blood velocities were obtained through PC-MRI measurement images, unlike the other authors who held the velocity at constant. The PC-MRI images were captured using 3.0 Tesla MR scanner. The 3D models of aneurysms were constructed from digital subtraction angiography (DSA) images using AMIRA software and were then exported to CD-Adapco software to generate the velocity flow field and WSS distribution with polyhedral meshing. The conditions applied on fluid were Newtonian, compressible with density and viscosity of 1,050 kg/m^3 and 0.035 Pa.s while the conditions applied on vessel wall were rigid and no-slip. Some details extracted from the articles are listed in Table 1.

3. Results

3.1 Principal Outcome: Velocity Flow Field Comparison

The results obtained by Boussel *et al.,* [1] on the flow conditions of aneurysms located at basilar trunk at peak systole which displayed a complete illustration of the flow complexity for measurements showed that the visual comparison with regard to velocity flow field of PC-MRI measurement has good agreement with the results obtained from CFD simulation. The visualizations of the velocity flow field for patient 1 and patient 3 were similar as compared to the PC-MRI images. However, the velocity flow field for patient 3 showed high visibility of the recirculating flow due to the high value of WSS in the region of fast passage in CFD simulation. Isoda *et al.,* [13] reported that the velocity flow fields generated from both measurements have a high level of agreement. The shearing velocities in PC-MRI images and CFD simulations were similar with regards to location and pattern. The authors also mentioned that minor shearing velocities were perceived above the 3D streamlines spiral flow and the only image which showed significant visualization at basilar artery-superior cerebellar artery (BA-SCA) (refer Figure 1). They claimed that the location at which the spiral flow was observed did not always correspond to what obtained in the MRFD image as compared with the CFD image.

The results obtained by Naito *et al.,* [12] showed that the 3D velocity flow fields have similarities in the results acquired from the PC-MRI image and CFD simulation. They also reported that CFD simulation showed less visualization in one case when evaluating the aneurysm flow but somehow CFD simulation managed to show unusual flow pattern at one posterior communicating artery (PcomA) aneurysm of a 72 years old patient before rupture (refer Figure 2) as compared to MRFD which was constructed based on PC-MRI measurement. The study by Rispoli *et al.,* [10] proposed an algorithm incorporating both the Newtonian fluid physics model and a linear PC-MRI signal model to generate the velocity flow field. Velocity flow fields with better agreement were generated through direct PC-MRI measurements (refer Figure 3). The proposed approach improved the exactitude of the velocity flow field estimations. Moreover, it thoroughly satisfied the fluid dynamics equations.

Table 1
Details of studied articles

Article, Year	Patient Age (years old)	Aneurysm Location	Simulation Software	Viscosity (Pa.s)	Velocity (cm/s)
Boussel *et al.,* [1], 2009	44	Basilar trunk	FLUENT	0.035	NA
	59	Basilar trunk	FLUENT	0.035	NA
	68	Basilar trunk	FLUENT	0.035	NA
Isoda *et al.,* [13], 2010	51 – 71	BA-SCA	ACUSIM	0.0038	NA
		IC-PC	ACUSIM	0.0038	NA
		IC-PC	ACUSIM	0.0038	NA
		MCA	ACUSIM	0.0038	NA
		IC-Oph	ACUSIM	0.0038	NA
Naito *et al.,* [12], 2012	63	AcomA	FLOVA	0.0049	10
	81	ICA	FLOVA	0.0049	10
	58	BA	FLOVA	0.0049	10
	50	ICA	FLOVA	0.0049	10
	54	PcomA	FLOVA	0.0049	10
	59	ICA	FLOVA	0.0049	10
	78	ICA	FLOVA	0.0049	10
	59	PcomA	FLOVA	0.0049	10
	65	BA	FLOVA	0.0049	10
	78	PcomA	FLOVA	0.0049	10
	56	ICA	FLOVA	0.0049	10
	66	MCA	FLOVA	0.0049	10
	76	ICA	FLOVA	0.0049	10
	72	PcomA	FLOVA	0.0049	10
	69	ICA	FLOVA	0.0049	10
van Ooij *et al.,* [11], 2013	NA	AcomA	FLUENT	0.0040	15
	Model	AcomA	FLUENT	0.0040	15
Rispoli *et al.,* [10], 2015	NA	NA	MATLAB	0.0050	8
Mohd Adib *et al.,* [26], 2017	NA	ICA	CD-Adapco	0.0035	21.2
	NA	ACA	CD-Adapco	0.0035	60.1
	NA	MCA	CD-Adapco	0.0035	29.4
	NA	BA	CD-Adapco	0.0035	72.9
	NA	ICA	CD-Adapco	0.0035	20.1
	NA	MCA	CD-Adapco	0.0035	33.5
	NA	ICA	CD-Adapco	0.0035	30.7
	NA	ACA	CD-Adapco	0.0035	73.1
	NA	ACA	CD-Adapco	0.0035	46.3
	NA	BA	CD-Adapco	0.0035	45.5

