Computational fluid dynamics for thin walled region

Previous computational fluid dynamics (CFD) studies reported the correlation of maximum pressure (Pmax) areas and thin walled region (TWR)s; however, the correlation with aneurysm rupture has not been established.

A study of Suzuki et al., from the Department of Neurosurgery, Massachusetts General Hospital, Jikei University School of Medicine, Tokyo and Niigata, aimed to investigate this hemodynamic correlation.

The aneurysmal wall surface at the Pmax areas was intraoperatively evaluated using a fluid flow formula under pulsatile blood flow conditions in 23 patients with 23 saccular middle cerebral artery bifurcation aneurysms (16 unruptured and 7 ruptured). The pressure difference (Pd) at the Pmax areas was calculated by subtracting the average pressure (Pave) from the Pmax and normalized by dividing this by the dynamic pressure at the aneurysm inlet side. The wall shear stress (WSS) was also calculated at the Pmax areas, aneurysm dome, and parent artery. These hemodynamic parameters were used to validate the correlation with TWRs in unruptured MCA aneurysms. The characteristic hemodynamic parameters at the rupture points in ruptured MCA aneurysms were then determined.

In 13 of 16 unruptured aneurysms (81.2%), Pmax areas were identified that corresponded to TWRs. In 5 of the 7 ruptured cerebral aneurysms, the Pmax areas coincided with the rupture point. At these areas, the Pd values were not higher than those of the TWRs in unruptured cerebral aneurysms; however, minimum WSS, time-averaged WSS, and normalized WSS at the rupture point were significantly lower than those of the TWRs in unruptured aneurysms ($p < 0.01$).

At the maximum pressure (Pmax) area of Thin walled regions (TWRs), decreased wall shear stress (WSS) appears to be the crucial hemodynamic parameter that indicates the risk of aneurysm rupture [1].

Higher pressure through the cardiac cycle may efficiently predict a thin-wall region within intracranial aneurysms, which strongly suggests that CFD analysis would be a valuable tool to determine the treatment strategy in patients with unruptured aneurysms [2].

Previously, pressure elevation at TWRs was reported with computational fluid dynamics (CFD) but not fully evaluated.

Fifty unruptured middle cerebral artery aneurysms were analyzed. Spatial and temporal maximum pressure (Pmax) areas were determined with a fluid-flow formula under pulsatile blood flow conditions. Intraoperatively, TWRs of aneurysm domes were identified as reddish areas relative to the healthy normal middle cerebral arteries; 5 neurosurgeons evaluated and divided these regions according to Pmax area and TWR correspondence. Pressure difference (PD) was defined as the degree of pressure elevation on the aneurysmal wall at Pmax and was calculated by subtracting the average pressure from the Pmax and dividing by the dynamic pressure at the aneurysm inlet side for normalization.

In 41 of the 50 cases (82.0%), the Pmax areas and TWRs corresponded. PD values were significantly higher in the correspondence group than in the noncorrespondence group (P = .008). A receiver-operating characteristic curve demonstrated that PD accurately predicted TWRs at Pmax areas (area under the curve, 0.764; 95% confidence interval, 0.574-0.955; cutoff value, 0.607; sensitivity, 66.7%; specificity, 82.9%).

A high PD may be a key parameter for predicting TWRs in unruptured cerebral aneurysms [3].

Image-based computational fluid dynamics (CFD) has shown potential to aid in the clinical management of intracranial aneurysms (IAs) but its adoption in the clinical practice has been missing, partially due to lack of accuracy assessment and sensitivity analysis. To numerically solve the flow-governing equations CFD solvers generally rely on two spatial discretization schemes: Finite Volume (FV) and Finite Element (FE). Since increasingly accurate numerical solutions are obtained by different means, accuracies and computational costs of FV and FE formulations cannot be compared directly. To this end, in this study we benchmark two representative CFD solvers in simulating flow in a patient-specific IA model: (1) ANSYS Fluent, a commercial FV-based solver and (2) VMTKLab multidGetto, a discontinuous Galerkin (dG) FE-based solver. The FV solver's accuracy is improved by increasing the spatial mesh resolution (134k, 1.1m, 8.6m and 68.5m tetrahedral element meshes). The dGFE solver accuracy is increased by increasing the degree of polynomials (first, second, third and fourth degree) on the base 134k tetrahedral element mesh. Solutions from best FV and dGFE approximations are used as baseline for error quantification. On average, velocity errors for second-best approximations are approximately 1cm/s for a [0,125]cm/s velocity magnitude field. Results show that high-order dGFE provide better accuracy per degree of freedom but worse accuracy per Jacobian non-zero entry as compared to FV. Cross-comparison of velocity errors demonstrates asymptotic convergence of both solvers to the same numerical solution. Nevertheless, the discrepancy between under-resolved velocity fields suggests that mesh independence is reached following different paths [4].

Previously, pressure elevation at thin walled regions (TWRs) was reported with computational fluid dynamics (CFD) but not fully evaluated.

Fifty unruptured middle cerebral artery aneurysms were analyzed. Spatial and temporal maximum pressure (Pmax) areas were determined with a fluid-flow formula under pulsatile blood flow conditions. Intraoperatively, TWRs of aneurysm domes were identified as reddish areas relative to the healthy normal middle cerebral arteries; 5 neurosurgeons evaluated and divided these regions according to Pmax area and TWR correspondence. Pressure difference (PD) was defined as the degree of pressure elevation on the aneurysmal wall at Pmax and was calculated by subtracting the average pressure from the Pmax and dividing by the dynamic pressure at the aneurysm inlet side for normalization.

