Proceedings of the 2020 Design of Medical Devices Conference
DMD2020
April 6, 7-9, 2020, Minneapolis, MN, USA

DMD2020-9100

ON THE MODAL ANALYSIS OF BLOOD FLOW DYNAMICS IN BRAIN ANEURYSMS

Trung Bao Le *
Department of Civil and Environmental Engineering
North Dakota State University
Fargo, North Dakota 58102

Lahcen Akerkouch
Department of Civil and Environmental Engineering
North Dakota State University
Fargo, North Dakota 58102

ABSTRACT

Complex, unstable inflow jet has been linked to aneurysm growth and rupture. However, methodologies to characterize this inflow jet have not been well established. Our previous works (Le et al., J. Biomech. Engr., 2010 and Le et al., Annals Biomedical Eng., 2013) have shown a possible transition from the stable mode (cavity) to the unstable mode (vortex ring) of this jet. We have proposed the use of a non-dimensional index called Aneurysm Number to characterize this transition (Le et al., 2013). However, the quantification of such a transition is lacking. Currently, there have no efforts in quantifying unstable flows in intracranial aneurysms, which is essential in stratifying rupture risks. In this work, the aneurysmal geometries from three patients at Sanford Health, North Dakota are reconstructed from Magnetic Resonance Angiogram and Digital Subtraction Angiogram data. Using our in-house CFD code (Virtual Flow Simulator), high-resolution flow data is obtained via numerical simulation. We perform modal analysis of blood flow dynamics for these cases using Proper Orthogonal Decomposition. Our results show that there are up to five dominant modes in the flow arising from the interaction of the incoming jet and the aneurysm dome. The spatial distribution of these modes reflect the characteristics of the inflow jet and can be used to quantify flow unsteadiness. Future works will be needed to apply the same procedure for a larger population of patients to examine its relevance in clinical practice.

NOMENCLATURE

4D Flow MRI	Four dimensional flow measurement using Magnetic Resonance Imaging
POD	Proper Orthogonal Decomposition

INTRODUCTION

Recent development of new modalities [1, 2] has provided rich descriptions of internal blood flow dynamics for brain aneurysms. Currently, Magnetic Resonance Imaging (4D-Flow MRI) [3] is the most popular method to measure blood flows in patients. However, 4D-Flow MRI technique is limited by its spatial ($\approx 1mm$) and temporal ($\approx 30ms$) resolutions [3]. Under the limitation of spatial and temporal resolutions, it is challenging to deduce clinically relevant information from the 4D-Flow MRI measurement [4].

Based on clinical observations, Schnell et al. [3] classified blood flows in brain aneurysms into two types: i) a wall jet with an associated slowly evolving flow and ii) a central-jet. These two types of jet flows are thought to associate with different aneurysm sizes and morphologies. The importance of the inflow jet dynamics has been well recognized [5]. In clinical practice, identifying the entrance location of the inflow jet is particularly important when endovascular coil embolization is carried out to prevent recanalization and rerupture [5].

In this work, we examine the possibility of using modal analysis to analyze the dynamics of the inflow jet. Specifically, we investigate the use of Proper Orthogonal Decomposition to extract dominant modes from low-resolution hemodynamic data similar to those obtained from 4D-Flow MRI. We hypothesize that the

---

*Corresponding author email: trung.le@ndsu.edu dominant modes of the flow can be captured at a certain level of temporal and spatial resolutions. Our work also aims at detecting complex flow patterns using the available low-resolution data available in clinical practice.

METHODOLOGY

Magnetic Resonance Angiogram (MRA) data of patients are selected restrospectively from the data bank of Sanford Health, Fargo, North Dakota. The patient-specific data has been reviewed, anonymized and approved by the Institutional Review Board (IRB) of Sanford Health. North Dakota State University IRB agreed to rely on the Sanford Health IRB for review and continued oversight of the research.

The scanned images are processed by the open-source imaging software - Slicer3D and Osirix. The entire surface is connected, smoothed out, and finally triangulated using the open-source software Meshlab and Meshmixer.

The numerical method employed in this work has been extensively described and thoroughly validated against experimental data for aneurysm geometry using three-dimensional volumetric measurements [6]. Therefore, only a brief description of the numerical method is presented in this section. For more details about the method the reader is referred to our previous publications [6, 7].

The governing equations for the fluid (blood) are the three-dimensional, unsteady incompressible continuity and Navier-Stokes equations for velocity vector $\vec{v}$ and pressure p. The fluid is assumed to be Newtonian, which is considered to be a good assumption for blood flow in large arteries such as the one used herein with approximately 3 *mm* diameter.

The governing equations are solved in a background curvilinear domain that contains the complex geometry of the intracranial aneurysm model using the sharp-interface curvilinear-immersed boundary (CURVIB) method [7]. The discrete equations are integrated in time using a fractional step method. A Newton-Krylov solver is used to solve the momentum equations in the momentum step and a GMRES solver with multigrid preconditioner is employed for the Poisson equation.