Abbreviations: BA basilar artery, *BA-SCA* basilar artery-superior cerebellar artery, *IC-PC* internal carotid-posterior communicating, *MCA* middle cerebral artery, *IC-Oph* internal carotid-ophthalmic, *AcomA* anterior communicating artery, *ICA* internal carotid artery, *PcomA* posterior communicating artery, *ACA* anterior cerebral artery, *NA* not available

Mohd Adib *et al.,* [26] compared three approaches, namely P-fixed, Q-control and V-optimized in their work of investigating the relationships of threshold values on the velocity flow field. They found that there was a smaller difference of 19.3% on the velocity flow field using a V-optimized approach as compared to other approaches. They claimed that the difference in the velocity flow field might be induced from the spatial resolution setting. However, they did mention that the assumptions used on the vessel wall might also affect the finding results as well.

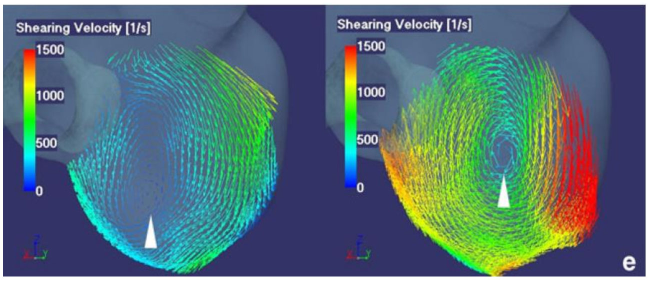


Fig. 1. Representation of shearing velocity image facing the apex of the spiral flow (temporal average) at BA-SCA of a 51 years old female patient. The MRFD image (left) is compared with CFD simulation image (right) [13]

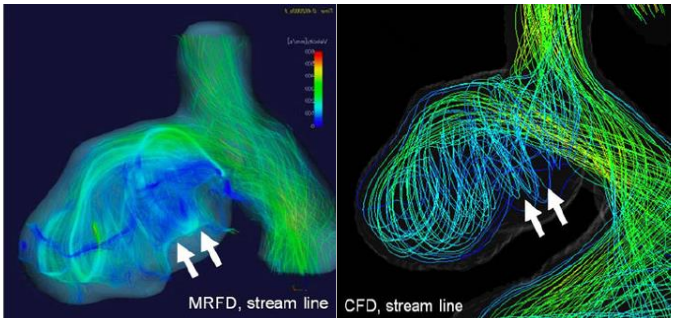


Fig. 2. Representation of specific flow patterns indicative of prospective rupture at PcomA. The MRFD image (left) is compared with CFD simulation image (right) [12]

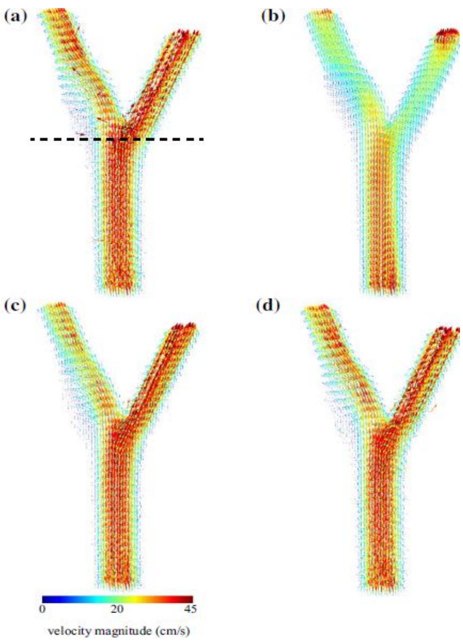


Fig. 3. Vector field representation: a) PC-MRI; b) CFD; c) CFD guided by PC-MRI measurement relating to the main velocity component; and d) CFD guided by PC-MRI measurement relating to all three velocity components [10]

