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ORIGINAL ARTICLE

Open surgical treatment of basilar artery aneurysms in the interventional therapy era

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Abstract

Purpose The purpose of this study was to describe the effectiveness and evaluation of open surgical treatment of basilar artery aneurysms in the context of interventional therapy era, including surgical clipping and blood reconstruction, by retrospectively analyzing the clinical data of basilar artery aneurysms in our center.

Methods Patients with basilar artery aneurysms who were treated at our center were retrospectively included according to the inclusion and exclusion criteria. The basic clinical data, surgical approach, clinical follow-up and prognosis of the enrolled patients were analyzed in detail. In this study, the mRS score was applied to assess the neurological prognosis of the patients, and the relevant data were statistically analyzed using SPSS.

Results A total of 104 eligible patients treated at our center from January 2010 to August 2023 were included in this study, of which 67 were treated by open surgery and 37 by bypass. For the 67 patients with open surgical clipping, the mean age was 60.0 (52.0, 65.0) years. The maximum diameter of the aneurysms ranged from 2.0 mm to 54.0 mm, with a mean of 13.9 (10.0, 19.0) mm. The mean follow-up time was 38 (20, 58) months. At the last follow-up, 61 (91.0%) completely obliterated aneurysms and 6 (9.0%) incompletely obliterated aneurysms were found. The prognosis was good in 59 (88.1%) patients and poor in 8 (11.9%). After surgical clipping, the difference between complete and incomplete postoperative aneurysm elimination was statistically significant between the favorable and poor prognosis groups ($P < 0.001$). For the 37 bypass group patients, the mean age was 52.0 (45.5, 59.0) years. The maximum diameter of the aneurysm ranged from 10.5 mm to 55.0 mm, with a mean of 28.55 ± 12.08 mm. Bypass combined with proximal occlusion was performed in 18 (48.6%) patients, and bypass only was performed in 19 (51.4%) patients. Clinical follow-up was 19.0 (10.5, 43.0) months. There were 19 (51.4%) patients with complete elimination of the aneurysm, 13 (35.1%) with incomplete elimination of the aneurysm, and 5 (13.5%) with aneurysm stabilization. The prognosis was good in 32 (86.5%) patients and poor in 5 (13.5%) patients.

Conclusion Treatment of basilar artery aneurysms is challenging. In the context of the rapidly evolving interventional therapy era, open surgery including surgical clipping and bypass is an ideal option for complex basilar artery aneurysms not amenable to intervention.

Keywords Basilar artery aneurysm · Surgical clipping · Bypass · Open surgery

Introduction

Intracranial aneurysm is an aneurysmal dilatation due to localized abnormalities of the blood vessel wall caused by various reasons, with a prevalence of approximately 3–5% in the population [7]. Intracranial aneurysms can rupture and bleed or cause space-occupying symptoms. Based on the location, cerebral aneurysms can be divided into two categories: anterior circulation aneurysms and posterior circulation aneurysms. Among them, posterior circulation aneurysms are mainly found in the basilar artery (BA), vertebral artery (VA), posterior cerebral artery (PCA), superior cerebellar artery (SCA),

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posterior inferior cerebellar artery (PICA) and anterior inferior cerebellar artery (AICA) [15]. Basilar artery aneurysms (BAAs) are a type of posterior circulation aneurysm with an overall low incidence of intracranial aneurysms. Combining autopsy and clinical imaging data, the prevalence of BAAs is approximately 0.1% to 2.6% [38]. Morphologically, they are classified as saccular aneurysms, fusiform aneurysms, or dissecting aneurysms. Saccular aneurysms are most common at the tip of the BA, whereas fusiform or dissecting aneurysms are more common in other parts of the BA. Classified by the rate of progression of the disease, BAAs can be divided into acute and chronic types [5]. Acute types, such as saccular or dissecting aneurysms, may present with subarachnoid hemorrhage (SAH) or acute ischemic stroke. Chronic types, such as fusiform aneurysms, may present with slow progression and eventually progress to giant aneurysms, causing a range of serious complications. Possible pathogenesis of BAAs includes congenital anomalies, inflammatory vasculopathy, mechanical injury due to post-stenotic turbulence, intimal disruption due to arterial dissection, and a severe lack of muscularis reticulata fibers [4, 32]. However, the exact pathogenesis of BAAs is still not well understood. Posterior circulation aneurysms are different from anterior circulation aneurysms. Effective treatment of BAAs has been challenging due to the complex anatomy and proximity to important neurovascular structures such as the brainstem.

The main treatment modalities for intracranial aneurysms include surgical clipping and endovascular therapy (EVT) [19, 42, 50]. BAAs are common in the posterior circulation, although they are not highly prevalent. BAAs are difficult to treat due to their location and anatomical relationship [2, 40]. With the continuous development of interventional devices and related techniques, EVT is becoming a more popular treatment modality for BAAs [20, 43]. However, open surgery to clip the BAA is also an option for patients with severely tortuous vascular paths that make it impossible for the interventional device to reach the target location or for patients who are unable to afford the high cost of interventional procedures [9]. Even for complex BAAs that are neither amenable to intervention nor surgical clipping, bypass may be a last resort [22, 34]. The purpose of this study is to provide an alternative treatment option for the treatment of BAAs by analyzing a single-center experience of open surgery, including surgical clipping and bypass, for the treatment of BAAs.

Materials and methods

Patient

This study was approved and supported by the Research Ethics Review Committee of Tianjin Huanhu Hospital in accordance with the Declaration of Helsinki. Written consent was obtained from the patients themselves or their guardians for the clinical cases involved in this study. The inclusion criteria were as follows: (1) preoperative computed tomography angiography (CTA) or magnetic resonance angiography (MRA) or digital subtraction angiography (DSA) clearly diagnosed BAA, (2) Patients were included regardless of whether they presented with SAH and, if so, with a Hunt-Hess grade (I-III), (3) aneurysm morphology including, but not limited to, saccular aneurysm or dissecting aneurysm, (4) complex BAAs, and (5) treatment modality of surgical clipping or bypass. The exclusion criteria were as follows: (1) aneurysm was not located in the basilar artery, (2) patients who are suitable and preferred for interventional therapy, (3) patients with SAH and a Hunt-Hess grade (IV-V), and (4) patients with severe underlying medical conditions that make them unable to tolerate surgery (e.g., severe cardiopulmonary disease, severe endocrine system disease, or other conditions that make them unsuitable for surgery, etc.). According to the summary of the relevant literature, complex aneurysms have the following characteristics: large or giant aneurysms that morphologically show dissecting or dolichoectatic dilatation, important penetrating arteries originating from the aneurysm itself, severe calcification or atherosclerosis of the aneurysm wall, and massive thrombosis within the aneurysm, etc. [16, 35, 44]. Patients who met at least one of the above inclusion criteria were included in this study. The baseline data of the enrolled patients, clinical presentation, surgical approach, treatment outcome and clinical follow-up were recorded in detail. The modified Rankin Scale (mRS) score was used to assess the neurological function and clinical prognosis of the patients.

