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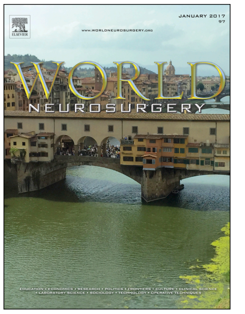

Bypass Surgery for Complex Internal Carotid Artery Aneurysms: 39 Consecutive Patients

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Bypass Surgery for Complex Internal Carotid Artery Aneurysms: 39 Consecutive Patients

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Abstract

Objective

Bypass surgery is a special technique used to treat complex ICA aneurysms. The aim of this retrospective study is to provide a comprehensive description of treatment and outcome of complex ICA aneurysms at different ICA segments (cavernous, supraclinoid, ICA bifurcation) treated with bypass procedures.

Methods

We identified 39 consecutive patients with 41 complex ICA aneurysms that were treated with 44 bypass procedures between 1998 and 2016. We divided the aneurysms into three anatomic subgroups to review our treatment strategy. All the imaging studies and medical records were reviewed for relevant information.

Results

The aneurysm occlusion (n=34, 83%) or flow modification (n=5, 12%) was achieved in 39 aneurysms (95%). The long-term bypass patency rate was 68% (n=30). Minor postoperative ischaemia or hemorrhage was commonly seen (n=20, 51%), but large-scale strokes were rare (n=1, 3%). Preoperative dysfunction of extraocular muscles (CN III, IV and VI) showed low to moderate improvement rates (20-50%). Preoperative vision disturbance (CN II) improved seldom (22%). At the latest follow-up (mean; 51 months) 29 patients (74%) were independent (mRS ≤2).

Conclusions

Bypass surgery for complex ICA aneurysms is a feasible treatment method with an acceptable risk profile. Patients should be informed of the uncertainty related to improvement of pre-treatment cranial nerve dysfunctions.

Key Words

Complex aneurysm, Intracranial aneurysm, Bypass, ELANA, Cranial nerve dysfunction

Introduction

Complex ICA aneurysms are a heterogenous group of challenging lesions, but as the classification has remained subjective, the incidence of these lesions is not exactly known.[1,2] It is estimated that complex ICA aneurysms represent less than 1% of all intracranial aneurysms. Many of these aneurysms are giant (≥25 mm) in size,[3,4] or fusiform in nature. The typical presenting symptoms of these lesions are cranial nerve dysfunctions (CND) or thromboembolic symptoms.[5–8]

The treatment of complex ICA aneurysms has to be tailored on case-by-case basis. Direct obliteration is seldom possible. More complex solutions such as proximal occlusion or trapping and the use of cerebrovascular bypasses are often necessary. Only in the recent years have flow diverters emerged as an endovascular treatment option for these lesions. Despite the technical development in the endovascular field, cerebrovascular bypass procedures still remain an important technique for treating some of the complex aneurysms.[9,10] Bypasses combined with arterial occlusions can also serve as salvage option when all other treatment modalities have failed.[10,11]

The series published on complex ICA aneurysms treated with bypasses are usually small and focus mainly on technical nuances, but a more general analysis of the treatment strategy is often lacking.[6,8,20,12–19] We present a single-center series of 39 consecutive patients with 41 complex or giant ICA aneurysms treated with 44 bypass procedures during 1998 - 2016. The aim of this study is to analyze bypass treatment and outcome for the ICA aneurysms at three separate anatomical segments (cavernous ICA, supraclinoid ICA and ICA bifurcation). In addition to aneurysm obliteration rate, the outcome analysis focuses on occurrence of ischaemic or hemorrhagic lesions and improvement of CNDs.

Methods

Patients and aneurysms

Data were retrieved from the Helsinki Bypass database, which includes all the patients treated with bypass procedures at the Department of Neurosurgery at Helsinki University Hospital (HUS) after 1998. We identified 39 consecutive patients with 41 complex ICA aneurysms treated with 44 bypass procedures between 1998 and 2016.

We divided the ICA aneurysms into three groups for the analysis: (i) cavernous segment ICA (ICAcav), (ii) supraclinoid and pre-bifurcation ICA (ICAsup), and (iii) ICA bifurcation (ICAbif). Treatment strategies and bypass options for each of these three segments differ due to the restrains given by the vascular anatomy.

