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# Assessing the risk of intracranial aneurysm rupture using computational fluid dynamics: a pilot study

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**Objective:** This study compared 2 representative cases with ruptured aneurysms to explore the role of hemodynamic and morphological parameters in evaluating the rupture risk of intracranial aneurysms (IAs).

**Methods:** CTA and 3-dimensional rotational angiography (3DRA) of 3 IAs in 2 patients were retrospectively analyzed in this study. Hemodynamics and morphological parameters were compared between a ruptured IA and an unruptured IA in case 1, and between before and after aneurysm rupture in case 2.

**Results:** In case 1, the ruptured aneurysm had larger morphological parameters including size ratio (SR), aspect ratio (AR), aneurysm vessel angle ( $\theta_f$ ), Aneurysm inclination angle ( $\theta_A$ ), Undulation index (UI), Ellipticity index (EI), and Non-sphericity Index (NSI) than the unruptured aneurysm. And oscillatory shear index (OSI) is also larger. Higher rupture resemblance score (RRS) was shown in the ruptured aneurysm. In case 2, the aneurysm had one daughter sac after 2 years. Partial morphological and hemodynamic parameters including SR, AR,  $\theta_f$ ,  $\theta_A$ , UI, EI, NSI, OSI, and relative residence time (RRT) increased, and normalized wall shear stress (NWSS) was significantly reduced. RRS increased during this period.

**Conclusion:** SR and OSI may have predictive values for the risk of intracranial aneurysm rupture. It is possible that WSS Changes before and after IA rupture, yet the influence of high or low WSS on growth and rupture of IA remains unclear. RRS is promising to be used in the clinical assessment of the rupture risk of IAs and to guide the formulation of treatment plans.

## KEYWORDS

intracranial aneurysms, rupture risk, hemodynamics, computational fluid dynamics, SAH, subarachnoid hemorrhage

## 1 Introduction

Although the incidence of intracranial aneurysms (IAs) is less than 10% of the total population, ruptured IAs are characterized by high morbidity and mortality (1–3). With the development of imaging technology, the detection rate of unruptured IAs is getting higher, especially for small aneurysms, which increases pressure to diagnosis and

treatment (4). On one hand, small IAs have a lower risk of rupture (5). But if they do rupture, it can cause significant harm and pose a risk to the patient's life. On the other hand, surgical treatment for small IAs may result in potential complications, such as intraoperative and postoperative bleeding, vasospasm, cerebral infarction, and so on (6). Therefore, before formulating a treatment plan for an aneurysm, doctors must balance the rupture risk of the aneurysm and the risk of surgical complications (Figure 1).

At present, the treatment standard of IAs is still stratified according to the aneurysm size. For unruptured IAs, the clinical standard of surgical intervention is the aneurysm  $\geq 7$  mm in diameter (7). However, partial unruptured IAs less than 7 mm were found by imaging in clinic, and some of them still ruptured during the follow-up, causing a series of neurological damage and complications, even endangering the patient's life (8, 9). In addition, although the risk of rupture of small IAs is currently low, our previous research (10) has shown that the proportion of ruptured small aneurysms is increasing every year. Therefore, the size of an aneurysm may be only one of the factors leading to its rupture, and the impact of hemodynamics cannot be ignored. When small aneurysms are detected, whether they will grow, change and rupture puzzles neurosurgeons and affects surgical decisions. Therefore, the size of aneurysm cannot completely guide clinicians to make surgical decisions on unruptured IA. Neurosurgeons need a more reliable evaluation method to guide the formulation of the treatment plan for unruptured small IAs.

The morphological and hemodynamic analysis of unruptured IAs provides great hope for the risk stratification of aneurysm rupture. The evaluation of the morphology and hemodynamics of IAs is mostly based on the establishment of the computational fluid dynamics (CFD) model of IAs, which aims to evaluate the morphological and

hemodynamic factors of aneurysms that may cause growth, change and rupture of IAs (11, 12). In the past 10 years, CFD has been a potential research tool for studying many aspects of IAs, the most important of which is to analyze and study the growth and rupture mechanism of IAs and their relationship with vascular hemodynamics (12–16). Since this model is currently unable to fully simulate the actual situation of blood, it is still a long way from practical clinical applications.

Therefore, there are still many different arguments about clinical effectiveness and practicability of hemodynamics in assessing the risk of aneurysm rupture (17, 18). This study aims to verify the effectiveness of CFD by analyzing two ruptured aneurysms in follow-up observation.

