Am J Transl Res 2022;14(7):4638-4647
www.ajtr.org /ISSN:1943-8141/AJTR0143926

Original Article

Effect of hemodynamic changes on the risk of intracranial aneurysm rupture: a systematic review and meta-analysis

Aximujiang Axier[1*], Nizamidingjiang Rexiati[1*], Zengliang Wang[1], Xiaojiang Cheng[1], Riqing Su[1], Rexidan Aikeremu[2], Maimaitili Aisha[1]

[1]*Department of Neurosurgery, The First Affiliated Hospital of Xinjiang Medical University, Urumqi 830054, Xinjiang, China;* [2]*Department of Medical Record Management, The First Affiliated Hospital of Xinjiang Medical University, Urumqi 830054, Xinjiang, China.* [*]*Equal contributors.*

Received May 5, 2022; Accepted June 10, 2022; Epub July 15, 2022; Published July 30, 2022

Abstract: Objective: In this study, the hemodynamic parameters of ruptured intracranial aneurysms (IAs) in various studies were summarized and analyzed to provide predictive parameters for IA rupture in clinical work. Methods: We searched PubMed, Web of science, Embase, and Cochrane databases for articles published before December 2021 to collect data on hemodynamic parameters associated with IA rupture. Differences in wall shear stress (WSS), oscillatory shear index (OSI), and low wall shear stress area (LSA) between ruptured and unruptured IAs in the literature were summarized and analyzed, and the standardized mean difference (SMD) of 95% CI was calculated by Review Manager 5.3. Results: By searching and screening the literature, this meta-analysis included 17 studies comprising 1,373 IA patients. In the ruptured aneurysm group, the level of WSS decreased significantly, while OSI and LSA increased obviously. Conclusion: Low WSS, high OSI, and high LSA are closely related to the rupture of IAs, indicating the role of WSS, OSI, and LSA as important hemodynamic parameters for predicting the rupture of IAs in clinical work.

Keywords: Intracranial aneurysm, meta-analysis, rupture, wall shear stress

Introduction

As imaging diagnosis technology constantly develops, the diagnosis rate of intracranial aneurysms (IAs) has gradually increased, with a reported incidence of unruptured IAs of about 3.7% in the Chinese population [1]. IA is a main inducement of non-traumatic subarachnoid hemorrhage. With the gradual increase of volume, IAs will compress local nerves and brain tissues, resulting in headache, dizziness, and blurred vision, which will have an adverse impact on patients' daily life [2]. In addition, rupture of IAs will seriously endanger the patient's life. At present, the treatment of IAs is a great challenge for clinicians, as it is difficult to make a decision to perform intervention surgery or follow-up. Since IAs grow over time, the specific intervention often depends on their size and location. While small IAs may have the risk of rupture, some relatively large ones may gradually tend to be stable. In addition, surgical treatment may cause related complications and even death [3]. Therefore, clinicians need to make an individualized assessment of the rupture risk in IA patients, so as to decide whether to take intervention measures.

Many risk factors, such as age, genetic factors, hypertension, tumor shape, and location, have been found to be associated with IA rupture. In addition, as one of the important mechanisms of IA rupture, hemodynamic factors have attracted increasing attention of clinical workers. At present, many studies have detected the hemodynamic parameters of IA patients by computational fluid dynamics (CFD) technology and analyzed their correlation with IA rupture. However, due to the small scale of these studies and inconsistent results, their guiding role for clinical treatment is limited.

For example, there are currently two theories about the effect of wall shear stress (WSS), the most frequently studied hemodynamic parameter in IAs, on IA rupture. Some scholars believe that high WSS is more likely to adversely affect vascular wall remodeling and aggravate endothelial injury [4, 5]. On the contrary, some studies have found that low WSS can easily lead to local blood flow stagnation in IAs, which will cause local inflammatory factor aggregation and endothelial dysfunction, contributing to aneurysmal wall degeneration [6, 7]. The conflicting conclusions may confuse clinical research and treatment of IAs.

In view of the inconsistent conclusions of previous studies and the complexity of hemodynamics in the occurrence of IAs, this meta-analysis aims to summarize and analyze the data of previous studies, so as to determine the hemodynamic parameters most relevant to IA rupture and provide guidance for clinical treatment.

Methods and materials

Data retrieval and collection

We searched PubMed, web of science, Embase, and Cochrane databases for relevant literature with the following keywords: “aneurysm”, “ruptured aneurysm”, “brain”, “internal”, “computational fluid dynamics”, “wall shear stress”, “low shear area”, and “oscillatory shear index”. All eligible papers published from January 2000 to December 2021 were searched. Two personnel with more than 3 years of retrieval experience were responsible for literature retrieval.

Inclusion criteria

(1) Prospective and retrospective studies; (2) Language: English; (3) Sample size: ≥ 10 subjects; (4) Subjects with ruptured or unruptured IAs; (5) The studies including relevant hemodynamic parameters (WSS, low wall shear stress area [LSA], oscillatory shear index [OSI], etc.).

Exclusion criteria

(1) Animal experimental research; (2) Case reports, reviews, comments, or guidelines; (3) Study on non-IA; (4) Inability to get complete data; (5) Duplicate literature.

Quality evaluation of included literature

Using the Newcastle-Ottawa Scale (NOS) [8], two researchers evaluated the quality of the included literature. Studies with a NOS score ≥ 6 points were defined as high-quality research.

Data extraction

For the literature included in the study, we extracted the author(s), year of publication, age, number of samples, aneurysm type, volume matching, time-point, mean WSS, Max WSS, min WSS, OSI, and LSA. If necessary, the author(s) of the article were contacted to obtain more detailed data.