In 41 of the 50 cases (82.0%), the Pmax areas and TWRs corresponded. PD values were significantly higher in the correspondence group than in the noncorrespondence group (P = .008). A receiver-operating characteristic curve demonstrated that PD accurately predicted TWRs at Pmax areas (area under the curve, 0.764; 95% confidence interval, 0.574-0.955; cutoff value, 0.607; sensitivity, 66.7%; specificity, 82.9%).

A high PD may be a key parameter for predicting TWRs in unruptured cerebral aneurysms [5].

Thin-walled regions of unruptured intracranial aneurysms colocalize with low wall shear stress (WSS), suggesting a cellular mechanotransduction link between areas of flow stasis and aneurysm wall thinning [6].

Results suggest that in contrast to the pathogenic effect of a high WSS in the initiating phase, a low WSS may facilitate the growing phase and may trigger the rupture of a cerebral aneurysm by causing degenerative changes in the aneurysm wall. The WSS of the aneurysm region may be of some help for the prediction of rupture [7]

Further investigations will elucidate the detailed hemodynamics effects on aneurysm rupture [8].

Thin walled regions of unruptured intracranial aneurysms colocalize with low wall shear stress (WSS), suggesting a cellular mechanotransduction link between areas of flow stasis and aneurysm wall thinning [9].

Case reports

Sejkorová et al., analyzed a case of a ruptured middle cerebral artery aneurysm for which they acquired imaging data at three time points, including at rupture. A patient with an observed MCA aneurysm was admitted to the emergency department with clinical symptoms of a subarachnoid hemorrhage. During three dimensional digital subtraction angiography (DSA), the aneurysm ruptured again. Imaging data from two visits before rupture and this 3D DSA images at the moment of rupture were acquired, and computational fluid dynamics (CFD) simulations were performed. Results were used to describe the time-dependent changes of the hemodynamic variables associated with rupture. Time-dependent hemodynamic changes at the rupture location were characterized by decreased wall shear stress WSS and flow velocity magnitude. The impingement jet in the dome changed its position in time and the impingement area at follow-up moved near the rupture location. The results suggest that the increased WSS on the dome and increased low wall shear stress area (LSA) and decreased WSS on the daughter bleb with slower flow and slow vortex may be associated with rupture. CFD performed during the follow-up period may be part of diagnostic tools used to determine the risk of aneurysm rupture [10].

References

[1]
Suzuki T, Stapleton CJ, Koch MJ, Tanaka K, Fujimura S, Suzuki T, Yanagisawa T, Yamamoto M, Fujii Y, Murayama Y, Patel AB. Decreased wall shear stress at high-pressure areas predicts the rupture point in ruptured intracranial aneurysms. J Neurosurg. 2019 Mar 15:1-7. doi: 10.3171/2018.12.JNS182897. [Epub ahead of print] PubMed PMID: 30875692.
[2]
Hori E, Oya KU, Hori S, Okamoto S, Shibata T, Kubo M, Horie Y, Koh M, Kashiwazaki D, Kuroda S. [Computational Fluid Dynamic Analysis of Intracranial Aneurysms Using Newly Developed Software:Can It Predict the Thin-Walled Region of Intracranial Aneurysm Preoperatively?]. No Shinkei

Geka. 2018 Mar;46(3):199-206. doi: 10.11477/mf.1436203705. Japanese. PubMed PMID: 29567869.

[3], [5]

Suzuki T, Takao H, Suzuki T, Kambayashi Y, Watanabe M, Sakamoto H, Kan I, Nishimura K, Kaku S, Ishibashi T, Ikeuchi S, Yamamoto M, Fujii Y, Murayama Y. Determining the Presence of Thin-Walled Regions at High-Pressure Areas in Unruptured Cerebral Aneurysms by Using Computational Fluid Dynamics. Neurosurgery. 2016 Oct;79(4):589-95. doi: 10.1227/NEU.0000000000001232. PubMed PMID: 27028475.

[4]

Burrowes KS, De Backer J, Kumar H. Image-based computational fluid dynamics in the lung: virtual reality or new clinical practice? Wiley Interdiscip Rev Syst Biol Med. 2017 Nov;9(6). doi: 10.1002/wsbm.1392. Epub 2017 Jun 13. Review. PubMed PMID: 28608962.

[6], [9]

Kadasi LM, Dent WC, Malek AM. Colocalization of thin-walled dome regions with low hemodynamic wall shear stress in unruptured cerebral aneurysms. J Neurosurg. 2013 Jul;119(1):172-9. doi: 10.3171/2013.2.JNS12968. Epub 2013 Mar 29. PubMed PMID: 23540271.

[7]

Shojima M, Oshima M, Takagi K, Torii R, Hayakawa M, Katada K, Morita A, Kirino T. Magnitude and role of wall shear stress on cerebral aneurysm: computational fluid dynamic study of 20 middle cerebral artery aneurysms. Stroke. 2004 Nov;35(11):2500-5. PubMed PMID: 15514200.

[8]

Omodaka S, Sugiyama S, Inoue T, Funamoto K, Fujimura M, Shimizu H, Hayase T, Takahashi A, Tominaga T. Local hemodynamics at the rupture point of cerebral aneurysms determined by computational fluid dynamics analysis. Cerebrovasc Dis. 2012;34(2):121-9. doi: 10.1159/000339678. Epub 2012 Aug 1. PubMed PMID: 22965244.

[10]

Sejkorová A, Dennis KD, Švihlová H, Petr O, Lanzino G, Hejčl A, Dragomir-Daescu D. Hemodynamic changes in a middle cerebral artery aneurysm at follow-up times before and after its rupture: a case report and a review of the literature. Neurosurg Rev. 2016 Nov 24. [Epub ahead of print] PubMed PMID: 27882440.