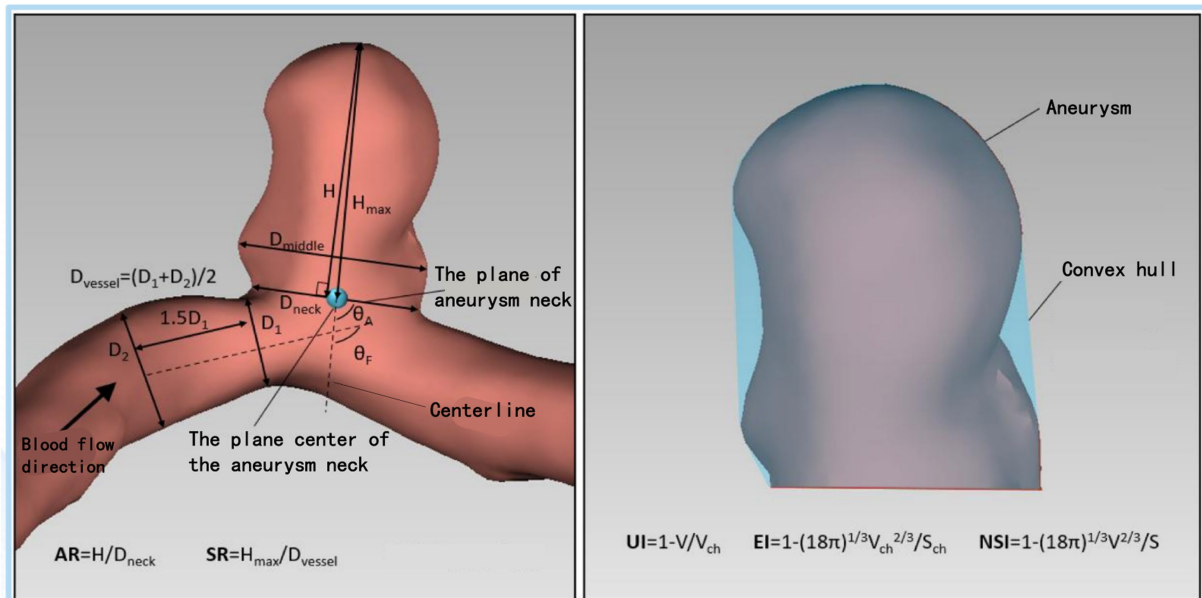
## 2 Methods

### 2.1 Ethics approval and consent to participate

This study involving human participants were obtained consent from the patients and reviewed and approved by the Ethics Committee of the First Affiliated Hospital of Chongqing Medical University. The committee's reference number: K2023-033.

### 2.2 Patient information

Case 1, an adult patient in 60s, was admitted to the hospital due to bilateral posterior communicating artery aneurysm (PcoAA) found



**FIGURE 1**  
Schematic diagram of the morphological parameters of the aneurysm.  $H_{max}$ , maximum aneurysm height;  $H$ , the vertical height of the aneurysm;  $D_{middle}$ , maximum cross-section diameter parallel to aneurysm neck plane;  $D_{neck}$ , diameter of the aneurysm neck plane;  $D_{vessel}$ , the diameter of the vessel of the parent artery; SR, size ratio; AR, aspect ratio;  $V$ , aneurysm volume;  $V_{ch}$ , the volume of the convex hull of an aneurysm;  $S$ , the surface area of the aneurysm sac;  $S_{ch}$ , the surface area the convex hull;  $\theta_F$ , Aneurysm vessel angle;  $\theta_A$ , Aneurysm inclination angle; UI, Undulation index; EI, Ellipticity index; NSI, non-sphericity index.

by head and neck CTA examination during physical examination. The left aneurysm was about  $5.3 \times 6.6$  mm in size, and the right aneurysm was about  $7.6 \times 7.5$  mm in size. It is planned to improve the head whole-brain angiography. During hospitalization, the aneurysm ruptured with a subarachnoid hemorrhage. According to the head CT (Figure 2) of the patient when the aneurysm ruptured, the right PcoAA was considered to be the responsible aneurysm.

Case 2, an adult patient in 70 s. Head and neck CTA examination revealed a left PcoAA in 2019, about  $3.0 \times 5.0$  mm in size. The patient chose conservative treatment. In 2021, the patient was admitted to the hospital due to a sudden explosive headache, and the head CT (Figure 2) showed subarachnoid hemorrhage. According to the CT results, the left PcoAA was judged to be the responsible aneurysm, with a size of  $5.0 \times 5.3$  mm.