Radiological data

Digital radiological images were recalled from the hospital's central digital archiving system (PACS; Agfa, Impax), launched in 1998. Imaging data were available for all the patients. Multiple imaging modalities were used in overlapping combinations. All patients had the preoperative digital subtraction angiography (DSA) study. Balloon test occlusion (BTO) was used to assess the arterial collateral blood flow in 25 (64%) cases. Altogether 26 patients (67%) had a preoperative computed tomography angiography (CTA) scan and 35 patients (90%) had a magnetic resonance imaging (MRI) scan. Additional CT perfusion or MRI perfusion studies were done in eight cases (21%). In all of the 41 aneurysms, the different imaging combinations ultimately led to a conclusion that a bypass procedure was indicated to treat the aneurysms.

Radiological assessment

The ICA aneurysms and their respective segments were identified from the radiological studies. Saccular aneurysms were measured for their largest diameter and fusiform aneurysms for the length of the affected artery segment. Arteries branching from the aneurysm wall, intraluminal thrombosis and wall calcifications were noted. The treatment strategy, its execution, patency of the bypass and aneurysm occlusion were reviewed from the patient records and the imaging studies.

Patient characteristics

During the 19 years, 39 patients with 41 ICA aneurysms were treated with 44 bypass procedures including three redo surgeries. Most patients were Finnish (n = 35, 90%) and 21 patients (54%) were female. The mean patient age at the time of surgery was 50 years. The baseline characteristics of the study population are presented in **Table 1**.

A majority of the patients were preoperatively independent (modified Rankin Scale [mRS] score ≤2; n=31, 79%). Two-thirds of the patients (n=26; 67%) had symptoms of mass effect as the main presenting symptom (i.e. cranial nerve dysfunction [CND]). About two-thirds of the aneurysms were giant (>25 mm) in size (n=26, 63%). Two patients had bilateral ICA aneurysms. Ten patients (26%) had previous history of treatment for their ICA aneurysm.

Use of bypass in aneurysms

Between 1998-2016, a total of 255 intracranial bypass operations were performed at our department. Almost half of these surgeries (n=124, 49%) were done for aneurysms. Complex ICA aneurysms represented 16% of the total case volume (n=41). The bypass technique evolved over the study period, which also affected our treatment decisions. Of the 255 bypasses, 224 (88%) were done using conventional techniques and 31 (12%) with the Excimer Laser-Assisted Non-occlusive Anastomosis (ELANA) technique. The ELANA technique was used during the years 2003-2010. The main reason for abandoning the ELANA technique later on was its complexity and unpredictability, while at the same time we had become more proficient and technically capable with the conventional bypasses. The graft and recipient selection in ICA bypass surgeries varied based on the technique used.

Outcome

The patency of the bypass and the obliteration of the target aneurysm were evaluated from the postoperative images. We were also interested in the postoperative ischaemic and hemorrhagic complications and later improvement of CNDs. The outcome was defined using the modified Rankin Scale (mRS) as good (≤2) and as poor (3-5); scores were assessed at discharge and at the latest follow-up visit.

Statistical methods

Commercial statistical software (IBM SPSS Statistics, version 25.0.0) was used to manage the data. The tools used were for descriptive and statistical analysis.

The Helsinki Cerebral Bypass database has the approval of the Ethics Committee of the Helsinki University Hospital (HUS).

Results

Treatment

Cavernous ICA aneurysms

There were 22 patients with 23 cavernous ICA (ICAcav) aneurysms including one patient with bilateral mirror aneurysms [**Figure 1; Figure 2A**]. Pre-treatment CNDs were seen in 20 patients (86%). One aneurysm was considered as acutely ruptured [epistaxes; no. 8]. The mean aneurysm size was 26 mm (range 12-37 mm). Characteristics of these cases are presented in **Table 2**.

The 22 patients underwent 25 bypass procedures (one bilateral case, two redo surgeries). The most frequent aneurysm treatment strategy was an EC-IC bypass followed by peroperative, proximal parent artery occlusion (PAO; n=20, 87%). Of the 23 aneurysms, 14 (61%) were treated with the ELANA technique.

During the early postoperative period (≤7 days), eight patients (36%) developed radiologic ischaemic lesions in varying combinations. Six of them (27%) were symptomatic. Small contusions due to retraction or manipulation around the anastomosis were seen in five cases (23%). On angiography, early bypass occlusion was detected in eight cases (32%; one redo) of which six cases were concurrent with ischaemic lesions. Only one bypass occlusion led to an extensive hemispheric infarct and resulted in a fatality [no. 18].

The latest angiography showed a total occlusion of 21 aneurysms (91%). Late occlusion of the bypass was seen in four patients (18%) without complications.