3.2 Secondary Outcome: WSS Distribution Comparison

The analysis performed by Boussel *et al.,* [1] showed that PC-MRI measurement provided a reliable velocity flow field pattern inside the aneurysm with satisfactory velocity values dedicated to clinical diagnostic. Nonetheless, the measurements of velocity gradients caused large errors which led to misinterpretation of maximum stress and WSS distribution in CFD simulation. The 4D flow MRI measurement delivered estimation on WSS distribution and it was incapable of providing accurate absolute measurements of WSS. The authors claimed that the average WSS magnitude of 4D flow MRI measurement was approximately eight times of that obtained in CFD simulation. There was a high discrepancy in the measurements and a low agreement on the WSS distribution between 4D flow MRI measurement and CFD simulation. Isoda *et al.,* [13] performed a regression study and the results showed a low degree of relationship in WSS distribution at aneurysms between MRFD produced from PC-MRI results and CFD simulations. The authors used the distinction of the interval, 0.575 and 0.009 mm of the WSS calculation point. This might be the factor contributing to the distinction of WSS distribution on the aneurysm wall between MRFD and CFD simulations. The research showed that WSS distribution obtained from CFD was 1.6 times greater than 4D flow MRI measurement. Naito *et al.,* [12] identified that there was good agreement on the overall magnitudes for WSS distribution in CFD simulations as compared to MRFD measurement. The authors interpreted the WSS distributions between MRFD and CFD simulations through a grid with 64 segments. The authors mentioned that more than 90% compatibility of WSS distribution on the overall investigated arteries. In spite of the fact that there was an issue of reliability on the absolute value of WSS between MRFD and CFD, the measurement of the comparative WSS distribution and flow fields can be utilized to anticipate the hazard of broadening or rupture of aneurysms.

From the analysis conducted by van Ooij *et al.,* [11], it was reported that the WSS approximations between 3D PC-MRI estimations and CFD simulation were moderate. The WSS magnitude derived through CFD simulation was doubled as compared to 3D PC-MRI estimations. The authors claimed that a huge difference in WSS distribution occurred in areas with maximum WSS such as dome and bleb of the aneurysms even though the boundary conditions used were the same for simulations. The research by Mohd Adib *et al.,* [26] reported that the flow pattern in WSS distribution was aligned and provided good agreement with CFD measurement provided that realistic boundary conditions based on V-optimized approach were applied in simulation. They also claimed that poor and unrealistic boundary conditions applied to fluid flow and geometry might lead to incorrect estimation on WSS distribution. The summary of studied articles on the level of agreement on WSS distribution is shown and illustrated in Table 2 and Figure 4, respectively.

Table 2
Summary of results on WSS distribution

Article, Year	Agreement on WSS Distribution
Boussel *et al.,* [1], 2009	Low with errors at high WSS area
Isoda *et al.,* [13], 2010	Low with MRFD
Naito *et al.,* [12], 2012	Good with MRFD
van Ooij *et al.,* [11], 2013	Moderate at high WSS area
Mohd Adib *et al.,* [26], 2017	Good with V-optimized approach

Abbreviations: WSS wall shear stress, *MRFD* magnetic resonance fluid dynamics, *V-optimized* velocity-field-optimized