Surgical procedure

The open surgery procedure is suitable for patients who have an extremely tortuous vascular path that prevents the interventional device from reaching the target vessel. The indications for open surgical treatment are as follows: (1) patients who have previously suffered aneurysm rupture and hemorrhage, (2) patients whose aneurysms have changed significantly in size or shape in a short period of time, (3) patients who have suffered two or more ischemic strokes and have failed to undergo conservative treatment, (4) patients whose aneurysms have significant space-occupying symptoms, (5) patients who are not suitable for interventional treatment due to very poor vascular conditions, and (6) patients who have the physical conditions that can tolerate the surgery and who have obtained consent from their guardians. Surgical treatment was not performed in patients who did not meet the above indications for surgery. The specific basis refers to the inclusion and exclusion criteria described in the previous section. Since the study of this paper is for open surgical treatment of patients with BAAs, the information of the part of patients who took interventional and conservative treatment was not included in this study. It will not be discussed in detail here. All patients underwent surgery under general anesthesia. Depending on the location of the BAA, either a middle skull base approach or an extended middle skull base approach is used. The patient was placed in the supine position with the head tilted to the contralateral side by 30°-45° so that the cheekbone was at its highest point. The incision begins at the lower edge of the ipsilateral zygomatic arch, curves upward anteriorly along the tragus, and crosses the midline to end within the contralateral hairline. The craniotomy was performed using an interfascial approach. Dissection is performed at both ends of the zygomatic arch. The zygomatic arch is not removed. The severed zygomatic arch is flipped downward along with the temporalis muscle in order to adequately visualize the middle skull base. A bone flap of the appropriate size is cut with a milling cutter according to the intraoperative needs. A high-speed milling drill is used to fully remove the sphenoid bone greater wing, the anterior clinoid process, and a portion of the middle skull base. Adequately free the oculomotor nerve and internal carotid artery (ICA) following the Dolonc approach [10, 11]. The PCA and the basilar artery apex can be visualized by gently lifting the temporal lobe. For some of the lower basilar arteries, the option is to continue to drill the middle skull base bone posteriorly. The basilar artery is further exposed by drilling the Kawase's triangle. This provides an advantage for temporary blockage of the parent artery during surgical clipping or bypass. A presigmoid approach combined with a far lateral approach is chosen when the aneurysm is located at the junction of the vertebrobasilar artery. The neck of the basilar aneurysm is fully exposed and clipped with an aneurysm clip. Intraoperative indocyanine green fluorescein angiography (IGFA) is applied to assess whether the parent artery is patent and whether the aneurysm is visualized. Refer to Fig. 1A.

For complex BAAs that are neither amenable to intervention nor surgical clipping, bypass or combined aneurysm trapping is the treatment of choice. All patients who underwent bypass treatment were started on oral aspirin 100 mg/day at least 7 days before surgery. It was not discontinued on the day of surgery. Regular dosing was continued postoperatively. Perioperative anticoagulation was not used. The craniotomy approach was chosen as either a middle skull base approach or an extended middle skull base approach. Detailed description was as described in the previous section. The operator determined whether to perform high flow bypass or low flow bypass based on adequate evaluation of the patient's preoperative clinical data. The high flow bypass modality involved in this study was external carotid artery-radial artery graft-posterior cerebral artery (ECA-RAG-PCA). Preoperatively, Allen's test was performed to assess the patient's forearm circulation. A section of radial artery of about 20-cm (cm) length was harvested and placed in papaverine heparin saline for backup. The radial artery spasm was managed using the pressure dilatation technique [30]. The ECA was first severed at the beginning of the main ECA, the proximal end of the ECA was anastomosed end-to-end with the proximal end of the RAG, and the distal end of the ECA was ligated. The RAG was introduced intracranially through a subcutaneous tunnel. A P2 segment of the PCA without a perforating artery was selected, and the distal end of the RAG was anastomosed end-to-side with P2. The low-flow bypass modalities involved in this study were single- or double-branch superficial temporal artery-PCA (STA-PCA), occipital artery-posterior inferior cerebellar artery (OA-PICA). The low-flow bypass, such as STA-PCA or OA-PICA, is implemented by end-to-side anastomosis. Adequate release of the STA or OA was performed. Excessive use of bipolar electrocoagulation was avoided. The donor and recipient arteries were anastomosed end-to-end using a segment of PCA or PICA without a perforating branch. Intraoperative IGFA was applied to assess bypass patency. Intraoperative DSA was applied to assess hemodynamic changes and BAA changes after bypass. If the reverse blood flow of bypass could return to the basilar artery, the proximal part of the basilar artery was occluded to partially trap the aneurysm. If the reverse blood flow

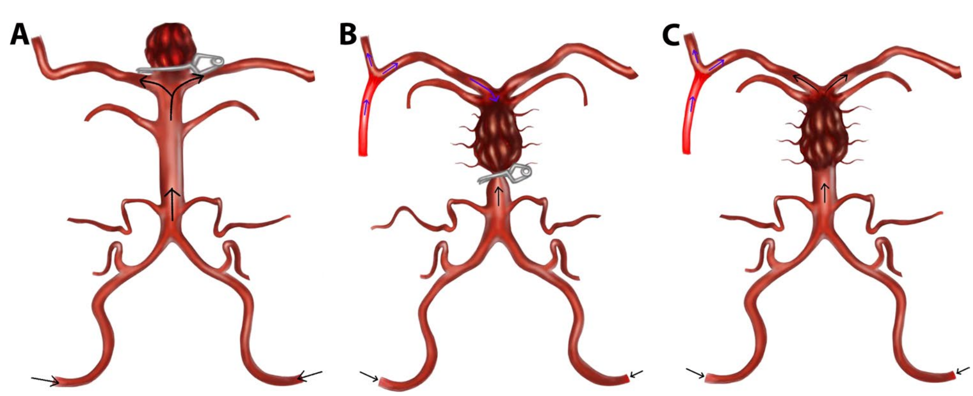

Fig. 1 Artwork of surgery. **A** indicates surgical clipping of BBAs. **B** indicates bypass combined with PO. **C** indicates implementation of bypass only. BBAs = basilar artery aneurysms, PO = proximal occlusion

from bypass could not return to the basilar artery, bypass alone was performed. Refer to Fig. 1B and Fig. 1C.

