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Surgical Neurology International
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SNI: Neurovascular

Editor
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SNI Open Access

Case Report

Hemodynamic analysis of a thrombosed bleb in an unruptured cerebral aneurysm

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Received: 15 July 2024
Accepted: 27 August 2024
Published: 04 October 2024

DOI
10.25259/SNI_584_2024

Quick Response Code:

ABSTRACT

Background: The intricate hemodynamic mechanisms of thrombosis in the bleb and/or dome of cerebral aneurysms remain unresolved. We encountered a unique case where the bleb of an unruptured internal carotid-posterior communicating artery (IC-PC) aneurysm underwent thrombosis over 7 years. Complete spontaneous thrombosis of a bleb in an unruptured cerebral aneurysm has not been previously reported. Therefore, a hemodynamic evaluation using computational fluid dynamics (CFD) analysis was conducted to examine the thrombotic development within the bleb of this aneurysm.

Case Description: We observed a case in which thrombosis led to the disappearance of a bleb in the dome of an unruptured IC-PC aneurysm over 7 years. CFD analysis was employed to investigate the hemodynamics of bleb thrombosis and the thrombosed bleb-neck regions of the dome in this IC-PC aneurysm. The reduction and disappearance of the bleb were associated with a decreased flow rate within the bleb, reduced magnitude of wall shear stress (WSSm), a lower WSSm ratio between the bleb and dome, increased vector direction of wall shear stress (WSSv), and discrete streamlines entering the bleb-neck region, resulting in stasis and subsequent thrombosis within the bleb. Seven years later, the dome region corresponding to the thrombosed bleb-neck exhibited localized areas with low WSSm and high WSSv along the dome wall.

Conclusion: Hemodynamically, spontaneously thrombosed bleb and thrombosed post-bleb-neck dome walls were characterized by low WSSm and high WSSv. These findings underscore the importance of CFD analysis in predicting thrombotic events in cerebral aneurysms, which can inform better clinical management strategies.

Keywords: Aneurysmal bleb, Computational fluid dynamics, Computed tomography angiography, Thrombosis, Wall shear stress

INTRODUCTION

The intricate hemodynamic mechanism underlying spontaneous thrombosis in cerebral aneurysms remains elusive.[10] We report a unique case of an unruptured internal carotid-posterior communicating artery (IC-PC) aneurysm featuring a bleb. Over 7 years, thrombosis led to the shrinkage and subsequent disappearance of the bleb, accompanied by enlargement of the dome. To the best of our knowledge, this represents the first report of complete spontaneous thrombosis of a bleb in an unruptured cerebral aneurysm. Computational fluid dynamics (CFD) analysis may provide valuable hemodynamic insights into understanding the thrombotic process in cerebral aneurysms.

CASE DESCRIPTION

The necessary patient informed consent was obtained for this study. A female in her 70s presented with headaches and mild cognitive impairment. Computed tomography angiography (CTA) revealed an unruptured right IC-PC aneurysm with a bleb. The patient and her family opted for conservative management, avoiding aggressive treatments such as neck clipping or embolization. Instead, they focused on blood pressure management without antiplatelet treatment and underwent clinicoradiological follow-up. Over a 7-year observational period, the bleb gradually diminished and disappeared by the 7th year. The patient remained asymptomatic, with no rupture of the cerebral aneurysm, and later passed away from an unrelated condition. The morphology of the bleb and dome was sequentially reconstructed using 3D CTA obtained during the 1st, 2nd, 5th, and 7th years, all projected from similar view directions [Figure 1]. Initially, the IC-PC aneurysm displayed a bleb measuring 3.54 × 3.07 mm and a dome size of 6.90 × 6.56 mm on the first CTA [Figure 1a]. The bleb diminished over the 7 years [Figures 1b and c], ultimately disappearing due to spontaneous thrombosis [Figure 1d].