At the inflow boundary, we prescribe uniform velocity profile varying in time in accordance with the prescribed flow waveform with the peak velocity of $U_0 = 0.7 m/s$. All cases simulated in this work employ the same uniform velocity profile approach at the inlet so that differences in the inflow conditions are excluded as a possible parameter influencing the dome hemodynamics. At the outflow boundary, Neumann-type boundary conditions are specified for the velocity components. No-slip and no-flux conditions are prescribed at all artery wall boundaries, which are considered rigid.

The computational domain is discretized into a structure mesh of size $201 \times 201 \times 380$ (approximately 10 million grid points). At the inlet, uniform flow is prescribed as the boundary condition. The time-dependent flow waveform is used to describe the pulsatile condition at the inlet. A traction-free boundary condition is applied at the outlet of the computational domain.

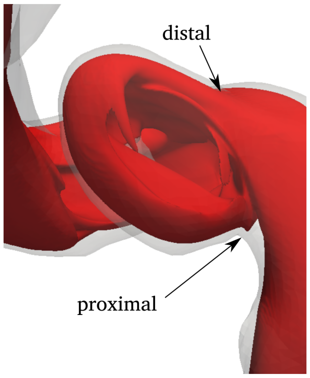

FIGURE 1. Three-dimensional structure of the inflow jet near peak systole $\frac{t}{T} = 0.25$ is visualized using the iso-surface of the velocity magnitute at $U_0 = 0.7 m/s$. The inflow jet enters the aneurysm dome via the distal end

RESULTS

The emergence of the inflow jet is patient-specific depending on the anatomy. In this case, the jet is directed to impinge on the distal end wall as shown in Figure 1. Such impingement near peak-systole directs the flow back to the proximal region and merge with the parent's artery flow.

Using the high-resolution simulation results, lower resolution data are generated by coarsening the original data systematically by four, eight and sixteen times. The analysis using POD is shown in Figure 2. The analysis shows that the flow contains roughly 40 modes. These modes can be revealed using POD analysis regardless of the grid resolution.

The spatial distribution of the modes is illustrated in Figure 3. In this analysis, Mode-1 represents the fluctuation of the internal dynamics of the inflow jet. Mode-2 shows the annihilation of the flow variation due to the interaction of the inflow jet with the distal wall. Mode-3 represents the backflow toward the proximal end. The separation of these modes indicate the different dynamics of the jet when interacting with the distal wall.

DISCUSSION

Due to the importance of hemodynamics in aneurysm rupture, previous works have made efforts to characterize the inflow jet dynamics as a predictor of rupture. Using numerical simulation, Cebral et al. [8] classified the inflow jet dynamics into concentrated and diffused types. Schnell et al. [3] noted that the inflow jet dynamics depend strongly on size and morphology of the

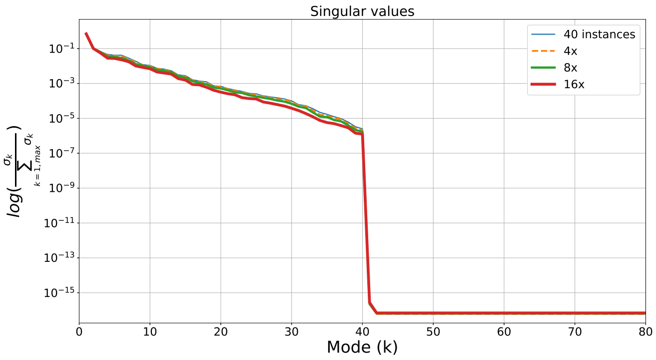

FIGURE 2. Distribution of singular values σ_k of blood flow dynamics of the brain aneurysm under different spatial resolution: a) original (40 instances); b) 4-time coarsening (4x); c) 8-time coarsening (8x) and d) 16-time coarsening (16x).

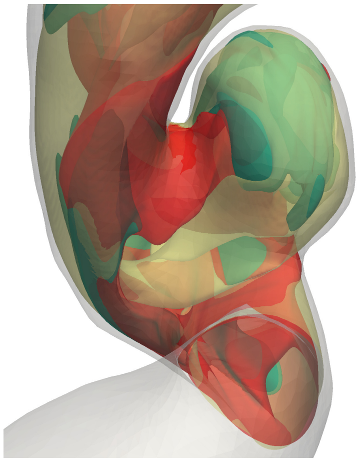

FIGURE 3. The spatial distribution of different modes: a) Mode-1 (yellow); b) Mode-2 (red) and c) Mode-3 (green). The modes are associated with different dynamics of the inflow jet.

aneurysm. Using $in-vivo$ 4D Flow MRI data, Futami et al. [9] further classified the inflow patterns into four categories (concentrated, diffused, neck-limited and unvisualized). The main challenge with this type of classification [9] is its dependence on the chosen threshold of velocity magnitude. Moreover, this type of classification does not quantify the temporal fluctuation of inflow jet (or flow instabilities), which has been thought to link with rupture.

In this work, we attempt to demonstrate the feasibility of quantifying inflow jet dynamics using modal analysis [10], which is free of thresholding problem. Our results in Figure 2 show that it is possible to quantify the inflow jet dynamics using low resolution data since the flow modes can be retrieved quite reasonably across different grid resolutions. In addition, the flow modes correspond well to the inflow jet dynamics as shown in Figure 3, which is promising to be used in future statistical studies in larger population of patients.