### 2.3 Acquisition of morphological and hemodynamic parameters

The calculation of the morphological and hemodynamic parameters of each aneurysm's 3DRA is described according to the description of Xiang et al. (19). Briefly, DICOM images were segmented in the region of interest, including aneurysm sac and adjacent parent vessels. Then eight morphological parameters (20, 21) were measured and calculated using AneuFlowTM (ArteryFlow, Hangzhou) (22), including  $H_{\max}$ , SR, AR,  $\theta_F$ ,  $\theta_A$ , EI, NSI, UI. As for CFD models, finite volume meshes with 0.5–1 million elements were imported into the CFD solver to calculate time-resolved 3D velocity and pressure fields. Three pulsatile cycles were simulated, and the last cycle being taken as output to ensure that numerical stability. WSS and streamlines profiles were time-average over the third pulsatile cycle of flow simulation. The average values of NWSS of aneurysm sac, OSI, and RRT were calculated based on previous research (19).

We scored the rupture risk of IAs, including RRSM, RRSB, and RRSC according to the RRS predictive regression model established by Xiang et al. (23).

## 3 Results: case-by-case description

Morphological and hemodynamic analysis of the bilateral aneurysms of case 1 was conducted (Table 1). For morphological parameters,  $H_{\max}$ ,  $H$ ,  $D_{\text{middle}}$ ,  $D_{\text{neck}}$ , volume, and surface area of the ruptured aneurysm were larger than those of the unruptured aneurysm, while the  $D_{\text{vessel}}$  was smaller. Therefore, the AR and SR of the ruptured aneurysm were larger than those of the unruptured aneurysm, and the SR of the ruptured aneurysm was 2.505, greater than the threshold value 1.75 reported previously (19). Both  $\theta_F$  and  $\theta_A$  of the ruptured aneurysm were larger, but not exceeding the threshold value (21). UI, NSI, and EI of the ruptured aneurysm were larger as well. In terms of hemodynamics, OSI of the ruptured aneurysm was larger, but NWSS and RRT of the unruptured aneurysm were larger (Figure 3). OSI had more significant difference. RRSB, RRSB, and RRSC of the ruptured aneurysm were all greater than 30%, while only the RRSB of the unruptured aneurysm was greater than 30%.

In case 2, a daughter sac in the aneurysm was appeared in 2021 (Figure 4). Morphological and hemodynamic analysis was conducted on aneurysms for two stages (Table 2). As for morphological parameters,  $H_{\max}$ ,  $H$ ,  $D_{\text{middle}}$ ,  $D_{\text{neck}}$ , volume, and surface area increased, while the diameter of parent artery decreased. Therefore, the AR and SR increased. Both  $\theta_F$  and  $\theta_A$  exceeded the threshold value and UI, NSI, and EI increased in 2021. For hemodynamics, OSI and RRT increased, while NWSS was smaller. OSI was 0.0049 in 2019, which exceeded the threshold. RRSB and RRSC were greater than 30% in 2021, while RRSB was less than 30%. All three RRS values were less than 30% in 2019.