Publication bias of included literature

Funnel plot was used to evaluate the publication bias of the included studies.

Statistical analysis

Revman 5.3 was used for meta-analysis. Among hemodynamic parameters, the continuous variables were expressed as standardized mean difference (SMD) and 95% confidence interval (CI), and a forest plot was generated by the fixed effect model. For each meta-analysis, Cochran Q and I^2 were used to evaluate the heterogeneity of the study. If the combined SMD of 95% CI in the meta-analysis didn’t overlap with 0, the effect of the outcome measure was considered to be statistically significant.

Results and discussion

Literature search

A total of 2,920 relevant literature records were screened by the keywords used. After deleting duplicate literature, we screened the remaining 2,564 records by title and abstract and excluded 2,132. The remaining 432 studies were further screened, among which 415 records, including 34 case studies, 177 reviews, 66 studies with insufficient data, 54 cases with less than 10 patients, and 54 animal studies, were further excluded. Finally, 17 studies were included, with a total of 1,373 IA patients [4-7, 9-21]. Of these, 6 studies had a sample size of more than 100 patients. The retrieval process is presented in **Figure 1**, and the research characteristics are shown in **Table 1**.

Quality evaluation

After evaluating the literature quality with the NOS (NOS), it was found that the proportion of literature with a NOS score >6 points was

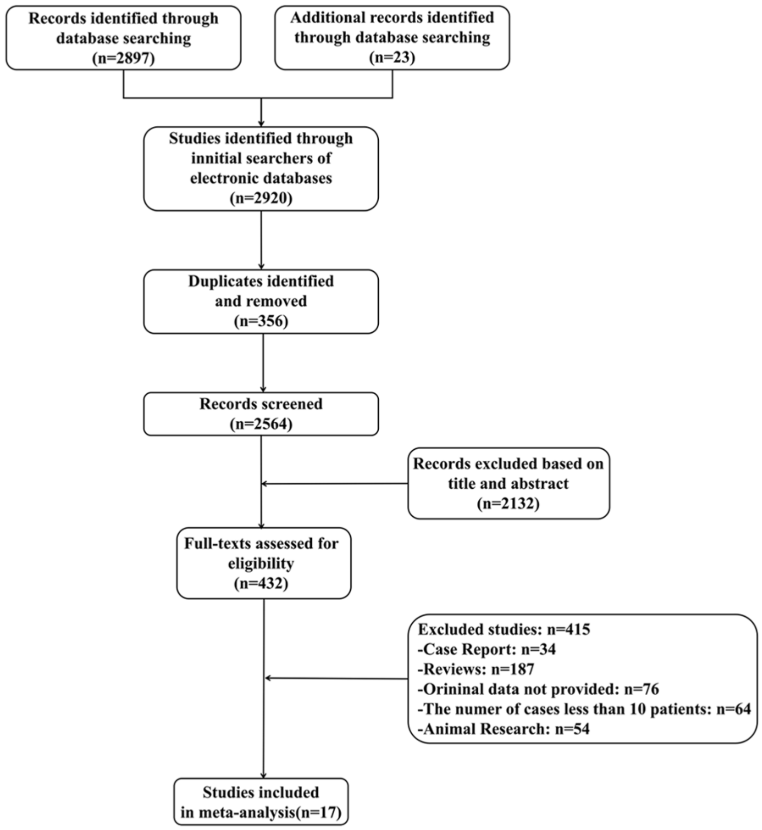

Figure 1. Flow diagram of data retrieval and collection.

94.12% (8 points for 6 items, 7 points for 5 items and 6 points for 5 items), suggesting that the included studies met the high quality standard, as shown in **Table 1** (continued). After the generation of the risk of bias graph/summary of the included studies, we found that the low bias risk mainly focused on the representativeness of "exposed group, non-exposed group" and "outcome indicators of positive observation", while the bias risk was not clear in "determining exposure factors" and "the integrity of follow-up", and the high bias risk was mainly concentrated in "long enough follow-up time" (**Figure 2**).

Correlation between changes of WSS and IA rupture

WSS mainly refers to the longitudinal shear force produced by the horizontal flow of blood flow on the arterial wall, which is the key factor influencing IA rupture. In order to further explore the correlation between WSS level and IA rupture, we included 14 studies with 15 groups of average WSS data. The study found that the average WSS was closely related to IA rupture. The average WSS level in the rupture group was relatively low, and its combined SMD was -0.38 (95% CI: 0.50 to -0.26; P<0.001) (**Figure 3A**). Besides, we further explored the correlation of max and min WSS with IA rupture. By summarizing the max WSS data of 8 groups in 7 studies, it was found that the max WSS was not significantly associated with IA rupture, and its combined SMD was 0.05 (95% CI: -0.09 to 0.20; P=0.48) (**Figure 3B**). After summarizing the min WSS data of 6 studies, we observed that the min WSS decreased significantly in IA rupture group, and its combined SMD was -0.29 (95% CI: -0.47 to -0.11; P=0.002) (**Figure 3C**).

Correlation between changes of OSI and IA rupture

OSI can be used to reflect the change of blood flow direction and intensity in IAs, which is helpful for effective evaluation of the stability of local blood flow. Through the summary and analysis of the data included in 13 studies, we found that OSI level was higher in the rupture group, and its combined SMD was 0.33 (95% CI: 0.20 to 0.46; P<0.001) (**Figure 4**). Hence, greater OSI will repeatedly damage the intima of the tumor wall, eventually leading to IA rupture.