CONCLUSIONS

The advancement of 4D Flow MRI has provided an abundant source of hemodynamics data for brain aneurysms. However, the current spatial and temporal resolution of 4D-Flow MRI are not sufficient to resolve all the scales in the flow dynamics [11], which is the barrier to establish the link between hemodynamics and pathological processes. It is important to determine how to use the acquired 4D-Flow MRI data with the least uncertainties.

In this work, we explore the use of Proper Orthogonal Decomposition in charaterizing the inflow jet dynamics, an important phenomenon in brain aneurysm. We first perform high resolution simulation using Direct Numerical Simulation, which resolve all the scales using the patient-specific anatomy. The simulation result is used as ground truth for the modal analysis at selected spatial and temporal resolution by coarsening the high resolution hemodynamic data up to the resolution of 4D-Flow MRI. Our results show that both POD can quantify spatial and temporal evolution of the inflow jet even at low resolution. Our results justify the use of modal analysis for brain aneurysm flow at sufficiently low resolution (e.g 1mm).

ACKNOWLEDGMENT

This project is partially supported by NSF ND EPSCOR project FAR0030612. We thank graduate student Venkata Kanumuru for preparing the three-dimensional model of the aneurysm. This work is supported by the start-up package of Trung Bao Le from the Department of Civil and Environmental Engineering, North Dakota State University, United States of America. The computational work has been performed using the computational resources of Center for Computationally Assisted Science and Technology (CCAST) at North Dakota State University.

REFERENCES

[1] Barfett, J. J., Velauthapillai, N., Fierstra, J., Crawley, A., Coolens, C., Crean, A., Jaskolka, J., Dufort, P., Krings, T., and Mikulis, D., 2014. "Intra-vascular blood velocity and volumetric flow rate calculated from dynamic 4d ct angiography using a time of flight technique". *The international journal of cardiovascular imaging,* ***30***(7), pp. 1383–1392.

[2] Bouillot, P., Brina, O., Chnafa, C., Cancelliere, N., Vargas, M., Radovanovic, I., Krings, T., Steinman, D., and

Pereira, V., 2019. “Robust cerebrovascular blood velocity and flow rate estimation from 4d-cta.”. *Medical physics,* ***46***(5), p. 2126.

[3] Schnell, S., Ansari, S. A., Vakil, P., Wasielewski, M., Carr, M. L., Hurley, M. C., Bendok, B. R., Batjer, H., Carroll, T. J., Carr, J., et al., 2014. “Three-dimensional hemodynamics in intracranial aneurysms: influence of size and morphology”. *Journal of Magnetic Resonance Imaging,* ***39***(1), pp. 120–131.

[4] Futami, K., Sano, H., Kitabayashi, T., Misaki, K., Nakada, M., Uchiyama, N., and Ueda, F., 2015. “Parent artery curvature influences inflow zone location of unruptured sidewall internal carotid artery aneurysms”. *American Journal of Neuroradiology,* ***36***(2), pp. 342–348.

[5] Futami, K., Sano, H., Misaki, K., Nakada, M., Ueda, F., and Hamada, J., 2014. “Identification of the inflow zone of unruptured cerebral aneurysms: comparison of 4d flow mri and 3d tof mra data”. *American Journal of Neuroradiology,* ***35***(7), pp. 1363–1370.

[6] Le, T. B., Troolin, D. R., Amatya, D., Longmire, E. K., and Sotiropoulos, F., 2013. “Vortex phenomena in sidewall aneurysm hemodynamics: experiment and numerical simulation”. *Annals of biomedical engineering,* ***41***(10), pp. 2157–2170.

[7] Le, T. B., Borazjani, I., and Sotiropoulos, F., 2010. “Pulsatile flow effects on the hemodynamics of intracranial aneurysms”. *Journal of biomechanical engineering,* ***132***(11), p. 111009.

[8] Cebral, J. R., Mut, F., Weir, J., and Putman, C. M., 2011. “Association of hemodynamic characteristics and cerebral aneurysm rupture”. *American Journal of Neuroradiology,* ***32***(2), pp. 264–270.

[9] Futami, K., Kitabayashi, T., Sano, H., Misaki, K., Uchiyama, N., Ueda, F., and Nakada, M., 2016. “Inflow jet patterns of unruptured cerebral aneurysms based on the flow velocity in the parent artery: evaluation using 4d flow mri”. *American Journal of Neuroradiology,* ***37***(7), pp. 1318–1323.

[10] Taira, K., Brunton, S. L., Dawson, S. T., Rowley, C. W., Colonius, T., McKeon, B. J., Schmidt, O. T., Gordeyev, S., Theofilis, V., and Ukeiley, L. S., 2017. “Modal analysis of fluid flows: An overview”. *Aiaa Journal*, pp. 4013–4041.

[11] Schnell, S., Wu, C., and Ansari, S. A., 2016. “4d mri flow examinations in cerebral and extracerebral vessels. ready for clinical routine?”. *Current opinion in neurology,* ***29***(4), p. 419.