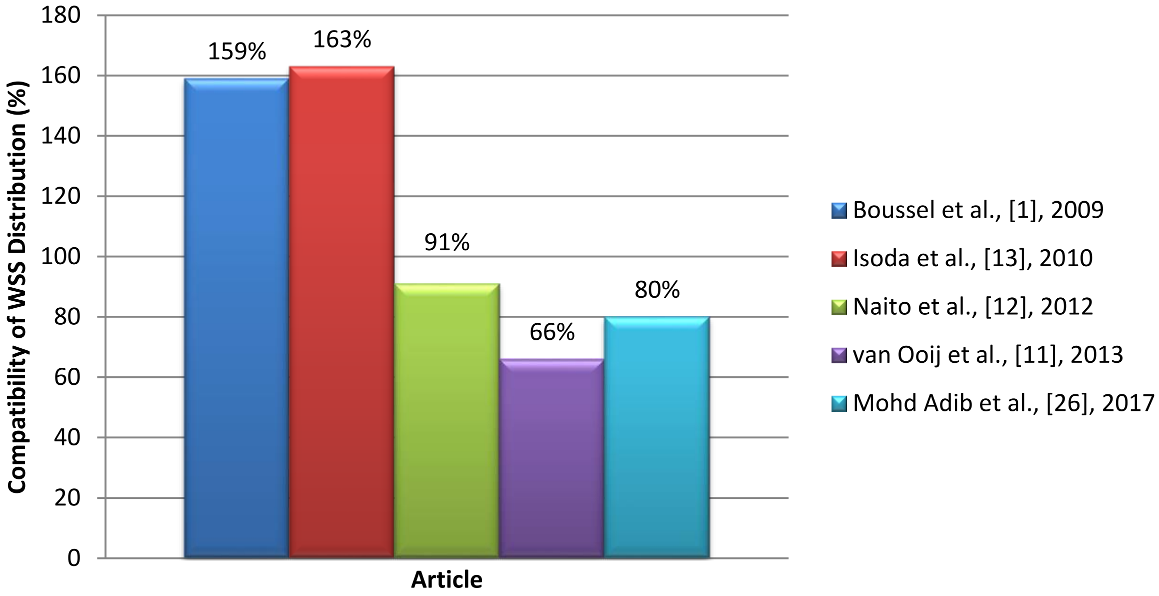


Fig. 4. Illustration on the compatibility of WSS distribution with article

4. Discussion

4.1 Summary of Findings

From the pooled analysis of the papers, most of the reliable discoveries with respect to the principal outcome on the velocity flow field comparison disclose that only the approximation of velocity flow fields obtained from both MRI measurement and CFD simulation has reasonable good agreement and significant spiral circulation of flow field can be observed clearly in CFD simulation as compared to MRI image with missing signals due to resolution profile.

Besides, the major consistent findings regarding the secondary outcome on WSS distribution between MRI measurement and CFD simulation exhibit that the CFD simulation has overestimated the WSS distribution as what obtained at MRI measurement and the difference between MRI measurement and CFD simulation on the WSS distribution is more pronounced at the area with high WSS. It is found that using an organized approach for simulation alleviates measurement errors.

4.2 Reasons for Discrepancy of WSS Distribution

The pre-processing and post-processing of measurements for the construction of the 3D model might be a factor contributing to the inconsistency of WSS distribution. There are several commercial software such as AMIRA, Aquilium64, VTMK and FLIRT used for image smoothing, image segmentation, improving signal-to-noise ratio and building 3D model but somehow, it also depends on the human factor in terms of techniques and opinions which is subjective and unique with individuals. Some authors claimed that the technique in processing images strongly affected the results of WSS estimations [27]. However, there are papers that do not clearly state the procedure in image processing. Although a traditional approach to process the image by setting all voxels at the exterior of vessel lumen to 0 m/s, the WSS values obtained may be unexpectedly high.

From the analysis performed by van Ooij *et al.,* [11] and Boussel *et al.,* [1] who utilized distinctive resolutions in CFD simulations, it was found that there was inconsistency with WSS distribution, especially at the high-velocity area. This shows that the difference in resolution setting between MRI measurement and CFD simulation is a significant contributor to WSS distributions or patterns

[2,27,28]. Most of the CFD simulations imported the inlet boundary conditions from MRI measurements which may affect the computation of CFD calculation. Stalder *et al.,* [29] mentioned in their research that the implementation of high spatial resolution showed a remarkable effect on WSS distributions however, their research was conducted on aorta instead of the aneurysm. This implies that the setting of spatial resolution is indeed an important factor in simulation. Mohd Adib *et al.,* [26] did mention in their paper that the use of low spatial resolution might lead to underestimation of vascular vessels and therefore, they introduced a physically consistent feedback control-based data assimilation (PFC-DA) method [30] to improve blood flow analysis by coupling the body force attributed to the velocity residual errors due to resolution settings with the pressure boundary condition for the pressure-driven blood flow system. Most of the authors did not mention the resolution settings which unconsciously contributed to inconsistency in result validations.