Correlation between changes of LSA and IA rupture

LSA can reflect the area of the whole tumor wall surface less than 10% of mean WSS, which can further evaluate the effect of WSS on IA rupture. After a comprehensive analysis of the data from 12 studies, it was found that LSA was an important risk factor for IA rupture, with 11 of the 12 studies indicating a positive correlation between high LSA and aneurysm rupture, and its combined SMD was 0.66 (95% CI: 0.52 to 0.80; P<0.001) (**Figure 5**).

Table 1. IA patients' basic information and aneurysms hemodynamic parameters of included studies

author, year	mean age (year)	aneurysm location	total patients		time-point	vm	mean WSS (pa)			max WSS (pa)			min WSS (pa)		
			rup	Unrup			rup	unrup	*p*	rup	unrup	*p*	rup	unrup	*p*
chung [4], 2017	nr	pcom	145	168	nr	no	24.17±23.21	22.34±20.16	0.59	341.3±299.9	231.54±172.1	<0.001	0.29±0.74	0.64±1.39	0.02
duan [6], 2016	60.5 (43-86)	pcom	6	24	nr	yes	0.433±0.242	0.901±0.322	0.005	nr	nr		nr	nr	
fan [7], 2015	60.6 (46-77)	mca, pcom	16	16	ed	nr	7.43±4.03	11.29±5.41	0.029	50.84±25.8	53.31±17.82	0.725	0.08±0.15	0.18±0.52	0.056
lauric [9], 2014	61.4 (38-77)	ica	9	9	ed	yes	0.161±0.111	0.309±0.188	0.06	3.331±4.403	5.003±4.231	0.45	0.001±0.002	0.31±0.033	0.03
li [10], 2020	nr	ica	23	133	ta	nr	1.0412±0.7201	1.2931±1.1705	0.534	3.9772±4.6113	5.8006±21.8439	0.69	0.9584±0.7999	1.046±0.914	0.816
liu [11], 2016	60.33±16.56	ica	3	8	es	yes	0.3±0.06	0.48±0.13	0.048	nr	nr	nr	nr	nr	nr
liu [12], 2019	57.7±6.4	ica, mca, acom	5	15	es	no	2.1±0.9	2.3±1.1	0.698	nr	nr	nr	nr	nr	nr
lu [13], 2011	54.4 (42-66)	aca, mca	9	9	ta	nr	6.49±3.48	9.8±4.12	nr	nr	nr	nr	nr	nr	nr
lv [14], 2016	58 (52-64)	pcom	33	21	nr	nr	0.4563±0.6037	0.7964±0.2942	0.018	nr	nr	nr	nr	nr	nr
miura [15], 2013	nr	mca	43	63	nr	yes	7.463±6.1894	9.6524±6.0317	0.0001	nr	nr	nr	nr	nr	nr
perera [16], 2020	nr	ica, pcom, acom, mca, ba	10	38	ta	yes	1.157±0.41	1.353±0.39	0.173	2.868±1.01	3.003±1.04	0.714	0.331±0.134	0.416±0.15	0.103
										13.687±9.15	12.412±5.98	0.596			
qiu [5], 2017	56.9±9.43	mca, pcom, aca, ca, oa	41	31	ta	nr	1.96±1.3	3.33±1.45	0.028	9.08±6.64	8.19±3.69	0.72	nr	nr	nr
							7.85±3.98	7.14±3.08	0.655						
xiang [17], 2011	nr	ica, mca, pcom, pca, acom, aca, ba, pica	38	81	nr	yes	0.33±0.28	0.68±0.4	<0.001	2.71±2.2	3.87±1.91	0.0002	nr	nr	nr
xu [18], 2018	nr	ica	10	25	ed	no	5.45±5.05	5.64±2.86	0.887	nr	nr	nr	0.5±0.5	0.59±0.4	0.575
yuan [19], 2020	50.67±7.94	pcom, oa, mca	12	12	es	nr	0.54±0.21	0.75±0.19	<0.001	nr	nr	nr	nr	nr	nr
yuan [20], 2021	58.18±11.22	pcom	72	72	ta	nr	8.2±3.36	11.56±5.28	<0.001	nr	nr	nr	nr	nr	nr

zhang [21], 2016	58.5±10.5	pcom	108	65	ta	yes	0.55±0.23	0.69±0.25	<0.001	1.97±0.51	2.05±0.43	0.311	nr	nr	nr

Author, year	OSI			LSA (%)			NOS score
	Rup	Unrup	*P*	Rup	Unrup	*P*	
Chung [4], 2017	0.017±0.015	0.013±0.014	<0.001	59.63±30.46	52.32±31.91	0.05	8
Duan [6], 2016	0.019±0.040	0.017±0.026	0.897	0.063±0.203	0.0005±0.013	0.01	6
Fan [7], 2015	0.0219±0.0189	0.0151±0.0234	0.319	5.83±21.27	0.41±1.56	0.020	8
Lauric [9], 2014	NR	NR	NR	NR	NR	NR	5
Li [10], 2020	0.01775±0.07042	0.01277±0.03591	0.912	NR	NR	NR	6
Liu [11], 2016	0.05±0.04	0.04±0.03	1	12.39±4.63	6.28±5.16	0.085	8
Liu [12], 2019	0.0076±0.003	0.0039±0.0031	0.031	0.35±0.15	0.48±0.13	0.028	7
Lu [13], 2011	0.0879±0.0764	0.0183±0.0191	0.008	12.2±18.08	3.96±6.91	0.015	7
Lv [14], 2016	0.02±0.0155	0.01±0.0159	NR	0.0442±0.062	0.0036±0.008	0.008	7
Miura [15], 2013	0.0196±0.0152	0.0149±0.0108	0.00891	NR	NR	NR	6
Perera [16], 2020	0.12 (0.08)	0.075 (0.08)	0.141	NR	NR	NR	6
	0.026 (0.02)	0.011 (0.01)	0.008				
Qiu [5], 2017	NR	NR	NR	0.34±0.308	0.093±0.125	0.015	8
Xiang [17], 2011	0.016±0.031	0.0035±0.0044	<0.0001	0.38±0.31	0.1±0.21	<0.0001	7
Xu [18], 2018	0.015±0.016	0.016±0.019	0.911	21.21±25.31	6.16±16.5	0.049	8
Yuan [19], 2020	0.026±0.009	0.023±0.01	0.136	0.1783±0.109	0.0295±0.0503	0.002	7
Yuan [20], 2021	0.025±0.015	0.023±0.01	0.452	9.8±7.37	2.89±2.73	<0.001	8
Zhang [21], 2016	NR	NR	NR	NR	NR	NR	6