CFD analysis

The hemodynamics of the IC-PC aneurysm were sequentially analyzed using CTA datasets obtained at the 1st, 2nd, 5th, and 7th years with a commercial CFD package (Hemoscope v1.4, EBM and AMIN Corp., Tokyo), as described. In the previous studies,[7] the aneurysmal dome with a bleb complex was quantified for surface area, volume, neck size, dome length, and aspect ratio [Table 1]. Hemodynamic parameters, including streamlines, pressure drop (mmHg), flow rate (ml/min), magnitude of wall shear stress (WSSm, Pa), and vector direction of wall shear stress (WSSv, degrees), were evaluated. The CFD analysis depicted WSSm and streamlines at the inflow parent vessel (C4 segment), aneurysm neck, dome-bleb region, and outflow parent vessels (C1 segment and posterior communicating artery) [Figures 1e-h]. The formation of the bleb was observed in the outflow region of the aneurysmal dome. Notably, the streamlined axis of blood flow diverged significantly outward as the dome enlarged. From the hemodynamic analysis, it was inferred that within the bleb, there was a decrease in flow rate, a reduction in WSSm and the bleb/dome ratio, an elevation in WSSv, and a dispersion of the blood flow axis from the bleb-neck region. These changes may have led to stasis within the bleb and promoted thrombosis, resulting in the shrinkage and subsequent disappearance of the bleb.

CFD follow-up in the bleb of the dome region

We presented a refined 7-year follow-up of hemodynamic analysis, specifically examining WSSm [Figures 2a-f] and WSSv [Figures 2e-h] in the bleb of the unruptured IC-PC

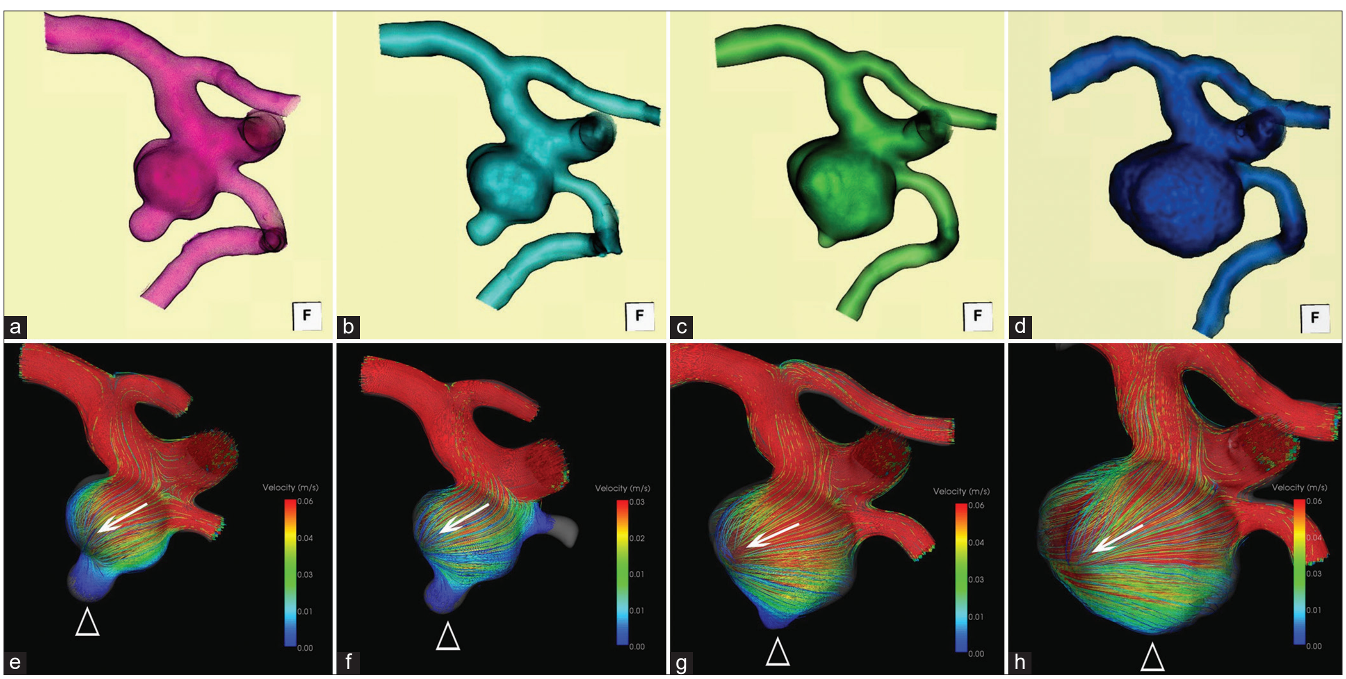

Figure 1: Seven-year follow-up of 3D-CTA and hemodynamics of the right unruptured IC-PC aneurysm. The morphology of the bleb and dome was sequentially reconstructed using 3D-CTA obtained (a) at the 1st year, (b) 2nd year, (c) 5th year, and (d) 7th year, projected from similar view directions. Hemodynamics (streamline and WSS) of the aneurysm were sequentially analyzed (e) at the 1st year, (f) 2nd year, (g) 5th year, and (h) 7th year. Arrows indicate the axis of the streamline, and empty arrowheads indicate the location of the bleb.