Clinical follow-up

Patients underwent rigorous clinical follow-up after surgery. Inpatient follow-up, outpatient follow-up, or telephone follow-up were included in this study. The outcomes of aneurysms included complete obliteration, incomplete obliteration, and stabilization. The mRS score was applied in this study to assess the neurological prognosis of the patients. In this study, the mRS score of 0–3 at the last follow-up was set as good prognosis, and the mRS score of 4–5 was set as poor prognosis.

Statistical analysis

Quantitative data that follow a normal distribution are expressed as mean ± standard deviation. Quantitative data that are non-normally distributed are expressed as median and interquartile range. Qualitative data are expressed as rates or component ratios. The statistical methods of *t*-test, Mann–Whitney test, chi-square ($\chi 2$) test, or Fisher's exact test were used to analyze differences between quantitative and qualitative data, respectively. A two-sided $P < 0.05$ was considered statistically significant. All statistical analyses were performed with IBM SPSS software, version 26 (IBM Software Group, Chicago, IL).

Results

This study retrospectively analyzed patients with BAAs who underwent open surgical treatment at our center from January 2010 to August 2023. There were 71 cases of surgical clipping, of which 4 patients were lost to follow-up, and no surgery-related deaths occurred. 42 cases were treated by bypass, of which 2 patients died postoperatively due to severe complications and 3 patients were lost to follow-up. Because of the lack of complete clinical information on the death cases or lost to follow-up cases, they were excluded from this study. Therefore, a total of 104 patients were enrolled in this study, of which 67 were surgical clipping and 37 were bypass treated. 13 patients had two or more aneurysms. In addition to BAAs, other aneurysms in combination included anterior communicating artery (AComA) aneurysms, posterior communicating artery (PComA) aneurysms, middle cerebral artery (MCA) aneurysms, or PICA aneurysms. This study was conducted with a focus on BAAs, so only data related to BAAs were included for analysis.

Outcomes of surgical clipping

The total number of patients with BAAs with surgical clipping was 67, of which 29 (43.3%) were males and 38 (56.7%) were females. After testing for normality, none of the quantitative data in this group conformed to a normal distribution, so the median and interquartile range were used to represent M (P_{25}, P_{75}). The age of the patients was 24–74 years, mean age 60.0 (52.0, 65.0) years. The aneurysm morphology was saccular. The maximum diameter of the aneurysms ranged from 2.0 (millimeter) mm-54.0 mm with a mean of 13.9 (10.0, 19.0) mm. In patients with BAAs in whom craniotomy was performed, 15 (22.4%) aneurysm ruptures were associated with SAH and 52 (77.6%) aneurysms did not rupture. Preoperative mRS scores of 0–3 were obtained in 60 (89.6%) patients and 4–5 in 7 (10.4%) patients. 8 BAAs were located at the junction of the vertebrobasilar arteries, and the presigmoid approach was used in conjunction with the far lateral approach. 59 BAAs were located in the basilar artery apex or in the upper segment of the basilar artery. Either the middle skull base approach or the extended middle skull base approach was used. Clinical follow-up ranged from 3 to 108 months. The mean follow-up time was 38 (20, 58) months. Aneurysms found to be completely obliterated at last follow-up were 61 (91.0%) and incompletely obliterated were 6 (9.0%). Of the 6 patients whose aneurysms were not completely obliterated, 2 had postoperative aneurysm rupture with a final mRS score of 5. In 1 case, the aneurysm was located in the inferior segment of the basilar artery, and in 1 case, the aneurysm was located at the junction of the vertebrobasilar artery. A presigmoid approach combined with a far lateral approach was used in the above 2 patients. In addition, there were 3 cases of basilar artery apex aneurysms and 1 case of vertebrobasilar junction aneurysm that were not completely clipped, and postoperative DSA showed that the aneurysms were not completely eliminated. All 4 patients with incompletely clipped aneurysms had serious postoperative complications of varying degrees. The last follow-up mRS score of 0–3 was 59 (88.1%) and 4–5 was 8 (11.9%). According to the criteria set in this study to assess the prognosis of the patients, the group had 59 (88.1%) patients with good prognosis and 8 (11.9%) patients with poor prognosis. Of the 61 patients in whom the aneurysm was completely eliminated, 59 had a favorable prognosis. These 59 patients had no postoperative complications or only mild symptoms of neurological deficit. All recovered well after rehabilitation during the follow-up period. The remaining 2 patients with poor prognosis included 1 patient with unexplained cerebral hemorrhage and 1 patient with acute brainstem infarction. 6 patients whose aneurysms were not completely obliterated had a poor prognosis. Detailed data is presented in Table 1.

Bypass treatment results

A total of 37 patients were treated with bypass or combined proximal occlusion (PO) of the parent artery. 28 (75.7%) were male and 9 (24.3%) were female. The age of the patients was 18–68 years, and the mean age was 52.0 (45.5, 59.0) years. The aneurysms in this group met the diagnostic criteria for complex BAAs. The maximum diameter of the aneurysms ranged from 10.5 mm to 55.0 mm, with a mean of 28.55 ± 12.08 mm. Ruptured patients with SAH were 3 (8.1%) and unruptured patients were 34 (91.9%). The preoperative mRS score of 0–3 was 21 (56.8%) and 4–5 was 16 (43.2%). Appropriate surgical strategies were selected according to the principle of individualized treatment. Bypass combined with PO treatment was performed in 18 (48.6%) patients, and bypass treatment alone was performed in 19 (51.4%) patients. Of these, ECA-RAG-PCA bypass was performed in 29 patients, STA-PCA bypass in 5 patients, and OA-PICA bypass in 3 patients. Clinical follow-up ranged from 3 to 73 months, with a mean of 19.0 (10.5, 43.0) months. The aneurysms were completely obliterated in 19 (51.4%) patients, incompletely obliterated in 13 (35.1%) patients, and stabilized in 5 (13.5) patients. 4 patients with bypass only and 15 patients with bypass combined with PO achieved complete obliteration of the aneurysm. 10 patients with bypass only and 3 patients with bypass combined with PO achieved incomplete elimination of the aneurysm. In 5 patients with bypass only, the aneurysm stabilized after surgery. All patients were found to have good bypass patency at the last follow-up. The mRS score at the last follow-up was 0–3 in 32 (86.5%) patients and 4–5 in 5 (13.5%) patients. According to the criteria set for prognostic assessment of patients in this study, 32 (86.5%) patients with good prognosis and 5 (13.5%) patients with poor prognosis in bypass group. The 32 patients with favorable prognosis had no obvious complications or only mild neurological deficits after the operation, and all of them recovered well in the later stages. Of the 5 patients with poor prognosis, 2 had cerebral infarction and dysphagia after surgery, 1 had reduced respiratory function and required ventilator support, 1 had prolonged lethargy, and 1 had severe pneumonia. Detailed data is given in Table 2.