Note: PCOM: posterior communicating artery; MCA: middle cerebral artery; ICA: internal carotid artery; ACOM: anterior communicating artery; ACA: anterior cerebral artery; BA: basilar artery; CA: carotid artery; OA: ophthalmic artery; PCA: posterior cerebral artery; PICA: posterior inferior cerebellar artery; NR, no report; TA, time averaged; ED, end-diastolic; ES, end-systolic.

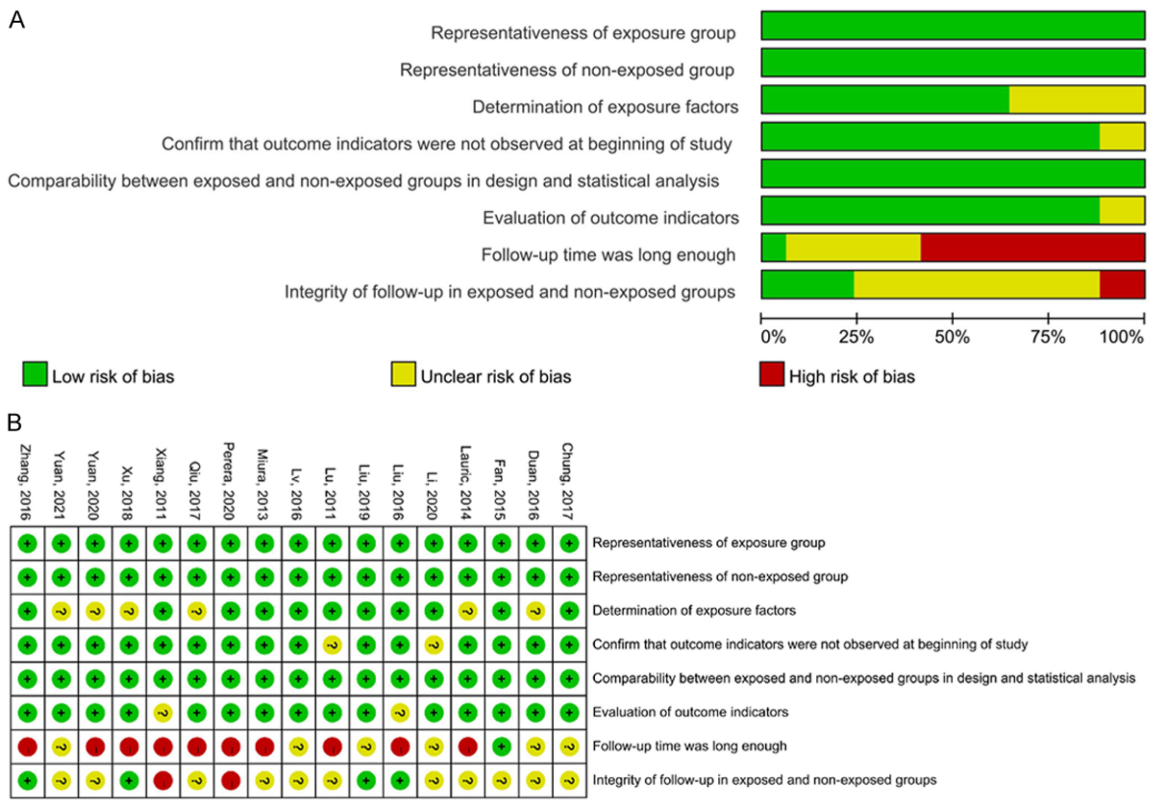

Figure 2. The risk of bias graph (A) and bias summary (B) of included studies.

Publication bias

We further evaluated whether the included studies were biased through funnel plot. It was found that the mean WSS (**Figure 6A**), OSI (**Figure 6B**), and LSA (**Figure 6C**) were basically symmetrically distributed, indicating no obvious evidence of publication bias.

Discussion

Hemodynamics is an important risk factor affecting the formation and rupture of IAs. Changes in blood flow within the aneurysm creates pressure on specific part of the aneurysm wall, resulting in endothelial cell damage and ultimately IA rupture [9]. At present, the study of hemodynamic parameters in aneurysms through CFD is a hot spot in clinical research, which can effectively analyze the blood flow parameters of various parts of aneurysms and understand the hemodynamic changes of ruptured aneurysms. The comparative analysis of various blood flow parameters helps doctors to comprehensively evaluate the risk of aneurysm rupture, thus effectively guiding the choice of aneurysm therapy [10]. At present, there are many clinical studies on the correlation between hemodynamic parameters and IA rupture. However, different indicators are detected in these studies, with inconsistent conclusions. Therefore, we summarized and analyzed the correlation between hemodynamic parameters and IA rupture in various studies to find representative indicators, so as to better guide clinical work.