Table 1: Hemodynamic and morphological parameters of a 7-year follow-up of an unruptured right internal carotid-posterior communicating artery aneurysm.

Regions	Flow Rate (mL/min)	Wall Shear Stress Mean (Pa)	Aneurysm	Aneurysm	Aneurysm	Aneurysm	Aneurysm	Flow Rate	WSS Rate	Flow Rate
			Surface (mm^2)	Volume (mm≥)	Neck Size (mm)	Depth (mm)	Aspect Ratio	An/C4	Bleb/ Dome	An/C2
1st Year										
Rt C4	210.27	3.76								
Rt C2	175.58	3.06								
Rt PComA	34.66	2.09								
Aneurysm dome	101.62	1.03	202.72	292.79	6.90	6.56	0.95	0.48	0.25	0.58
Bleb	4.12	0.26	36.25	25.83	3.54	3.07	0.87	0.02	NA	0.02
2nd Yyear										
Rt C4	200.80	4.59								
Rt C2	200.67	3.86								
Rt PComA	43.28	4.40								
Aneurysm dome	62.20	0.50	166.36	274.06	7.67	6.06	0.79	0.31	0.64	0.31
Bleb	3.15	0.32	26.90	16.84	2.97	2.84	0.96	0.02	NA	0.02
5th Year										
Rt C4	175.03	3.55								
Rt C2	141.69	3.56								
Rt PComA	34.25	3.14								
Aneurysm dome	123.07	1.07	287.08	578.36	8.69	8.11	0.93	0.70	0.02	0.87
Bleb	2.18	0.45	10.28	4.15	2.84	1.37	0.48	0.01	NA	0.02
7th Year										
Rt C4	236.71	4.29								
Rt C2	179.98	3.60								
Rt PComA	57.59	3.83								
Aneurysm dome	136.26	1.11	445.15	1017.55	8.91	10.51	1.18	0.58	NA	0.76
10th Year										
Rt C4	294.76	6.24								
Rt C2	222.37	3.55								
Rt PComA	73.72	3.80								
Aneurysm	150.01	0.91	533.79	1341.48	9.55	12.12	1.27	0.51	NA	0.67

The aneurysm dome with a bleb complex was quantified for surface area (mm^2), volume (mm^3), neck size (mm), dome length (mm), aspect ratio, flow rate of the aneurysm/C4, wall shear stress ratio of bleb/dome, and flow rate of the aneurysm/C2. C4: C4 segment of the internal carotid artery; C2: C2 segment of the internal carotid artery.
Over the 7 years, within the bleb, there was a decrease in flow rate, a reduction in WSSm, and a decrease in the bleb/dome ratio. WSS: Wall shear stress, PComA: Posterior communicating artery, WSSm: Magnitude of wall shear stress.

aneurysm, as shown in Figure 2 (from the perspective of the bleb). In the initial image, low WSSm and high WSSv were observed throughout the bleb and bleb-neck. At the 2-year follow-up, the bleb slightly reduced in size, with similar hemodynamic findings observed. By the 5-year follow-up, the bleb had further diminished, continuing a trend of low WSSm and high WSSv. By the 7-year follow-up, the bleb completely disappeared due to thrombosis; however, localized areas with low WSSm and high WSSv were noted in the dome region corresponding to the thrombosed bleb area.