The assumptions or boundary conditions are crucial for solving the Navier-Stokes equation and yet, the validation of the result is still uncertain. Boussel *et al.,* [1] assumed the wall vessel to be lack elastin but somehow, in reality, the healthy elastin-containing vessel does account for compliance and the hemodynamics effect was not aligned with the wall compliance. Besides, the vessel wall is flexible as assumed in CFD simulation albeit, with inherent elasticity, this unconsciously leads to an overestimation of CFD measurements due to the use of rigid phantom in reality [3,31,32]. Furthermore, as mentioned by Mohd Adib *et al.,* [26] in their paper, the assumptions used in simulation might affect the finding results. Most of the authors might apply no-slip condition on the vessel wall but there is research concluded that it is more preferable to apply slip condition on vessel wall as it is more similar to the actual characteristic of the human vessel and might give a better approximation on hemodynamics [33].

Besides, it could be noticed that most of the studied articles in this review paper assumed Newtonian as the blood flow property but non-Newtonian by Naito *et al.,* [12]. The study conducted by Mohamad Shukri *et al.,* [34] claimed that assuming non-Newtonian as the fluid property for simulation induced profound effects on blood flow pattern and WSS distribution, especially at the bifurcation and blood recirculation areas. They concluded that non-Newtonian models have to be utilized in simulations relating to blood flow investigations which give more reliable approximations than Newtonian models and this might be the contributing factor leading to good agreement of WSS distribution in CFD simulation as reported by Naito *et al.,* [12]. However, the research work conducted by Sabaruddin *et al.,* [35] indicated that Newtonian fluid model showed no effect on the velocity profile and streamline pattern but on temperature distribution and temperature profile of blood flow, especially at the bifurcated arteries with different stenosis shapes establishing different blood flow profiles. The authors claimed that different Reynold number would be the dominant factor affecting the velocity profile and streamline pattern. Yet, the effects of Newtonian and non-Newtonian have to be further explored in more detailed to provide new anticipation on hemodynamics in blood flow analysis.

4.3 Limitations

The inconsistency of the result obtained especially for WSS distribution may be due to the broad consensus among researchers in performing experiments or simulations. The methodologies held by researchers vary in terms of measurement format, software for image processing and simulation, assumption of boundary conditions and strength of scanner. The diversity in methodologies held by researchers leads to many uncontrollable variables and causes inconsistent results. The type and specification of the instrument (software) have to be clearly stated.

The parameter to be reported among researchers has to be consistent. In the pooled analysis with a large volume of measurement, this may make researchers confused to concisely report the results obtained in the study. It is also subjective to the researchers on which parameter to report. Some researchers may not mention at which orientation or angle the image is captured, what meshing size is used for simulation, which WSS (average or maximum) is reported and which cardiac cycle the WSS is extracted. Consequently, the accuracy of the extracted measurement is affected.

5. Conclusions

The advancement in medical imaging techniques has contributed to the high specification diagnosis of small patient-specific cerebral aneurysms. Consequently, this has drawn the attention of researchers and clinicians to approach the imaging strategies which can help in stratifying the hazard of cerebral aneurysm rupture. This can also bring better intervention to deal with the aneurysm. The velocity flow field and WSS have seemed to have potential in stratifying risk in various vascular diseases, just that there is controversy whether low or high WSS leads to initiation, growth and rupture of cerebral aneurysm and which method is perfectly used to stratify the risk as well as to study the hemodynamics. In this paper, MRI measurement seems to have a better visualization of the velocity flow field as CFD simulation but MRI measurement seems to underestimate the WSS distribution obtained from CFD simulation. Thus, MRI measurement is still considered as the potential clinical decision-making tool for diagnosis as it has high feasibility and less complexity. However, the diagnosis of vascular disease can be more practical and accurate with a more advanced method. The CFD simulation is capable to achieve good agreement with MRI measurement, yet the result for WSS distribution has to be further improved and justified with consistent assumptions and techniques.

Acknowledgement
The support of the Universiti Malaysia Pahang under grant RDU190153, KPT grant (FRGS/1/2019/ICT02/UMP/02/1) and MedEHiT are gratefully acknowledged.