WSS is closely related to IA rupture, and its effect in aneurysms has been widely studied. A large retrospective study with about 200 cases showed an association between low and high WSS and aneurysm rupture status, a seemingly contradictory phenomenon that may simply reflect the double-sided nature of aneurysm wall remodeling. WSS can effectively maintain the shape of the aneurysm wall, and the change of its value will increase the risk of aneurysm rupture. After a comprehensive analysis of the data of mean WSS in the aneurysm rupture group of 14 studies, it was found that only two groups of data indicated elevated mean WSS in the rupture group, while the rest

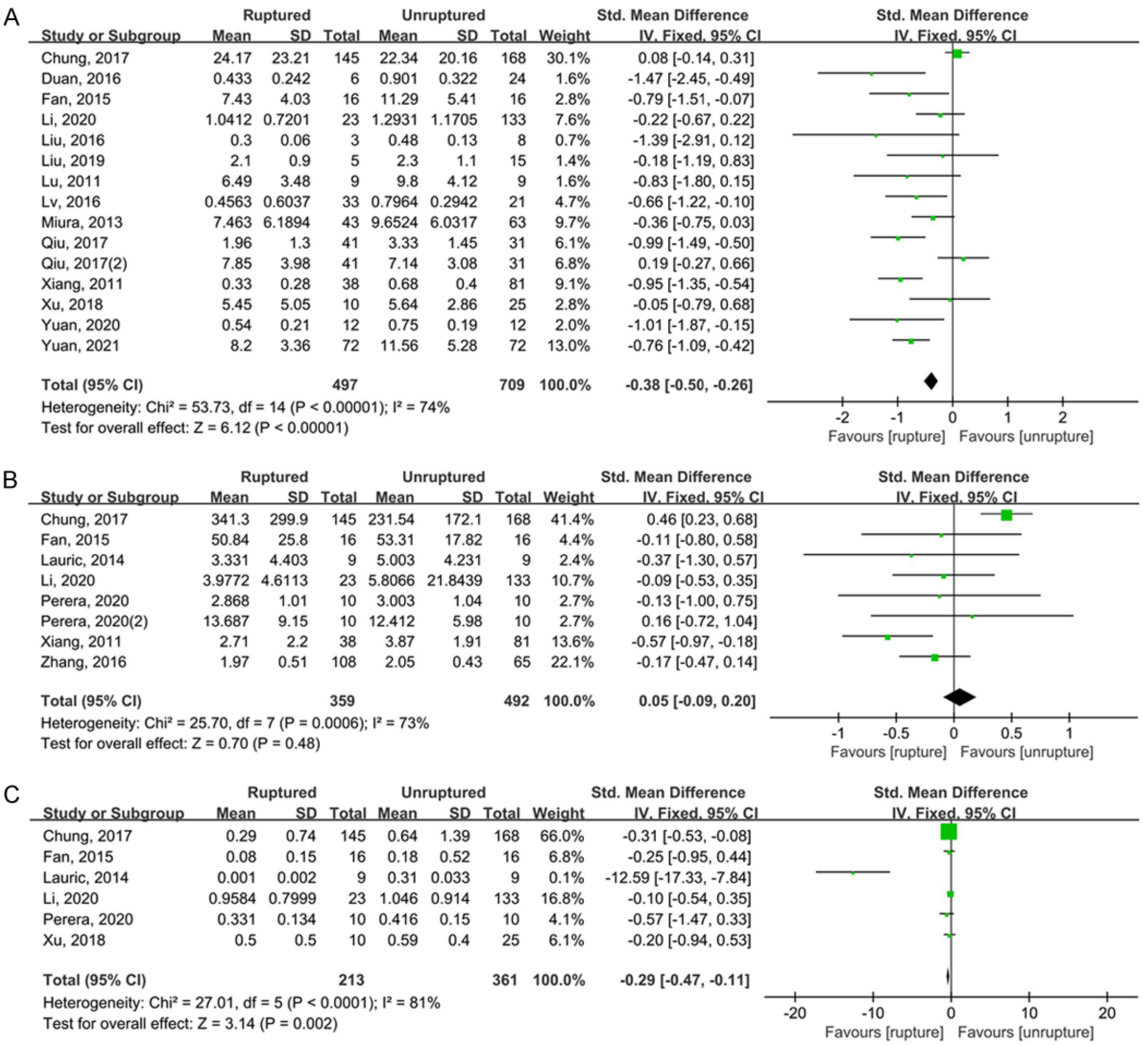

Figure 3. Meta-analysis of WSS between ruptured and unruptured aneurysms. A. Forest plot of mean WSS. B. Forest plot of max WSS. C. Forest plot of min WSS. Wall shear stress (WSS).