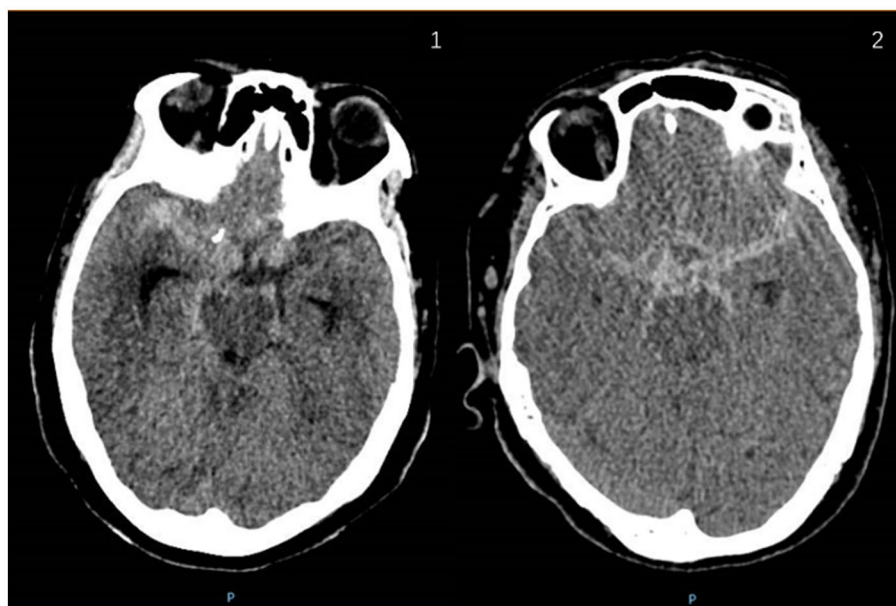


FIGURE 2  
Head CT images of case 1 and case 2 with ruptured aneurysm and subarachnoid hemorrhage. 2.1: case 1; 2.2: case 2.

## 4 Discussions

### 4.1 SR, AR, $\theta_F$ , $\theta_A$ , UI, EI, and NSI

At present, there have been many studies about the morphological changes of IAs after rupture (16, 24–27), and morphological parameters have also been enriched with the deepening of research.

TABLE 1 Morphological and hemodynamics parameters of the aneurysms in case 1.

	Parameters	Position		Threshold
		Left	Right	
Morphology parameters of aneurysms	$H_{max}$ (mm)	5.311	7.578	/
	$H$ (mm)	5.138	6.865	/
	$D_{middle}$ (mm)	6.649	9.143	/
	$D_{neck}$ (mm)	6.589	7.446	/
	$D_{vessel}$ (mm)	3.76	3.025	/
	$V$ (mm <sup>3</sup> )	140.293	333.099	/
	$S$ (mm <sup>2</sup> )	108.671	206.884	/
	$\theta_F$ (deg)	111.71	132.38	>118.25
	$\theta_A$ (deg)	82.4	89.36	>96.1
	AR ( $H/D_{neck}$ )	0.78	0.922	>1.6
	SR ( $H_{max}/D_{vessel}$ )	1.413	2.505	>1.75
	UI	0.017	0.044	>0.09
	EI	0.044	0.097	>0.13
NSI	0.046	0.108	>0.16	
Hemodynamic parameters of aneurysms	NWSS	0.504	0.549	<0.39
	OSI	0.0073	0.0215	>0.0036
	RRT	0.405	0.387	>2.7
Rupture Resemblance Scores	$RRS_M$	14.99%	40.55%	>30%
	$RRS_H$	37.58%	86.77%	>30%
	$RRS_C$	21.50%	81.20%	>30%

Based on previous research, the 3 IAs mentioned above were analyzed by AR, SR,  $\theta_B$ ,  $\theta_A$ , UI, EI, NSI, and other morphological parameters.

Among the above analysis parameters, SR was previously considered most related to aneurysm rupture because it simultaneously focuses on the relationship between aneurysm size and the diameter of the parent artery. Kashiwazaki et al. (24) and Tremmel et al. (28) proposed that SR can highly predict the rupture state of small aneurysms (<5 mm). Our analysis shows that SR of the ruptured aneurysm was far greater than that of the unruptured aneurysm in Case 1. It even exceeds the threshold value of rupture risk. Besides, Dhar et al. (20) proposed that aneurysms are at risk of rupture when SR is greater than 2.05, by an analysis of SR of ruptured and unruptured aneurysms. This is similar to the analysis results of Case 1. The uniqueness of this case is in the fact that it involves a pair of mirrored aneurysms. The CT findings and CTA results alone are insufficient to fully determine the responsible aneurysm for SHA. Nevertheless, the assessment of the SR value can aid in identifying the responsible aneurysm and formulating an optimal surgical treatment plan.

However, although the SR of the aneurysm in case 2 increased by about one time during 2 years, it did not exceed the threshold value of rupture risk after the rupture. But it is worth noting that SR changes significantly. According to these analysis results, we are currently unsure of the accuracy and effectiveness of SR in predicting the risk of aneurysm rupture. Although no research currently focuses on the impact of the dynamic changes of SR on aneurysm rupture, we suggest that clinicians should be aware that an increasing trend of SR during follow-up may indicate that the aneurysm is developing toward rupture.