DISCUSSION

Thrombosis in the bleb and/or dome of cerebral aneurysms

Spontaneous thrombosis commonly occurs in the dome of ruptured cerebral aneurysms, with an incidence rate of 1–2%.[10] Among unruptured giant cerebral aneurysms, 10–30% exhibit spontaneous partial thrombosis in the dome. Histopathologically, thrombosis is instigated by endothelial damage in the aneurysmal dome wall, which exposes subendothelial tissue and activates the coagulation

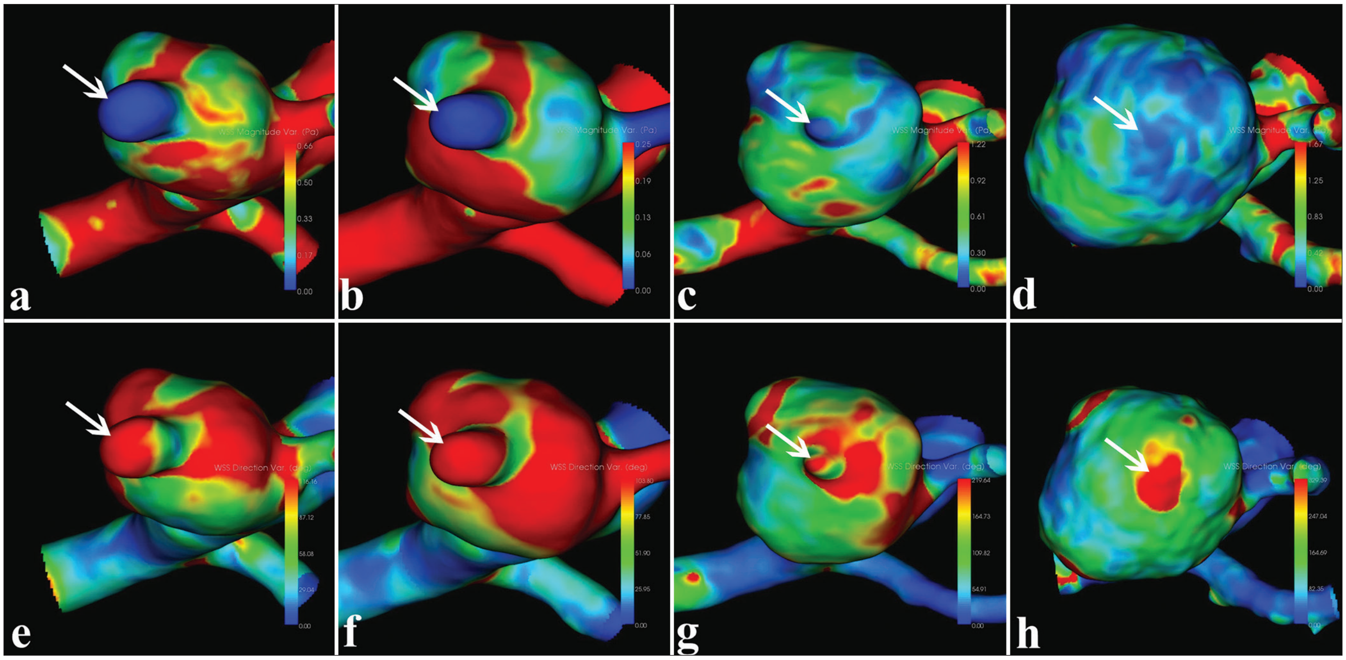

Figure 2: Seven-year follow-up CFD analysis of WSSm and WSSv at the bleb of the right unruptured IC-PC aneurysm. (a) at the 1st year, (b) 2nd year, (c) 5th year, and (d) 7th year, respectively. Note: At the 7-year follow-up, the bleb completely disappeared due to thrombosis, but localized areas with low WSSm-variation and high WSSv-variation were observed in the dome region corresponding to the thrombosed bleb area. Arrows indicate the location of the bleb and the corresponding thrombosed bleb at the dome wall.

cascade.[3] From a hemodynamic perspective, the creation of a localized microenvironment conductive to coagulation and inflammation within the aneurysm wall is believed to promote intraluminal thrombosis. Factors such as decreased WSSm and the attenuation of pulsatile flow contribute to blood stasis within the aneurysm, thereby exacerbating thrombus formation.[5] Conversely, complete spontaneous thrombosis in the dome of non-giant cerebral aneurysms is rare, with only 26 reported cases comprising 27 instances to date; the intricate mechanisms underlying thrombosis in these cases remain poorly understood.[10] The presented case involves a 7-year follow-up of an unruptured right IC-PC aneurysm, in which the bleb within the dome underwent partial thrombosis that gradually progressed to complete thrombosis, resulting in contrast unenhancement observed by CTA. To the best of our knowledge, this represents the first reported instance of complete spontaneous thrombosis of the bleb in an unruptured cerebral aneurysm.