Table 1 Surgical clipping for BAAs

Characters	Values
NO. of Patients	67
Gender	
Male	29 (43.3%)
Female	38 (56.7)
Age (years)	
M (P_{25}, P_{75})	60.0 (52.0, 65.0)
Range	24–74
Aneurysm size (mm)	
M (P_{25}, P_{75})	13.9 (10.0, 19.0)
Range	2.0–54.0
SAH	
Yes	15 (22.4%)
No	52 (77.6%)
Preoperative mRS	
0–3	60 (89.6%)
4–5	7 (10.4%)
Follow up (months)	
M (P_{25}, P_{75})	38 (20, 58)
Range	3–108
Aneurysm obliteration	
Complete	61 (91.0%)
Incomplete	6 (9.0%)
Latest mRS	
0–3	59 (88.1%)
4–5	8 (11.9%)
Prognosis	
Favorable	59 (88.1%)
Poor	8 (11.9%)

BAAs = basilar artery aneurysms, NO. = number, M = median, IQR = InterQuartile Range, IQR = P_{75}-P_{25}, mm = millimeter, mRS = modified Rankin Scale

There were 2 patients in the bypass group who died because of serious postoperative complications. A 48-year-old male patient underwent ECA-RAG-PCA bypass combined with PO of BA for a giant dissecting BAA. 1 week postoperatively, the bypass patency was good, but an acute cerebral infarction developed. The patient continued to deteriorate 1 month after surgery and died after resuscitation. Our team analyzed the cause of death as a severe brainstem infarction due to massive thrombosis of the BA. The other patient who died was a 57-year-old woman. The patient was treated with ECA-RAG-PCA bypass combined with irregular aneurysm clipping because of a dissecting BAA combined with multiple irregular saccular aneurysms. In the postoperative period, the patient recovered well with good bypass patency. Unfortunately, half a month after the surgery, the patient's condition suddenly deteriorated and he suffered from respiratory and cardiac arrest. Our team analyzed that the cause of this patient's death was the re-rupture and bleeding of multiple irregular saccular aneurysms of the BA.

Results of statistical analysis

Patients were divided into favorable prognosis and poor prognosis groups based on the results of the final follow-up. For the surgical clipping group, the quantitative data after grouping did not exactly fit the normal distribution in the favorable and poor prognosis groups. Therefore, the

Table 2 Bypass for BAAs

Characters	Values
NO. of Patients	37
Gender	
Male	28 (75.7%)
Female	9 (24.3%)
Age (years)	
M (P_{25}, P_{75})	52.0 (45.5, 59.0)
Range	18–68
Aneurysm size (mm)	
Mean ± SD	28.55 ± 12.08
Range	10.5–55.0
SAH	
Yes	3 (8.1%)
No	34 (91.9%)
Preoperative mRS	
0–3	21 (56.8%)
4–5	16 (43.2%)
Surgery algorithm	
Bypass	19 (51.4%)
Bypass + PO	18 (48.6%)
Follow up (months)	
M (P_{25}, P_{75})	19.0 (10.5, 43.0)
Range	3–73
Aneurysm obliteration	
Complete	19 (51.4%)
Incomplete	13 (35.1%)
Stabilization	5 (13.5%)
Latest mRS	
0–3	32 (86.5%)
4–5	5 (13.5%)
Bypass patency rate	100%
Prognosis	
Favorable	32 (86.5%)
Poor	5 (13.5%)

BAAs = basilar artery aneurysms, NO. = number, SD = standard deviation, M = median, IQR = InterQuartile Range, IQR = P_{75}-P_{25}, mm = millimeter, mRS = modified Rankin Scale, PO = proximal occlusion of parent artery

Mann–Whitney test was used for the quantitative data in the surgical clipping group. Chi-square ($\chi 2$) test or Fisher exact test was used for qualitative data according to the appropriate statistical conditions. Variables such as age, aneurysm size, presence of SAH, preoperative mRS score, and whether the aneurysm was completely obliterated postoperatively were included for statistical analysis. The results showed that the difference between complete and incomplete postoperative aneurysm obliteration was statistically significant between the favorable prognosis group and the poor prognosis group ($P < 0.001$). The differences in the remaining variables were not statistically significant ($P > 0.05$). For the bypass group, the quantitative data after grouping conformed to a normal distribution in both the favorable prognosis group and the poor prognosis group. Therefore, the *t*-test was used for quantitative data in the bypass group. For qualitative data, chi-squared test ($\chi 2$) or Fisher exact test was used according to the appropriate statistical conditions. Variables such as age, aneurysm size, presence of SAH, preoperative mRS score, different surgical modalities, and whether the aneurysm was completely obliterated postoperatively were included for statistical analysis. The results showed that the differences in the above variables were not statistically significant ($P > 0.05$). Detailed data and results are shown in Table 3 (Figs. 2, 3 and 4).

Illustration cases

A 62-year-old female patient with an aneurysm of the basilar artery apex was treated with surgical clipping of the BAA. (A) is a preoperative brain CT showing SAH. (B) and (C) are preoperative CTA and DSA showing a BAA, respectively. (D), (E) and (F) are intraoperative procedures to reveal the basilar artery and clip the aneurysm. (G) is intraoperative IGFA showing complete obliteration of the aneurysm. (H) is a postoperative brain CT showing no hemorrhagic complications. (I) and (J) are follow-up CTAs showing no recurrence of the aneurysm. CT = computed tomography, SAH = subarachnoid hemorrhage, CTA = computed tomography angiography, DSA = digital subtraction angiography, BBA = basilar artery aneurysm, IGFA = indocyanine green fluorescein angiography.

A 31-year-old female patient with a large aneurysm of the upper segment of the basilar artery with dissecting manifestations was treated with ECA-RAG-PCA bypass through the extended middle skull base approach. (A) and (B) are preoperative CTA and DSA, respectively, showing a large aneurysm in the upper segment of the basilar artery. (C) and (D) are intraoperative bypass procedures. (E) Intraoperative IGFA showing good bypass patency. (F) and (G) are postoperative CT and MRI, respectively, showing no hemorrhage and ischemic complications. (H) is the follow-up CTA. (I) and (J) are the follow-up review DSA showing complete elimination of the aneurysm and good bypass patency. CTA = computed tomography angiography, DSA = digital subtraction angiography, IGFA = indocyanine green fluorescein angiography, CT = computed tomography, MRI = magnetic resonance imaging.