References
[1] Boussel, Loic, Vitaliy Rayz, Alastair Martin, Gabriel Acevedo-Bolton, Michael T. Lawton, Randall Higashida, Wade S. Smith, William L. Young, and David Saloner. "Phase-contrast magnetic resonance imaging measurements in intracranial aneurysms in vivo of flow patterns, velocity fields, and wall shear stress: comparison with computational fluid dynamics." *Magnetic Resonance in Medicine: An Official Journal of the International Society for Magnetic Resonance in Medicine* 61, no. 2 (2009): 409-417. https://doi.org/10.1002/mrm.21861

[2] Tan, Ka-Kheng. "Theory of Boundary Layer Instability: Particle or Wave?." In *IUTAM Symposium on One Hundred Years of Boundary Layer Research*, pp. 483-494. Springer, Dordrecht, 2006. https://doi.org/10.1007/978-1-4020-4150-1_47

[3] Lantz, Jonas, Johan Renner, and Matts Karlsson. "Wall shear stress in a subject specific human aorta—influence of fluid-structure interaction." *International Journal of Applied Mechanics* 3, no. 04 (2011): 759-778. https://doi.org/10.1142/S1758825111001226

[4] Secomb, Timothy W. "Hemodynamics." *Comprehensive Physiology* 6, no. 2 (2011): 975-1003. https://doi.org/10.1002/cphy.c150038

[5] Weir, Bryce. "Unruptured intracranial aneurysms: a review." *Journal of neurosurgery* 96, no. 1 (2002): 3-42. https://doi.org/10.3171/jns.2002.96.1.0003

[6] Ghani, Ailani Ab, Saiful Azli Mat Nayan, Regunath Kandasamy, Azmin Kas Rosman, and Abdul Rahman Izani Ghani. "Characteristics and outcomes of patients with anterior circulation intracranial aneurysm managed with clipping in Hospital Sungai Buloh." *The Malaysian journal of medical sciences: MJMS* 23, no. 6 (2016): 113-117. https://doi.org/10.21315/mjms2016.23.6.12

[7] Austin, G., S. Fisher, D. Dickson, D. Anderson, and S. Richardson. "The significance of the extracellular matrix in