It seems inaccurate to assess the rupture risk of aneurysms only from SR of aneurysms. Some studies (29, 30) consider that AR is another parameter to predict the risk of aneurysm rupture. Weir et al. (29) shows that 88% of ruptured aneurysms had an AR > 1.6, while 56% of unruptured aneurysms had an AR ≤ 1.6. However, all IAs' AR did not exceed the threshold value in our study. Although our research results differ from previous studies because we analyzed only three aneurysms in two cases, our results cannot deny the predictive value of AR for the risk of IA rupture. Besides, Yin et al. (31) believe that

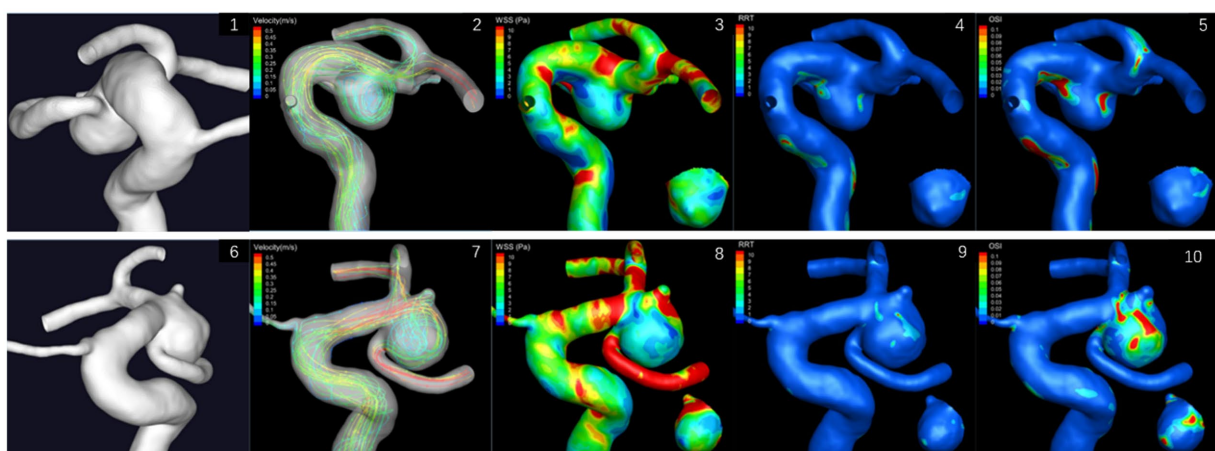
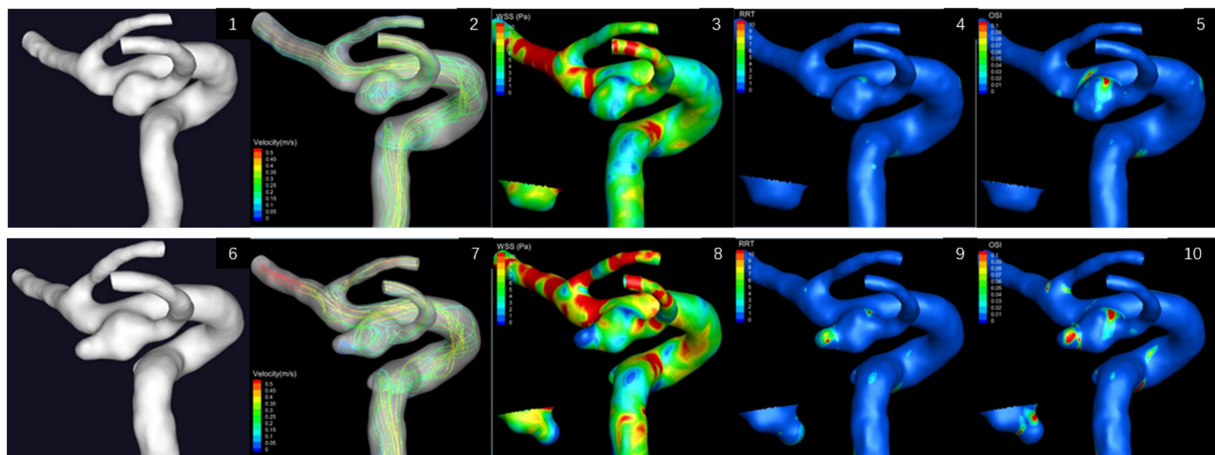


FIGURE 3 Hemodynamic results of bilateral posterior communicating aneurysms of case 1. The small image shows the aneurysm from the back view. 3.1–3.5: left aneurysm; 3.6–3.10: right aneurysm.



**FIGURE 4** Hemodynamic results of left posterior communicating aneurysms in two stages of case 2. The small image shows the aneurysm from the back view. 4.1–4.5: in 2019; 4.6–4.10: in 2021.