A 63-year-old male patient with a basilar artery dissecting aneurysm was treated with ECA-RAG-PCA bypass through the extended middle skull base approach. (A) is the preoperative brain CT. (B) and (C) are the preoperative CTA and DSA, respectively, showing the basilar artery dissecting aneurysm. (D) is the intraoperative bypass procedure. (E) is an intraoperative IGFA showing good bypass patency. (F) is a postoperative

Table 3 Statistical analysis of the prognosis

Variate	NO	Favorable prognosis	Poor prognosis	*P* value
Surgical clipping group				
Age (years)	67	61.0 (52.0, 65.0)	58.0 (54.0, 66.8)	$0.885
Size (mm)	67	14.0 (10.0, 19.0)	12.85 (10.5, 22.1)	$0.969
SAH				
Yes	15	13 (22.0%)	2 (25.0%)	&1.000
No	52	46 (78.0%)	6 (75.5%)	
Preoperative mRS				
0–3	60	52 (88.1%)	8 (100.0%)	*0.586
4–5	7	7 (11.9%)	0 (0.0%)	
Aneurysm obliteration				*
Complete	61	59 (100.0%)	2 (25.0%)	**< 0.001**
Incomplete	6	0 (0.0%)	6 (75.0%)	
Bypass group				
Age (years)	37	50.9 ± 11.18	56.8 ± 8.64	#0.269
Size (mm)	37	28.58 ± 11.96	28.40 ± 14.29	#0.976
SAH				
Yes	3	2 (6.3%)	1 (20.0%)	*0.362
No	34	30 (93.8%)	4 (80.0%)	
Preoperative mRS				
0–3	21	20 (62.5%)	1 (20.0%)	*0.144
4–5	16	12 (37.5%)	4 (80.0%)	
Surgery algorithm				
Bypass	19	17 (53.1%)	2 (40.0%)	&0.660
Bypass + PO	18	15 (46.9%)	3 (60.0%)	
Aneurysm obliteration				
Complete	19	18 (56.3%)	1 (20.0%)	
Incomplete	13	10 (31.3%)	3 (60.0%)	
Stabilization	5	4 (12.5%)	1 (20.0%)	*0.301

NO. = number, SAH = subarachnoid hemorrhage, mRS = modified Rankin Scale, mm = millimeter, $ = Mann–Whitney test, # = *t*-test, & = chi-square (χ^2) test, * = Fisher exact test, PO = proximal occlusion of parent artery