intracranial aneurysms." *Annals of Clinical & Laboratory Science* 23, no. 2 (1993): 97-105.
[8] Smith, M., and G. Citerio. "What's new in subarachnoid hemorrhage." *Intensive Care Medicine* 41, no. 1 (2015): 123-126.
https://doi.org/10.1007/s00134-014-3548-5
[9] Szajer, Jeremy, and Kevin Ho-Shon. "A comparison of 4D flow MRI-derived wall shear stress with computational fluid dynamics methods for intracranial aneurysms and carotid bifurcations—a review." *Magnetic resonance imaging* 48 (2018): 62-69.
https://doi.org/10.1016/j.mri.2017.12.005
[10] Rispoli, Vinicius C., Jon F. Nielsen, Krishna S. Nayak, and Joao LA Carvalho. "Computational fluid dynamics simulations of blood flow regularized by 3D phase contrast MRI." *Biomedical engineering online* 14, no. 1 (2015): 110.
https://doi.org/10.1186/s12938-015-0104-7
[11] van Ooij, Pim, Wouter V. Potters, Annetje Guédon, Joppe J. Schneiders, Henk A. Marquering, Charles B. Majoie, Ed vanBavel, and Aart J. Nederveen. "Wall shear stress estimated with phase contrast MRI in an in vitro and in vivo intracranial aneurysm." *Journal of magnetic resonance imaging* 38, no. 4 (2013): 876-884.
https://doi.org/10.1002/jmri.24051
[12] Naito, Takehiro, Shigeru Miyachi, Noriaki Matsubara, Haruo Isoda, Takashi Izumi, Kenichi Haraguchi, Ichiro Takahashi, Katsuya Ishii, and Toshihiko Wakabayashi. "Magnetic resonance fluid dynamics for intracranial aneurysms—comparison with computed fluid dynamics." *Acta neurochirurgica* 154, no. 6 (2012): 993-1001.
https://doi.org/10.1007/s00701-012-1305-5
[13] Isoda, Haruo, Yasuhide Ohkura, Takashi Kosugi, Masaya Hirano, Marcus T. Alley, Roland Bammer, Norbert J. Pelc, Hiroki Namba, and Harumi Sakahara. "Comparison of hemodynamics of intracranial aneurysms between MR fluid dynamics using 3D cine phase-contrast MRI and MR-based computational fluid dynamics." *Neuroradiology* 52, no. 10 (2010): 913-920.
https://doi.org/10.1007/s00234-009-0634-4
[14] Cibis, Merih, Wouter V. Potters, Mariana Selwaness, Frank J. Gijsen, Oscar H. Franco, Andres M. Arias Lorza, Marleen de Bruijne et al. "Relation between wall shear stress and carotid artery wall thickening MRI versus CFD." *Journal of biomechanics* 49, no. 5 (2016): 735-741.
https://doi.org/10.1016/j.jbiomech.2016.02.004
[15] Papathanasopoulou, Panorea, Shunzhi Zhao, Uwe Köhler, Malcolm B. Robertson, Quan Long, Peter Hoskins, X. Yun Xu, and Ian Marshall. "MRI measurement of time-resolved wall shear stress vectors in a carotid bifurcation model, and comparison with CFD predictions." *Journal of Magnetic Resonance Imaging* 17, no. 2 (2003): 153-162.
https://doi.org/10.1002/jmri.10243
[16] Ian Marshall, Shunzhi Zhao, Uwe Köhler, Malcolm B. Robertson, Quan Long, Peter Hoskins, X. Yun Xu, and Papathanasopoulou, Panorea. "MRI measurement of time-resolved wall shear stress vectors in a carotid bifurcation model, and comparison with CFD predictions." *Journal of Magnetic Resonance Imaging* 17, no. 2 (2003): 153-162.
https://doi.org/10.1002/jmri.10243
[17] Cebral, Juan R., Christopher M. Putman, Marcus T. Alley, Thomas Hope, Roland Bammer, and Fernando Calamante. "Hemodynamics in normal cerebral arteries: qualitative comparison of 4D phase-contrast magnetic resonance and image-based computational fluid dynamics." *Journal of engineering mathematics* 64, no. 4 (2009): 367-378.
https://doi.org/10.1007/s10665-009-9266-2
[18] 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.
https://doi.org/10.1016/j.jbiomech.2003.09.032
[19] Aurélien F. Stalder, Bock, Jelena, Alex Frydrychowicz, Thorsten A. Bley, Hans Burkhardt, Jürgen Hennig, and Michael Markl. "4D phase contrast MRI at 3 T: Effect of standard and blood-pool contrast agents on SNR, PC-MRA, and blood flow visualization." *Magnetic Resonance in Medicine: An Official Journal of the International Society for Magnetic Resonance in Medicine* 63, no. 2 (2010): 330-338.
https://doi.org/10.1002/mrm.22199
[20] Pelc, Norbert J., Robert J. Herfkens, Ann Shimakawa, and Dieter R. Enzmann. "Phase contrast cine magnetic resonance imaging." *Magnetic resonance quarterly* 7, no. 4 (1991): 229-254.
[21] Harloff, A., F. Albrecht, J. Spreer, A. F. Stalder, J. Bock, A. Frydrychowicz, J. Schöllhorn et al. "3D blood flow characteristics in the carotid artery bifurcation assessed by flow-sensitive 4D MRI at 3T." *Magnetic Resonance in Medicine: An Official Journal of the International Society for Magnetic Resonance in Medicine* 61, no. 1 (2009): 65-74.
https://doi.org/10.1002/mrm.21774