**TABLE 2** Morphological and hemodynamics parameters of the aneurysm in two stages in case 2.

	Parameters	Time (year)		Threshold
		2019	2021	
Morphology parameters of aneurysms	$H_{max}$ (mm)	2.968	4.905	/
	$H$ (mm)	2.145	4.032	/
	$D_{middle}$ (mm)	4.944	5.194	/
	$D_{neck}$ (mm)	4.981	5.246	/
	$D_{vessel}$ (mm)	4.295	3.727	/
	$V$ (mm <sup>3</sup> )	27.768	48.090	/
	$S$ (mm <sup>2</sup> )	35.333	58.129	/
	$\theta_F$ (deg)	/	153.45	>118.25
	$\theta_A$ (deg)	/	125.42	>96.1
	AR ( $H/D_{neck}$ )	0.431	0.769	>1.6
	SR ( $H_{max}/D_{vessel}$ )	0.691	1.316	>1.75
	UI	0.018	0.131	>0.09
	EI	0.001	0.094	>0.13
	NSI	0.004	0.127	>0.16
Hemodynamic parameters of aneurysms	NWSS	0.958	0.487	<0.39
	OSI	0.0049	0.0157	>0.0036
	RRT	0.312	0.808	>2.7
Rupture	RRS <sub>M</sub>	6.73%	13.52%	>30%
Resemblance	RRS <sub>H</sub>	7.60%	74.2%	>30%
Scores	RRS <sub>C</sub>	3.99%	42.35%	>30%

there is a U-shaped correlation between AR and the risk of aneurysm rupture, with a negative correlation range of  $1.08 < AR \leq 1.99$  and a positive correlation range of  $3.42 < AR \leq 4.08$ . Further research with a larger sample size is needed to validate the ability of AI to assess the risk of aneurysm rupture. AR does only predict the rupture risk of IAs from the shape of the aneurysm itself, ignoring the impact of the parent artery on the aneurysm rupture. Further research with a larger

sample size is needed to validate the ability of AR to assess the risk of aneurysm rupture.

The positional relationship between the parent artery and the aneurysm can often be reflected by  $\theta_F$  and  $\theta_A$ . The growth direction and the thin-wall regions of an aneurysm can be inferred by  $\theta_F$  and  $\theta_A$ , which affect the changes of aneurysms, and assess the risk of aneurysm rupture. At present, there are not many analytical studies on  $\theta_F$  and  $\theta_A$ , and different studies on the correlation between aneurysm rupture and  $\theta_F$  and  $\theta_A$  have not maintained a consistent view (21, 32, 33). According to the analysis of this study, after the rupture of the aneurysm in case 2,  $\theta_F$  and  $\theta_A$  were greater than the threshold value of the rupture risk. While in case 1, the ruptured aneurysm's  $\theta_A$  was less than the threshold value of the rupture risk. Our results are different from those of Zheng et al. (33) and Dhar et al. (20). The research results of Bahagoglu et al. (21) inclined that  $\theta_F$  is an important indicator to judge the rupture risk of an aneurysm, which is more consistent with our research results.  $\theta_F$  and  $\theta_A$ , as morphological parameters, have been studied relatively few so far. Their effects on the growth pattern and the role on the rupture risk prediction of IAs remain controversial and have great potential research value.

As we all know, EI, UI, and NSI are commonly used to describe the shape characteristics of IAs. The previous studies (19, 34) have shown that ruptured aneurysms have characteristics of high UI, EI, and NSI. The analysis results of the 3 aneurysms in this paper were very consistent with previous studies. The UI, EI, and NSI of ruptured and unruptured aneurysms were significantly different. Particularly in case 2, the UI, EI, and NSI of the aneurysm were significantly increased, and the UI even exceeded the threshold value of the rupture risk. Therefore, it is reasonable to assume that UI, NSI, and EI have a high predictive value for the rupture risk of IAs.

### 4.2 WSS, OSI, and RRT

In the last 10 years, an increasing number of studies have recognized that hemodynamic changes in aneurysms are greatly related to the rupture of IAs, and studies based on CFD analysis of aneurysm hemodynamics are also very extensive (13, 19, 20, 35–44).