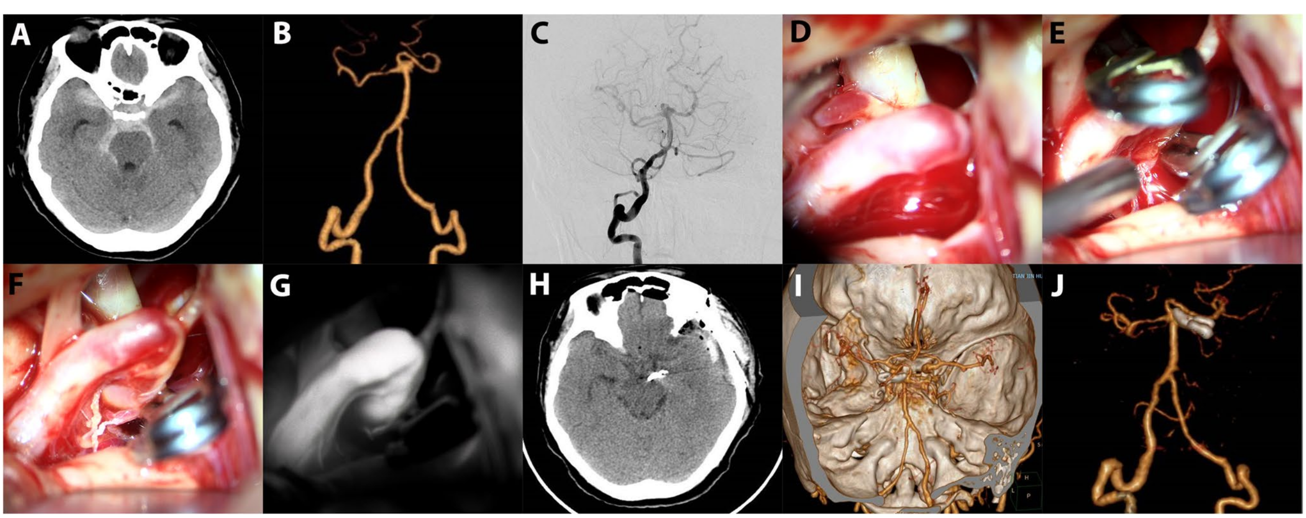

Fig. 2 Illustration case 1

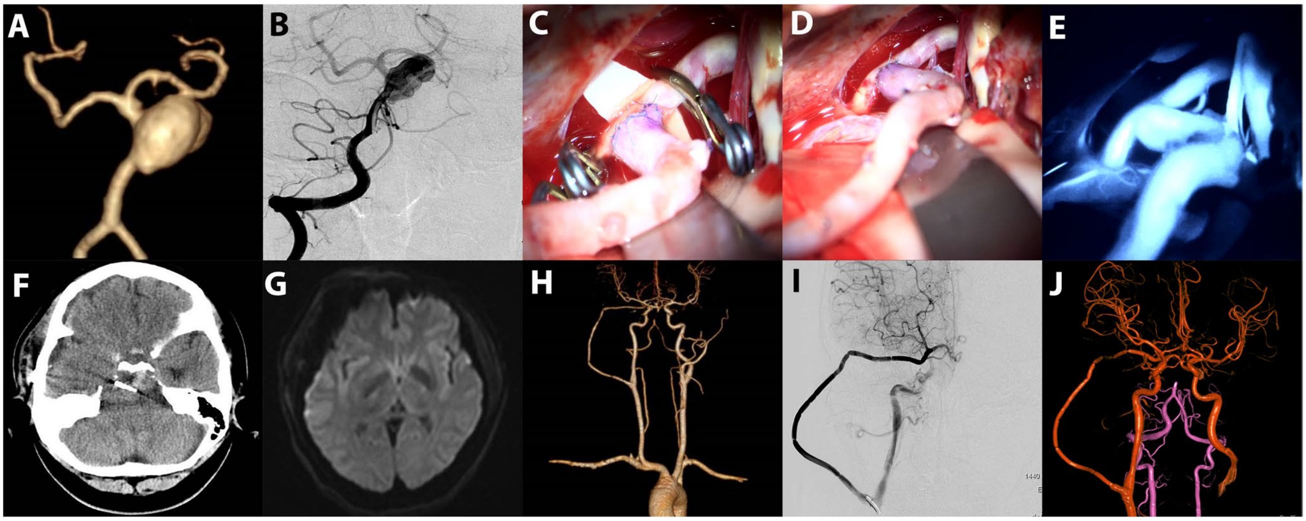

Fig. 3 Illustration case 2

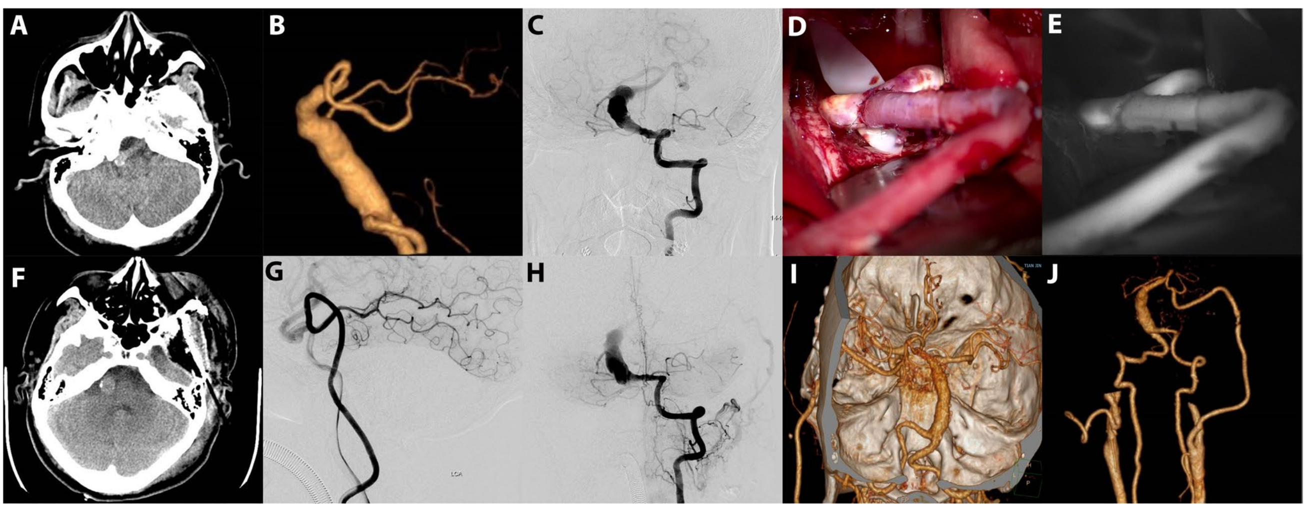

Fig. 4 Illustration case 3

brain CT showing no hemorrhage complications. (G) and (H) are postoperative review DSAs showing good bypass patency and lightening of the dissecting aneurysm visualization. (I) and (J) are follow-up CTAs showing good bypass patency and a smaller dissecting aneurysm compared to the preoperative period. CT = computed tomography, CTA = computed tomography angiography, DSA = digital subtraction angiography, IGFA = indocyanine green fluorescein angiography.

Discussion

This paper presents a clinical study of open surgical treatment of eligible patients with BAAs based on inclusion and exclusion criteria. Surgical clipping was performed in 67 patients and bypass was performed in 37 patients. Of the 67 patients who underwent surgical clipping, 91.0% had complete obliteration of the aneurysm. Most of the patients had a favorable clinical prognosis except for 2 patients who developed serious complications. This conclusion was also demonstrated in Table 3 of the statistical analysis results. In the favorable prognosis and poor prognosis groups, the difference between whether the aneurysm was completely obliterated or not was statistically significant ($P < 0.001$). This finding suggests that complete clipping of the aneurysm contributes to a better clinical prognosis. In patients with BAAs who are suitable for surgical clipping, the operator should make every effort to achieve complete clipping of the aneurysm. Although patient age, aneurysm size, presence of SAH, and preoperative mRS scores did not show statistically significant differences in clinical prognosis, this finding may be due to the small sample size. Of the 37 patients who underwent bypass, 51.4% had complete obliteration of the aneurysm. This result was not as encouraging as the complete elimination of aneurysms in the surgical clipping group, but there was a significant reduction in aneurysm size in 35.1%. The remaining 13.5% of aneurysms tended to stabilize over time. Nevertheless, a favorable clinical prognosis was achieved in 86.5% of patients. Overall, this is a satisfactory result. In our center's experience, patients undergoing bypass surgery generally have complex aneurysms that are not candidates for surgical clipping. The aneurysm itself is usually not directly addressed during the procedure. The principle of the bypass procedure for treating complex BAAs is to cure the aneurysm by counteracting the positive blood flow to the aneurysm with the reverse blood flow from the graft, which promotes thrombosis within the aneurysm and thus cures the aneurysm [21]. This procedure also ensures the blood supply to the involved perforator vessels. Therefore, the rate of complete aneurysm obliteration after bypass surgery may not be too high, but this rate will gradually increase over time. This study showed that the long-term prognosis of bypass surgery for complex BAAs is still optimistic.

BAAs are common aneurysms of the posterior circulation, accounting for about 5% of intracranial aneurysms [26]. Located in the posterior circulation, BAAs are difficult and risky to perform open surgery due to their deep anatomical location and the complexity of the adjacent neurovascular relationships [3, 25, 36, 53]. Endovascular interventions in the field of BAAs have achieved satisfactory results [39]. In addition, with the rapid development of interventional techniques and interventional devices in recent years, EVT has gradually become the mainstream treatment for aneurysms of the posterior circulation. However, not all aneurysms are suitable for interventional therapy because of their individual characteristics. Zhong W et al. found that EVT for BAAs is feasible and effective, but the risk of cerebral ischemia and hemorrhagic complications need to be taken into account [51]. For those BAAs that are not suitable for intervention, surgical clipping or flow reconstruction become alternative treatment options. In this study, we analyzed the treatment and clinical prognosis of patients with BAAs who underwent surgical clipping or flow reconstruction at our center and obtained satisfactory results.

Current status of BAAs treatment

The ultimate goal of aneurysm treatment is to minimize the risk of rupture and bleeding by isolating the aneurysm from the circulation. Surgical clipping and interventional therapies are the most common ways to treat an aneurysm. Surgical clipping is the application of an aneurysm clip to block the neck of the aneurysm, thereby preventing blood from impinging on the inside of the aneurysm [41, 48]. Craniotomy has the disadvantages of being more invasive and having a longer recovery time for the patient. Interventional therapy involves occlusion of the aneurysm by filling the aneurysm with Guglielmi detachable coils (GDCs) or stent-assisted embolization [45]. The introduction and development of flow diverter (FD) devices has led to a new era of interventional therapy for aneurysms, but the long-term prognosis needs to be further validated [27, 33]. With the advantages of less invasiveness and faster patient recovery, interventional therapy has gradually become the mainstream treatment for intracranial aneurysms. Especially with the continuous innovation and development of interventional devices, interventional therapy is being accepted by more and more doctors and patients. Church EW et al. found that 37% of posterior circulation aneurysms were treated with microsurgery, and 63% were treated with EVT [8]. However, interventional therapy is not a panacea. In some cases, the intervention fails because the microguidewire and microcatheter cannot reach the target location due to severe tortuosity of the vessel. There are also cases where intervention is abandoned due to the patient's own financial reasons. In these cases, open surgical treatment needs to be considered. Nagashima H et al. conducted a comparative study of clipping or embolization of BAAs. According to this research, although endovascular intervention is an effective treatment for aneurysms of the basilar artery apex, one quarter of the aneurysms are not completely eliminated [31]. For BAAs, it is wise to choose the appropriate individualized treatment plan based on the patient's specific situation.