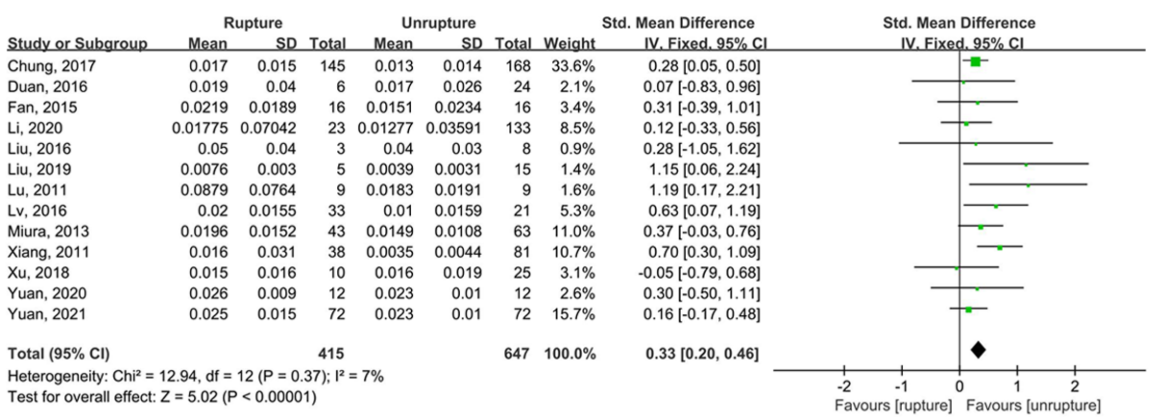

Figure 4. Meta-analysis of OSI between ruptured and unruptured aneurysms.

suggested a low mean WSS in ruptured IAs compared with unruptured IAs, suggesting that IA rupture is closely related to WSS insufficiency. The reason maybe that low WSS will lead to

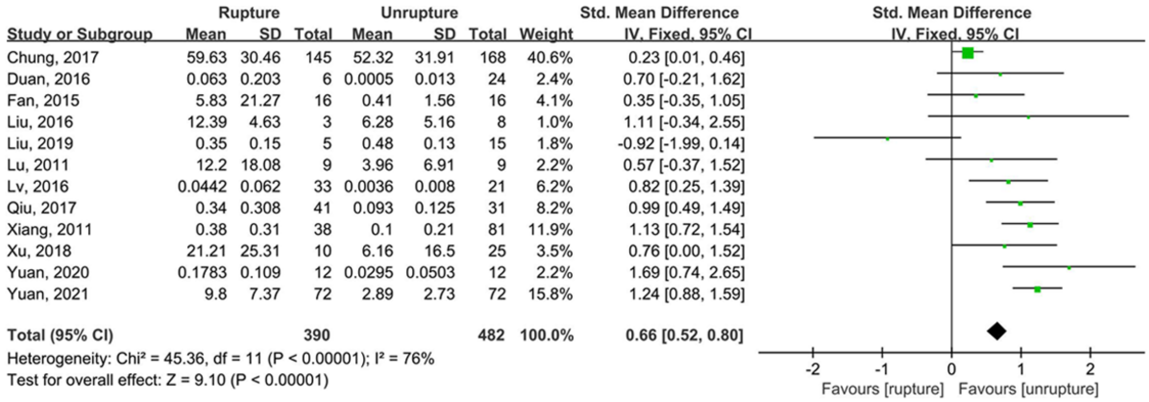

Figure 5. Meta-analysis of LSA between ruptured and unruptured aneurysms.

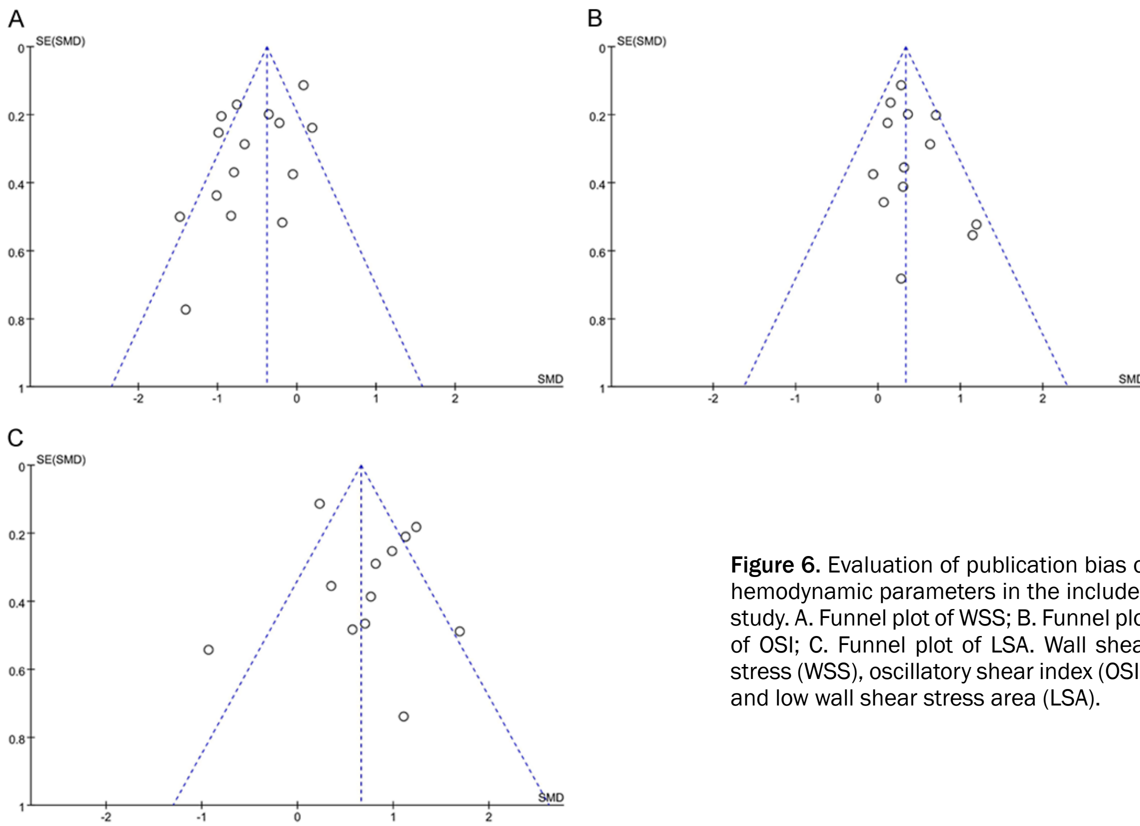

Figure 6. Evaluation of publication bias of hemodynamic parameters in the included study. A. Funnel plot of WSS; B. Funnel plot of OSI; C. Funnel plot of LSA. Wall shear stress (WSS), oscillatory shear index (OSI), and low wall shear stress area (LSA).