WSS is one of the most studied hemodynamic parameters in recent years. But different studies hold different views on the specific role of WSS in predicting the rupture risk of IAs, so many scholars still doubt the effectiveness of WSS in predicting the rupture risk of IAs. There are two claims regarding the effect of WSS on aneurysm growth and rupture. (1) High WSS (35–37) is closely associated with aneurysm rupture because high WSS on the aneurysmal wall stimulates abnormal remodeling of endothelial cells, leading to aneurysm growth and ultimately aneurysm rupture. (2) Low WSS (13, 19, 37–41) is related with aneurysm rupture because low WSS on the aneurysm wall disrupts the aneurysmal rupture by provoking an inflammatory response that prompts endothelial cell degeneration. They speculated that high WSS and low WSS may, respectively, play different mechanisms in different stages of aneurysm initiation and progression. In order to make the comparison more referential, we use the NWSS value obtained by normalizing WSS via the parent artery. From the results of the aneurysm analysis of the two cases in this study, it can be seen that the ruptured aneurysm of case 1 had slightly higher NWSS than the unruptured aneurysm before rupture. Unfortunately, we did not have the image of this case after the rupture to conduct hemodynamic analysis. However, in case 2, NWSS was significantly lower after the aneurysm rupture. It is evident that the rupture of the aneurysms in these two cases seems to be influenced by high and low NWSS, respectively. In our opinion, limited by case screening and image acquisition, investigators focusing more on the appearance of reduced WSS after aneurysm rupture, but ignoring the dynamic changes of WSS throughout the growth of aneurysms.

Other hemodynamic parameters, such as OSI and RRT, have been proposed based on WSS studies, and have received attention because of their predictive value of aneurysm rupture risk. OSI in particular, demonstrated by numerous studies (25, 42–45), has been identified as helpful in predicting the risk of aneurysm rupture. Lu et al. (42) studied 9 pairs of mirrored aneurysms, and they suggested that the mean OSI in the ruptured group was 4 times that in the unruptured group. Their findings are very consistent with the results of aneurysm analysis in this study. Therefore, we believe that OSI may be effective and accurate in predicting the risk of aneurysm rupture. At present, the research on RRT is limited. Riccardello et al. proposed that ruptured aneurysms have prolonged RRT compared with unruptured aneurysms (41). Lu et al. also proposed that prolonged RRT is associated with intracranial vascular atherosclerosis and that structural remodeling of the vessel wall is one of the causes of ruptured aneurysms (14). The prolongation of RRT is mostly accompanied by low WSS and high OSI in aneurysms, which predicts a disturbed blood flow status and leads to a long residence of blood flow. Blood flow with such characteristic may trigger a series of inflammatory reactions responsible for a series of changes in endothelial cells. All of the above claims are currently at the hypothesis stage, and further research and exploration are still needed regarding the specific effect of RRT on the aneurysm.

### 4.3 RRS

A logistic regression model can be developed based on the differences of morphologic and hemodynamic parameters including SR, WSS, and OSI between ruptured and unruptured IAs (46). The model has also been used to predict the rupture probability of

unruptured aneurysms, thus measuring their similarity to ruptured aneurysms. This probability of rupture is also known as the RRS, which proposed by Xiang et al. (23). The three scoring modalities, RRSM, RRSR, and RRSC, were established based on different parameter combination. All three prediction models had high sensitivity and specificity, especially the RRSR had the highest sensitivity and specificity. Our results also well printed the conclusion of the study by Xiang et al. (23). Therefore, we believe that the rupture of IAs depends more on hemodynamic changes, which may also be one of the reasons why many IAs are small in size but still rupture in clinic practice. Although the RRSM is less sensitive than the RRSR, it still exhibits good predictive value for aneurysm rupture, which may contribute to the utilization of SR rather than size as a key factor. This also exemplifies the potential value of SR for rupture risk assessment of IAs. Therefore, it is an important issue for neurosurgeons to consider whether the guiding criteria of rupture risk assessment and surgical intervention of unruptured IAs should be shifted from aneurysm size to more comprehensive morphological and hemodynamic analysis.

## 5 Limitations

There are also many shortcomings in our study. First, the number of cases in our study was small and not fully comprehensive. We were only able to verify whether there was consistent with previous findings based on the available results and to propose corresponding hypotheses. Second, this study only involved the morphological and hemodynamic analysis of posterior communicating artery aneurysms, and whether IAs in other locations also have corresponding characteristics cannot be determined. Finally, our hemodynamic analysis model adopts some assumptions and cannot fully reflect the real situation, which might be one reason for the discrepancy between our analysis results with those of other investigators.