Surgical clipping

Among the patients in this study who underwent surgical clipping, 91.0% had complete obliteration of the aneurysm and 88.1% achieved a favorable clinical prognosis. The above results suggest that surgical clipping is of great value and importance in the treatment of BAAs. Previous studies and related literature also support the results of this study. Surgical clipping of an aneurysm at the basilar artery apex is a preferred option when interventional therapy fails [18]. Sanai N et al. treated aneurysms of the posterior circulation by surgical clipping, resulting in complete obliteration of the aneurysm in 98.1% of cases [37]. For surgical clipping of BAAs, choosing the right surgical approach is key to success. In this study, the presigmoid approach was combined with the far lateral approach in 8 patients whose aneurysms were located at the vertebrobasilar junction and the middle skull base approach or the extended middle skull base approach in 59 patients whose aneurysms were located at the apex of the basilar artery. The above procedures were very smooth and successful. The basilar artery apex and bilateral PCAs, as well as peripheral vascular-neurologic structures, can be adequately exposed through a middle skull base approach or an extended middle skull base approach. The infratemporal approach, which is the classic surgical approach of Professor Drake, can be used to clip the BAA with relative ease in appropriate cases [12, 13]. However, the disadvantage of the Drake approach is that the temporal lobe can be easily damaged by pulling on it. If the location of the BAA is too high or too low, the Drake approach is not suitable. According to the Kawase approach and the Hakuba approach, the middle skull base approach or the extended middle skull base approach can allow the bone of the skull base to be trimmed to obtain a larger exposure space and avoid excessive pulling of the brain tissue [17, 24]. Compared with the inferotemporal approach, the middle skull base approach or extended middle skull base approach adopted in this study has a wider surgical field and less pulling on the brain tissue, which provides more favorable conditions for surgical safety. For aneurysms located at the junction of the vertebrobasilar artery and suitable for clipping, a presigmoid approach combined with a far lateral approach is recommended. The results of this study showed that the success rate of complete obliteration of the aneurysm was 91.0%, and 88.1% of the patients had a favorable clinical prognosis.

Bypass for complex BAA

Complex BAAs, especially those with important perforating arteries originating from the aneurysm itself, are not effectively treated with either traditional surgical clipping or interventional therapies. Conventional surgical clipping does not effectively clip the neck of the aneurysm while maintaining patency of the involved parent arteries. Interventional embolization, which involves the placement of a FD device into the target site of a complex aneurysm, may result in occlusion of the involved critical perforating arteries, leading to severe cerebral ischemic complications [14, 52]. In such cases, bypass may be the last and effective treatment strategy [6, 23]. Of the patients in this study who underwent bypass for BAAs, 86.5% achieved a favorable clinical prognosis and had significant shrinkage or complete obliteration of the aneurysm. The remaining aneurysms that did not change significantly were also shown to stabilize over time during clinical follow-up. All bypasses were well patent. The results of this study demonstrate that bypass is safe and effective in the treatment of complex BAAs. As early as 1997, Amin-Hanjani S et al. used the concept of flow reversal in the treatment of dissecting BAAs with favorable results. They had presented a systematic review of bypass combined with proximal occlusion for the treatment of dissecting BAAs [1]. Miyamoto S et al. and Mai JC et al. have accumulated a wealth of successful experience in the treatment of BAAs by flow reconstruction techniques [28, 29]. Bypass treatment of complex BAAs can change the hemodynamics of the aneurysm by counteracting the positive flow from the parent artery with the reverse flow from the graft vessel, promoting thrombus formation within the aneurysm without directly occluding the parent artery and the perforating artery, and thus achieving safe treatment of complex BAAs [21, 46]. In some patients, bypass combined with proximal occlusion of the parent artery can be performed. The prerequisite for this is that intraoperative DSA can confirm that the reverse blood flow from the bypass graft can return sufficiently to the basilar artery to ensure blood supply to the distal basilar artery and its branches. This procedure essentially partially traps the complex BAA and promotes thrombus formation within the aneurysm while maintaining patency of the perforating arteries, thereby achieving safe treatment of the complex BAA. If the bypass is performed after 1 month or more, more aggressive treatments such as occlusion of the parent artery are also safe and reliable. This is because by this time, the high-flow bypass performed previously will have provided a steady blood flow and ensured blood supply to the corresponding area of the original parent artery. Our team has successful experience in the treatment of complex BAAs. Our medical center's experience has been confirmed in our previous studies and others' studies. The results of our previous research have shown that the treatment of complex BAAs by ECA-RAG-PCA high-flow bypass has achieved satisfactory clinical results [49]. Yanagisawa T et al. also achieved good long-term clinical prognosis for the treatment of the basilar artery giant aneurysms by using saphenous vein graft for reconstruction of the blood flow [47]. Complex BAAs are deeply located, adjacent to important neurovascular structures such as the brainstem, with complex anatomical relationships and high surgical risks. Therefore, the treatment of complex BAAs has always been a difficult problem in the field of neurosurgery. The results of this study showed that the success rates of bypass or combined proximal occlusion of the parent artery for complete obliteration and incomplete obliteration of complex BAAs were 51.4% and 35.1%, respectively. Complex BAAs were effectively treated in 86.5% of cases and stabilized in 13.5% of cases. A favorable clinical prognosis was achieved in 86.5% of patients with complex BAAs treated with bypass surgery. Both our previous and current findings confirm the efficacy and safety of high-flow bypass for the treatment of complex BAAs.

Statistical analysis of the results based on the two groups with favorable and poor prognosis showed that whether the aneurysm was completely obliterated or not showed a statistically significant difference only in the surgical clipping group. However, whether the aneurysm was completely obliterated or not did not show a statistically significant difference in the bypass group. Our team analyzed this statistic for two main reasons. One reason is that due to the small sample size of the bypass group, statistical bias may have affected the results. The other reason is that the principle of bypass for complex BAAs is not to directly treat the aneurysm itself in most cases, but rather to rely on long-term and slow hemodynamic changes to achieve treatment of the aneurysm. This is in contrast to surgical clipping, which directly treats the aneurysm so that it is completely obliterated, where the immediate changes in the aneurysm are significantly different. For the other variables included, such as patient age and aneurysm size, this study did not show a statistically significant difference. Anyway, taking active measures to make the aneurysm significantly smaller or obliterate it completely while ensuring the safety of the procedure is helpful in obtaining a good clinical prognosis.