Supraclinoid ICA aneurysms

Supraclinoid ICA (ICAsup) aneurysm was treated in 12 patients. Of the branching arteries, the Pcom most frequently originated from the aneurysm dome (n=5) [**Figure 1; Figure**

2B]. Two-thirds of these patients (n=8, 66%) presented with CNDs. The mean aneurysm size was 26 mm (range 2-79 mm). Characteristics of these cases are presented in **Table 3**.

The 12 patients underwent 13 bypass procedures (one redo surgery). The most frequent aneurysm treatment strategy was an EC-IC bypass followed by peroperative proximal PAO (n=7, 58%). In two cases the aneurysm had been previously treated elsewhere only with proximal ICA occlusion, and the remaining retrograde filling through the Pcom was then occluded by endovascular means [no. 23 and 26]. In one case, the bypass served only as a protective bypass during the successful direct clipping of the aneurysm [no. 31]. Of the 12 aneurysms, only two (17%) were treated with the ELANA technique.

During the early postoperative period (≤7 days), half of the patients (n=6) developed new radiologic ischaemic lesions, of which four (33%) were symptomatic. Small contusions due to manipulation were seen in two cases (17%). On angiography, all but one intraoperatively occluded bypass were patent (92%).

The latest angiography showed total obliteration of ten aneurysms (83%). One foreign patient had follow-up elsewhere [no. 25]. The bypass had silently occluded in one case at the latest follow-up with no clinical consequences [no. 32].

ICA-bifurcation aneurysms

There were five patients with six ICA aneurysms affecting the ICA bifurcation (ICAbif) region including one patient with bilateral mirror aneurysms. In all of these aneurysms, the proximal M1 and A1 branches originated from the aneurysm dome [**Figure 1; Figure 2C**]. Aneurysm mass effect caused CNDs in three cases (60%). All of the aneurysms were giant (≥25 mm) with the mean diameter of 40 mm (range 25-70 mm). Characteristics of these cases are presented in **Table 4**.

The five patients underwent six bypass procedures (one bilateral case). The conventional EC-IC bypasses were followed by various strategies to treat the aneurysm (trapping, n=2;

clip reconstruction, n=1; proximal occlusion, n=1; Crutchfield apparatuses for bilateral aneurysms).

During the early postoperative period (≤7 days), three patients (50%) developed symptomatic perforator ischaemia. Additionally, in one of these three cases, the proximal ICA balloon occlusion induced thrombosis of the Pcom proximal to the aneurysm, and subsequent ischaemia mainly in the posterior cerebral artery (PCA) region [no. 38]. None of the patients had manipulation-related contusions. All the bypasses were patent on angiograms.

At the latest follow-up, the treated aneurysm was occluded in three cases (50%). Small remaining aneurysmatic pouches were seen in the case of remodeled aneurysm [no. 35]. In the case of bilateral aneurysms, one Crutchfield apparatus was left partly open as a protective measure [no. 39]. The long-term bypass status remained the same.

Ischaemic complications

New postoperative radiologic ischaemic lesions were seen in 17 patients (43%), of which 13 patients (33%) were symptomatic. The frequencies of these complications were higher in the intradural subgroups (ICAcav [n=8, 36%]; ICAsup [n=6, 50%]; ICAbif [n=3, 50%]). The ratio of perforator and main trunk ischaemia varied according to aneurysm location (ICAcav, 3:6; ICAsup, 3:4; ICAbif, 3:1). The most common specific location for ischaemic lesions was the capsular region (n=8). Only six cases (15%) had concurrently deep and superficial ischaemia, and three cases (8%) had concurrent contusions.

The bypass was thrombosed in most of the ICAcav aneurysm cases with postoperative ischaemia (n=6, 75%). However, in most of these patients (n=5) the ischaemic lesions were limited. There was only one patient with full hemispheric infarct. Unlike in the ICAcav cases, the bypass was patent in all of the ICAsup and ICAbif patients with postoperative ischaemic findings.

Antiplatelet medication (acetylsalicylic acid [ASA]; 100 mg daily) was used in 36 patients (92%) postoperatively. All of the patients with new ischaemic complications were on antiplatelet therapy, and postoperative low-molecular-weight heparin (LMWH) was used in combination with ASA in eight cases (47%). This combined medication was used also in four of the occluded ICAcav bypass cases (50%).