Hemodynamic perspectives of cerebral aneurysms

Numerous studies employing CFD have investigated the occurrence and growth of cerebral aneurysms, with many reports available.[1,2,4,6-9] Aneurysm initiation typically occurs at branching points, bifurcations, or outer walls of curved arteries. Flow collision at the apex of bifurcations or sharply curved vessels generates unstable helical flow patterns near the affected wall. Repetitive flow collisions induce morphological and functional changes in the endothelium due to vascular wall fatigue, leading to localized increases in static wall pressure at collision points. Hemodynamically, high WSSm, as well as high temporal and spatial gradients of wall shear stress (WSS) and pressure gradients, are associated with aneurysm initiation. In addition, dome growth is influenced by disrupted flow and decreased WSS, which trigger inflammatory responses that affect aneurysm growth and rupture through vascular wall remodeling. Aneurysm rupture occurs when the tension in the aneurysm wall – proportional to intraluminal pressure and radius but inversely proportional to wall thickness – exceeds the mechanical strength of the wall tissue. This process is exacerbated by factors such as high intraluminal pressure, large aneurysm size, and thin wall thickness.

Hemodynamic analysis of a thrombosed bleb in the presented case

In this instance, the outer surface of the aneurysmal dome extended into and impinged on the inner aspect of the temporal lobe hippocampal gyrus, where a bleb was identified. The emergence of such blebs has been linked to various factors, including intraluminal blood flow dynamics, pathological changes within the aneurysm wall, and interactions with adjacent tissues (peri-aneurysmal contact).[7,8] Hemodynamic analysis, focusing on parameters such as WSSm and streamline patterns, revealed the presence of a bleb within the outflow zone of the dome. This suggests that the interplay of intraluminal hemodynamic forces, biological interactions with endothelial cells along the aneurysm wall, structural weaknesses within the aneurysm, and contact with surrounding brain tissue may influence the bleb. Hemodynamically, stagnation of blood flow within the bleb led to thrombosis, resulting in shrinkage and subsequent disappearance. This process was influenced by factors such as decreased flow rate within the bleb, reduced WSSm, a lower WSSm ratio between the bleb and the dome, elevated WSSv, and dispersion of the blood flow axis entering the dome away from the bleb-neck region.

Hemodynamic perspectives of the thrombosed bleb-neck region of the dome

The thrombosed bleb persists morphologically without disappearing and remains at the bleb-neck region. Hemodynamic analysis of the bleb-neck region revealed that spontaneous thrombosis and disappearance of the bleb occurred due to interruption of blood flow within the bleb, resulting in a lack of contrast enhancement observed by CTA. However, localized areas with low WSSm and high WSSv were noted in the dome region corresponding to the thrombosed bleb-neck. It is speculated that the thrombosed bleb-neck region exhibited different wall characteristics compared to the surrounding dome wall. From the hemodynamic analysis in this case, both the spontaneously thrombosed bleb and the thrombosed post-bleb-neck dome region exhibited characteristic hemodynamic findings of reduced variation in WSSm and multidirectional changes in WSSv.

CONCLUSION

CFD analysis enabled the hemodynamic evaluation of bleb thrombosis and the post-thrombosis bleb-neck dome wall. Complete thrombosis was observed in spontaneously thrombosed blebs due to stagnation of blood flow within the bleb. Localized areas with low values of WSSm and high values of WSSv were observed in dome wall regions corresponding to the thrombosed bleb-neck post-thrombosis. These findings underscore the importance of CFD analysis in predicting thrombotic events in cerebral aneurysms, which can inform better clinical management strategies.

Ethical approval

The research/study approved by the Institutional Review Board at The Institutional Review Board (IRB) of Satoh Neurosurgical Hospital, number 2024–04, dated May 03, 2024.

Declaration of patient consent

The authors certify that they have obtained all appropriate patient consent.

Financial support and sponsorship

Nil.

Conflicts of interest

There are no conflicts of interest.

Use of artificial intelligence (AI)-assisted technology for manuscript preparation

The authors confirm that there was no use of artificial intelligence (AI)-assisted technology for assisting in the writing or editing of the manuscript and no images were manipulated using AI.

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How to cite this article: Satoh T. Hemodynamic analysis of a thrombosed bleb in an unruptured cerebral aneurysm. Surg Neurol Int. 2024;15:357. doi: 10.25259/SNI_584_2024