the dysfunction of local vascular endothelial cells that will affect their barrier function, which causes the invasion of harmful substances in the blood into the vascular wall, resulting in the degeneration and fracture of elastic fibers in the tumor wall and finally causing the rupture of IAs. In addition, we found that the occurrence of IA rupture was not significantly associated with max WSS but was significantly associated with min WSS. By using CFD simulations, Shojima et al. [22] and Jou et al. [23] found that IA rupture occurred not only at high values of hemodynamic parameters, but also at their low values, such as low values of WSS.

OSI is an important index reflecting the rapid change of blood flow direction in aneurysms. Through the comprehensive analysis of the data in 13 studies, we found decreased OSI levels in ruptured IAs in only one group of data, while higher OSI levels in ruptured IAs compared with unruptured IAs in the rest. High OSI means that the direction of WSS in aneurysms is more likely to change, which will have a greater oscillatory effect on the tumor wall. After reaching a certain threshold, vascular endothelial cells will be damaged and collagen fibers will be exposed, resulting in platelet adhesion at the injury site and thrombosis, and finally inducing the rupture of aneurysms under the action of fibrinolytic reaction. Perera R et al. [16] identified in the multivariate analysis that OSI was the only significant biomarker for predicting aneurysm rupture risk. Meng et al. [24] also proposed that aneurysm wall degeneration induced by high OSI may be triggered by destructive remodeling mediated by inflammatory cells.

In addition, after a comprehensive analysis of 12 groups of data on the correlation between LSA and aneurysm rupture, we found that high LSA was an important risk factor for IA rupture. LSA mainly reflects the area of less than 10% mean WSS on the tumor surface. A higher value indicates a higher possibility of the aneurysm to be affected by low WSS, and consequently a higher likelihood of the endothelial cells to be damaged and fall off from the tumor wall, all of which results in the destruction of the integrity of the vascular wall and an increased risk of aneurysm rupture. The meta-analyses conducted by Can and Du showed significantly higher LSA in the ruptured IAs [25]. Zhang et al. [26] also noted that the ruptured aneurysms had significantly higher LSA than the unruptured aneurysms.

This study mainly analyzed the influence of hemodynamic parameters on IA rupture. However, many studies include aneurysms in multiple locations, making it difficult to analyze the hemodynamic parameters of aneurysms in different locations. In addition, the risk of IA rupture increases with the patient's age and tumor diameter. Subgroup analysis of different ages and tumor diameters is not carried out in this study, so more data should be continuously collected in the later stage for a more detailed summary.

Conclusion

In conclusion, low mean WSS, low min WSS, high OSI, and high LSA are important risk factors for IA rupture, which can help predict the risk of aneurysm rupture in clinic to better guide clinical treatment.

Disclosure of conflict of interest

None.

Address correspondence to: Maimaitili Aisha, Department of Neurosurgery, The First Affiliated Hospital of Xinjiang Medical University, No. 137 Liyushan South Road, Urumqi 830054, Xinjiang, China. Tel: +86-0991-4366120; E-mail: mmtlaisha@163.com; Rexidan Aikeremu, Department of Medical Record Management, The First Affiliated Hospital of Xinjiang Medical University, No. 137 Liyushan South Road, Urumqi 830054, Xinjiang, China. Tel: +86-0991-4366120; E-mail: rxd1108@sina.com

References

[1] Chen J, Liu J, Zhang Y, Tian Z, Wang K, Zhang Y, Mu S, Lv M, Jiang P and Duan C. China Intracranial aneurysm project (CIAP): protocol for a registry study on a multidimensional prediction model for rupture risk of unruptured intracranial aneurysms. J Transl Med 2018; 16: 263.

[2] Park YK, Yi HJ, Choi KS, Lee YJ and Chun HJ. Intraprocedural rupture during endovascular treatment of intracranial aneurysm: clinical results and literature review. World Neurosurg 2018; 114: e605-e615.

[3] Bonares MJ, Egeto P, de Oliveira Manoel AL, Vesely KA, Macdonald RL and Schweizer TA. Unruptured intracranial aneurysm treatment effects on cognitive function: a meta-analysis. J Neurosurg 2016; 124: 784-790.

[4] Chung BJ, Doddasomayajula R, Mut F, Detmer F, Pritz MB, Hamzei-Sichani F, Brinjikji W, Kallmes DF, Jimenez CM and Putman CM. Angioarchitectures and hemodynamic characteristics of posterior communicating artery aneurysms and their association with rupture status. AJNR Am J Neuroradiol 2017; 38: 2111-2118.

[5] Qiu T, Jin G, Xing H and Lu H. Association between hemodynamics, morphology, and rupture risk of intracranial aneurysms: a computational fluid modeling study. Neurol Sci 2017; 38: 1009-1018.

[6] Duan G, Lv N, Yin J, Xu J, Hong B, Xu Y, Liu J and Huang Q. Morphological and hemodynamic analysis of posterior communicating artery aneurysms prone to rupture: a matched case-control study. J Neurointerv Surg 2016; 8: 47-51.