## 6 Conclusion

Based on the morphological and hemodynamic analysis of IAs, SR, and OSI may have predictive values for the risk of IA rupture. It is possible that WSS changes before and after IA rupture, yet the influence of high or low WSS on growth and rupture of IA remains unclear. Moreover, RRS is promising to be used in the clinical assessment of the rupture risk of IAs and to guide the formulation of treatment plans.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Ethics statement

The studies involving humans were approved by the Ethics Committee of the First Affiliated Hospital of Chongqing Medical University. The studies were conducted in accordance with the local

legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

## Author contributions

YZ: Investigation, Writing – original draft, Data curation, Project administration. RZ: Formal analysis, Methodology, Software, Writing – original draft. XS: Writing – review & editing. XL: Conceptualization, Investigation, Writing – original draft. JX: Formal analysis, Methodology, Writing – review & editing. ZG: Funding acquisition, Writing – review & editing. HS: Writing - review & editing.

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## Conflict of interest

RZ and JX were employed by ArteryFlow Technology Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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## Glossary

$H_{\max}$	Maximum aneurysm height. Maximum distance from the neck center to the sac surface of the aneurysm.
$H$	The vertical height of the aneurysm. The maximum vertical distance from the neck plane to the top of the sac of the aneurysm.
$D_{\text{middle}}$	Maximum cross-section diameter parallel to aneurysm neck plane.
$D_{\text{neck}}$	Diameter of the aneurysm neck plane.
$D_{\text{vessel}}$	The diameter of the vessel of the parent artery.
$V$	Aneurysm volume.
$V_{\text{ch}}$	The volume of the convex hull of an aneurysm. The convex hull is the smallest convex body that completely surrounds the aneurysm.
$S$	The surface area of the aneurysm sac.
$S_{\text{ch}}$	The surface area the convex hull. Aneurysm vessel angle ( $\theta_v$ ), angle between the centerline of the inlet of the parent artery and the maximum height of the aneurysm (inflow direction side). Aneurysm inclination angle ( $\theta_\lambda$ ), the angle between the line of maximum height and the plane of the neck of the aneurysm (inflow direction side).
SR	Size ratio ( $H_{\max}/D_{\text{vessel}}$ ). The ratio of the maximum height of an aneurysm to the diameter of the parent artery.
AR	Aspect ratio ( $H/D_{\text{neck}}$ ). Ratio of maximum vertical height to aneurysm neck diameter.
UI	Undulation index. $UI = 1 - V/V_{\text{ch}}$ . The difference between the volume of the aneurysmal bulge and the volume of the aneurysm divided by the volume of the aneurysmal bulge quantifies the concavity of the aneurysmal surface.
EI	Ellipticity index. $EI = 1 - (18\pi)^{1/3} V_{\text{ch}}^{2/3} / S$ . Quantifying the deviation of aneurysm convex hull shape from the perfect hemisphere.
NSI	Non-sphericity Index. $NSI = 1 - (18\pi)^{1/3} V^{2/3} / S$ . Quantifying the degree of deviation of aneurysm shape from the perfect hemisphere.
WSS	Wall shear stress. Friction generated by the flow of blood along the aneurysm wall. $WSS = \frac{1}{T} \int_0^T  wss_i  dt$ , ( $wss_i$ is the instantaneous shear stress vector and $T$ is the duration of the cycle).
NWSS	Normalized wall shear stress.
OSI	Oscillatory shear index. Dimensionless measurements of the alignment between instantaneous vectors of wall shear stress and time-averaged vectors of wall shear stress were taken to quantify changes in the direction of wall shear stress during cardiac cycles. $OSI = \frac{1}{2} \left\{ 1 - \frac{\left  \int_0^T wss_i dt \right }{\int_0^T  wss_i  dt} \right\}$ , ( $wss_i$ is the instantaneous WSS vector and $T$ is the duration of the cycle).
RRT	Relative residence time. Residence time of elements in the blood near the vessel wall. $RRT = \frac{1}{(1 - 2 \times OSI) \times WSS} = \frac{1}{T \left  \int_0^T wss_i dt \right }$ .
RRSM	Rupture resemblance score based on morphological parameters of the aneurysm.
RRSH	Rupture resemblance score based on hemodynamic parameters of the aneurysm.
RRSC	Rupture resemblance score based on both morphological and hemodynamic parameters of the aneurysm.