[22] Markl, Michael, Frandics P. Chan, Marcus T. Alley, Kris L. Wedding, Mary T. Draney, Chris J. Elkins, David W. Parker et al. "Time-resolved three-dimensional phase-contrast MRI." *Journal of Magnetic Resonance Imaging: An Official Journal of the International Society for Magnetic Resonance in Medicine* 17, no. 4 (2003): 499-506.
https://doi.org/10.1002/jmri.10272
[23] Harloff, Andreas, Andrea Nußbaumer, Simon Bauer, Aurélien F. Stalder, Alex Frydrychowicz, Cornelius Weiller, Jürgen Hennig, and Michael Markl. "In vivo assessment of wall shear stress in the atherosclerotic aorta using flow-sensitive 4D MRI." *Magnetic Resonance in Medicine: An Official Journal of the International Society for Magnetic Resonance in Medicine* 63, no. 6 (2010): 1529-1536.
https://doi.org/10.1002/mrm.22383
[24] Canstein, C., P. Cachot, A. Faust, A. F. Stalder, J. Bock, A. Frydrychowicz, J. Küffer, J. Hennig, and Michael Markl. "3D MR flow analysis in realistic rapid-prototyping model systems of the thoracic aorta: comparison with in vivo data and computational fluid dynamics in identical vessel geometries." *Magnetic Resonance in Medicine: An Official Journal of the International Society for Magnetic Resonance in Medicine* 59, no. 3 (2008): 535-546.
https://doi.org/10.1002/mrm.21331
[25] Taylor, Charles A., and David A. Steinman. "Image-based modeling of blood flow and vessel wall dynamics: applications, methods and future directions." *Annals of biomedical engineering* 38, no. 3 (2010): 1188-1203.
https://doi.org/10.1007/s10439-010-9901-0
[26] Adib, Mohd Azrul Hisham Mohd, Satoshi Ii, Yoshiyuki Watanabe, and Shigeo Wada. "Minimizing the blood velocity differences between phase-contrast magnetic resonance imaging and computational fluid dynamics simulation in cerebral arteries and aneurysms." *Medical & biological engineering & computing* 55, no. 9 (2017): 1605-1619.
https://doi.org/10.1007/s11517-017-1617-y
[27] Petersson, Sven, Petter Dyverfeldt, and Tino Ebbers. "Assessment of the accuracy of MRI wall shear stress estimation using numerical simulations." *Journal of Magnetic Resonance Imaging* 36, no. 1 (2012): 128-138.
https://doi.org/10.1002/jmri.23610
[28] Cibis, Merih, Wouter V. Potters, Frank JH Gijsen, Henk Marquering, Ed VanBavel, Antonius FW van der Steen, Aart J. Nederveen, and Jolanda J. Wentzel. "Wall shear stress calculations based on 3D cine phase contrast MRI and computational fluid dynamics: a comparison study in healthy carotid arteries." *NMR in Biomedicine* 27, no. 7 (2014): 826-834.
https://doi.org/10.1002/nbm.3126
[29] Stalder, Aurélien F., M. F. Russe, A. Frydrychowicz, J. Bock, J. Hennig, and M. Markl. "Quantitative 2D and 3D phase contrast MRI: optimized analysis of blood flow and vessel wall parameters." *Magnetic Resonance in Medicine: An Official Journal of the International Society for Magnetic Resonance in Medicine* 60, no. 5 (2008): 1218-1231.
https://doi.org/10.1002/mrm.21778
[30] Ii, Satoshi, Mohd Azrul Hisham Mohd Adib, Yoshiyuki Watanabe, and Shigeo Wada. "Physically consistent data assimilation method based on feedback control for patient-specific blood flow analysis." *International journal for numerical methods in biomedical engineering* 34, no. 1 (2018): 1-20.
https://doi.org/10.1002/cnm.2910
[31] Michiko Sugawara, Xu, Lijian, Gaku Tanaka, Makoto Ohta, Hao Liu, and Ryuhei Yamaguchi. "Effect of elasticity on wall shear stress inside cerebral aneurysm at anterior cerebral artery." *Technology and Health Care* 24, no. 4 (2016): 605.
https://doi.org/10.3233/THC-161135
[32] Zhao, S. Z., X. Y. Xu, A. D. Hughes, S. A. Thom, A. V. Stanton, B. Ariff, and Q. Long. "Blood flow and vessel mechanics in a physiologically realistic model of a human carotid arterial bifurcation." *Journal of biomechanics* 33, no. 8 (2000): 975-984.
https://doi.org/10.1016/S0021-9290(00)00043-9
[33] Nolte, David, and Cristóbal Bertoglio. "Reducing the impact of geometric errors in flow computations using velocity measurements." *International journal for numerical methods in biomedical engineering* 35, no. 6 (2019): 1-19.
https://doi.org/10.1002/cnm.3203
[34] Mohamad Shukri Zakaria, Siti Hajar Zainudin, Haslina Abdullah, Cheng See Yuan, Mohd Juzaila Abd Latif, Kahar Osman. "CFD Simulation of Non-Newtonian Effect on Hemodynamics Characteristics of Blood Flow through Benchmark Nozzle." *Journal of Advanced Research in FluidMechanics and Thermal Sciences* 64, no. 1 (2019): 117–125.
[35] M. Sabaruddin, A. Jamali, and Z. Ismail. "Simulation of Heat Transfer on Blood Flow through a Stenosed Bifurcated Artery." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 60, no. 2 (2019): 310–323.