Surgical Strategies of our Center

Patients diagnosed with BAA need to complete relevant medical examinations after admission. Multi-disciplinary treatment (MDT) including neurosurgery, radiology, and intervention is essential. All patients with BAAs were evaluated by MDT. As shown in Fig. 5. For patients who were eligible for both open surgical and interventional treatment, interventional treatment was prioritized. This is because interventional treatment is less invasive, and the patient recovers faster. Unless the patient refuses intervention. For patients with extremely poor vascular conditions resulting in extremely high interventional risk or patients who cannot afford interventional therapy due to economic factors can choose surgical clipping treatment. For complex BAAs, which are neither suitable for traditional surgical clipping nor interventional embolization, bypass surgery is recommended. Low-flow bypass is recommended if the PComA is well compensated or only requires supplemental blood flow. After low-flow bypass, aneurysm trapping or partial trapping can be performed. High-flow bypass is recommended if the PComA is poorly compensated or if complete replacement of posterior circulation blood flow is required. Intraoperative DSA is performed for all high-flow bypasses, and proximal occlusion of the parent artery may be performed if intraoperative DSA suggests that flow from the graft vessel can be reversed to the mid- to upper basilar artery. High-flow bypass is performed alone if intraoperative

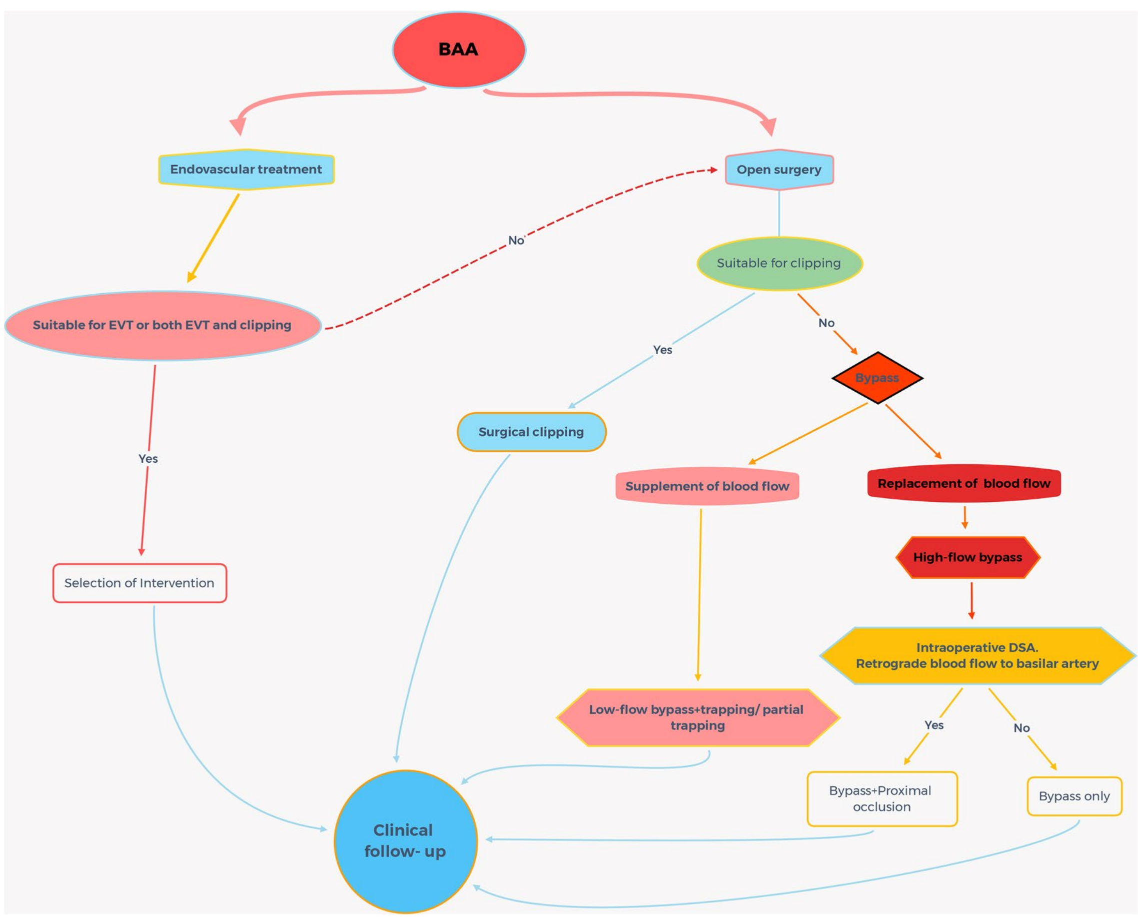

Fig. 5 Surgical algorithm

DSA suggests that flow from the graft vessel is not able to be reversed to the mid- to upper basilar artery. After 1 to 3 months of stable high-flow bypass and good patency, the aneurysm can be treated with interventional therapy or occlusion of the parent artery, which is a safe surgical procedure. The above surgical strategy is based on the surgical experience of our center. The principle of individualized treatment is equally important.

The surgical algorithm for BAAs is shown in the figure. For a detailed description, please refer to the description in the original article. BBAs = basilar artery aneurysms, EVT = endovascular treatment, DSA = digital subtraction angiography.

Limitations of the study

This study was a retrospective single-center study. The number of cases included was small and bias may be present. The results and conclusions obtained in this study are based on the data and experience of our center, and there may be potential limitations to broad applicability and generalization.

Conclusion

Treatment of BAAs is challenging. Surgical clipping may still play an important role in BAAs that are not suitable to intervention. For complex BAAs that are not amenable to intervention and surgical clipping, bypass may be the ideal last resort. Surgical clipping and bypass measures are safe and effective in the treatment of BAAs. Significant reduction or complete obliteration of BAAs contributes to a favorable clinical prognosis. Open surgery still plays an important role in the interventional era. Skilled microsurgical maneuvers and superior vascular neurosurgical techniques are essential for safe surgery.

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Data availability The data and materials supporting this study can be obtained from the corresponding author upon reasonable request.

Declarations

Consent to participate Informed consent was obtained from all individual participants included in the study.

Ethics approval This study was approved and supported by the Research Ethics Review Committee of Tianjin Huanhu Hospital in accordance with the Declaration of Helsinki.

Consent to publish Patients signed informed consent regarding publishing their data and photographs.

Competing interests The authors have no competing interests to declare that are relevant to the content of this article.

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