[7] Fan J, Wang Y, Liu J, Jing L, Wang C, Li C, Yang X and Zhang Y. Morphological-hemodynamic characteristics of intracranial bifurcation mirror aneurysms. World Neurosurg 2015; 84: 114-120, e112.
[8] Stang A. Critical evaluation of the Newcastle-Ottawa scale for the assessment of the quality of nonrandomized studies in meta-analyses. Eur J Epidemiol 2010; 25: 603-605.
[9] Lauric A, Hippelheuser J, Cohen AD, Kadasi LM and Malek AM. Wall shear stress association with rupture status in volume matched sidewall aneurysms. J Neurointerv Surg 2014; 6: 466-473.
[10] Li W, Wang S, Tian Z, Zhu W, Zhang Y, Zhang Y, Wang Y, Wang K, Yang X and Liu J. Discrimination of intracranial aneurysm rupture status: patient-specific inflow boundary may not be a must-have condition in hemodynamic simulations. Neuroradiology 2020; 62: 1485-1495.
[11] Liu J, Fan J, Xiang J, Zhang Y and Yang X. Hemodynamic characteristics of large unruptured internal carotid artery aneurysms prior to rupture: a case control study. J Neurointerv Surg 2016; 8: 367-372.
[12] Liu Q, Jiang P, Wu J, Li M, Gao B, Zhang Y, Ning B, Cao Y and Wang S. Intracranial aneurysm rupture score may correlate to the risk of rebleeding before treatment of ruptured intracranial aneurysms. Neurol Sci 2019; 40: 1683-1693.
[13] Lu G, Huang L, Zhang X, Wang S, Hong Y, Hu Z and Geng D. Influence of hemodynamic factors on rupture of intracranial aneurysms: patient-specific 3D mirror aneurysms model computational fluid dynamics simulation. AJNR Am J Neuroradiol 2011; 32: 1255-1261.
[14] Lv N, Yu Y, Xu J, Karmonik C, Liu J and Huang Q. Hemodynamic and morphological characteristics of unruptured posterior communicating artery aneurysms with oculomotor nerve palsy. J Neurosurg 2016; 125: 264-268.
[15] Miura Y, Ishida F, Umeda Y, Tanemura H, Suzuki H, Matsushima S, Shimosaka S and Taki W. Low wall shear stress is independently associated with the rupture status of middle cerebral artery aneurysms. Stroke 2013; 44: 519-521.
[16] Perera R, Isoda H, Ishiguro K, Mizuno T, Takehara Y, Terada M, Tanoi C, Naito T, Sakahara H and Hiramatsu H. Assessing the risk of intracranial aneurysm rupture using morphological and hemodynamic biomarkers evaluated from magnetic resonance fluid dynamics and computational fluid dynamics. Magn Reson Med Sci 2020; 19: 333-344.
[17] Xiang J, Natarajan SK, Tremmel M, Ma D, Mocco J, Hopkins LN, Siddiqui AH, Levy EI and Meng H. Hemodynamic-morphologic discriminants for intracranial aneurysm rupture. Stroke 2011; 42: 144-152.
[18] Xu L, Liang F, Gu L and Liu H. Flow instability detected in ruptured versus unruptured cerebral aneurysms at the internal carotid artery. J Biomech 2018; 72: 187-199.
[19] Yuan J, Huang C, Lai N, Li Z, Jiang X, Wang X, Zhao X, Wu D, Liu J and Xia D. Hemodynamic and morphological analysis of mirror aneurysms prior to rupture. Neuropsychiatr Dis Treat 2020; 16: 1339-1347.
[20] Yuan J, Huang C, Li Z, Jiang X, Zhao X, Wu D, Lai N, Liu J, Zhang B and Qin F. Hemodynamic and morphological parameters of ruptured mirror posterior communicating artery aneurysms. Front Neurol 2021; 12: 653589.
[21] Zhang Y, Jing L, Liu J, Li C, Fan J, Wang S, Li H and Yang X. Clinical, morphological, and hemodynamic independent characteristic factors for rupture of posterior communicating artery aneurysms. J Neurointerv Surg 2016; 8: 808-812.
[22] Shojima M, Oshima M, Takagi K, Torii R, Hayakawa M, Katada K, Morita A and Kirino T. Magnitude and role of wall shear stress on cerebral aneurysm: computational fluid dynamic study of 20 middle cerebral artery aneurysms. Stroke 2004; 35: 2500-2505.
[23] Jou LD, Lee DH, Morsi H and Mawad ME. Wall shear stress on ruptured and unruptured intracranial aneurysms at the internal carotid artery. AJNR Am J Neuroradiol 2008; 29: 1761-1767.
[24] Meng H, Tutino V, Xiang J and Siddiqui A. High WSS or low WSS? Complex interactions of hemodynamics with intracranial aneurysm initiation, growth, and rupture: toward a unifying hypothesis. AJNR Am J Neuroradiol 2014; 35: 1254-1262.
[25] Can A and Du R. Association of hemodynamic factors with intracranial aneurysm formation and rupture: systematic review and meta-analysis. Neurosurgery 2016; 78: 510-520.
[26] Zhang Y, Yang X, Wang Y, Liu J, Li C, Jing L, Wang S and Li H. Influence of morphology and hemodynamic factors on rupture of multiple intracranial aneurysms: matched-pairs of ruptured-unruptured aneurysms located unilaterally on the anterior circulation. BMC Neurol 2014; 14: 253.