Hemorrhagic complications

Post-operative extra-axial hemorrhage requiring surgical removal was seen in three cases (7%); epidural (n=2) or subdural (n=1). All three patients had different regimes for perioperative use of antithrombotics [no. 15, 18 and 27]. Manipulation-, or retraction-related contusions were seen in seven patients (18%). The contusions alone caused the postoperative symptoms in two cases, concurrently with ischaemia in three cases, and two other cases had only radiologic findings. All the contusions were associated with deeper anastomosis sites, and often with the ELANA technique (n=6, 86%). Peroperative heparin use had some overrepresentation in cases with contusions (n=4, 57%) when compared to the other cases of the series (n=6, 18%). There were no intraparenchymal or subarachnoid hemorrhages requiring intervention.

Cranial nerve dysfunctions

A total of 29 patients (74%) had dysfunction of at least one cranial nerve as a presenting symptom. Most common was the CN VI dysfunction (n=15, 38%). Combined preoperative CNDs were associated only with the ICAcav aneurysms (n=6, 15%). Additionally, nine patients (23%; two cases preoperatively asymptomatic) developed a new postoperative CND, which was most frequently CN III weakness (n=6, 67%). During follow-up, eight patients (26 %; including two cases of only postoperative CND) had full and seven patients (23%) had partial improvement of their CNDs. More specifically, CN IV-VI functions improved most frequently among the presenting symptoms (correspondingly 1/2, 2/5 and 6/15; 40-50%) and CN III function among the complications (5/6; 83%). On the other hand, preoperative visual disturbance (CN II) or CN III dysfunction showed improvement only infrequently (correspondingly 2/9 and 2/10; 22-25%). Strabismus surgery corrected two additional cases of CN VI weakness (13%).

Clinical outcome

The mean follow-up time was 51 months (median 29; range 0 – 201; 0 being for three foreign patients and for two cases of death [one case fatality; one death was intoxication not related to aneurysm disease or treatment]). At discharge, 17 patients (44%) had worse mRS score than preoperatively, and of these, 11 patients (28%) dropped from good (≤2) to poor (≥3) mRS score group. However, between discharge and the latest follow-up, 20 patients (51%) improved on the mRS scale while the scores of 9 patients (23%) rose from poor to good mRS score group mostly balancing the initial drop [**Figure 3**]. Of the patients with poor preoperative score (n=8, 21%), only two patients (5%) recovered into good score group. The mRS score distribution at the latest follow-up was as follows; ≤2 (n=29, 74%), 3-5 (n=9, 23%), and 6 (n=1, 3% case fatality rate). Expectedly, all four patients (10%) who deteriorated permanently into the poor mRS score group were cases with postoperative ischaemic lesions or contusions. The case scores of different subgroups on modified Ranking Scale (mRS) are presented in **Table 5**.

Discussion

Bypass procedures are an acknowledged strategy to treat complex intracranial aneurysms.[9,21,22] Fewer studies have focused only on complex ICA aneurysms.[8,12,13,16,20,23] It is difficult to obtain large series of complex ICA aneurysms due to their rarity and heterogenous nature. In our series, emphasis was on different segmental subgroups (ICAcav; ICAsup; ICAbif) and their relation to treatment strategy.

Aneurysm occlusion strategy

Aneurysm occlusion rates of 91-100% have been reported previously for complex ICA aneurysms treated with bypass procedures, but variable patient selection or study focus (specific treatment method, combination of aneurysm locations, or the symptoms and related improvement) makes comparison between the series difficult.[6,8,9,13,20,21] In our series, the latest angiography showed that 83% of aneurysms were occluded (one case was lost to follow-up elsewhere). However, the goal of flow reversal or flow modification was achieved in 95%.

For ICAcav aneurysms the obliteration strategy with PAO alone is straightforward as no major outflow branches or terminal arteries originate from this segment. Aneurysm occlusion rates of up to 100% have been reported for endovascular PAO without any revascularization.[24,25] In our series, ICAcav aneurysm occlusion rate of 91% (n=21) was ultimately achieved. We did the PAO immediately after intraoperative confirmation of the bypass patency, and often chose endovascular PAO if the STA was used as donor artery.

For ICAsup aneurysms, there is more uncertainty in achieving aneurysm occlusion with simple proximal PAO as the branching arteries (OphtA, Pcom) may retrogradely fill the aneurysm, or even one another [**Figure 1**]. We generally choose to keep these branching arteries intact to avoid ischaemic complications. If Pcom occlusion is needed, exact surgical clip ligation rather than endovascular occlusion of a longer artery segment is probably safer strategy to keep perforators intact. Small superior hypophyseal artery (SHA) divisions are relatively safe to sacrifice in a unilateral procedure,[26] and have no major role in our occlusion strategy planning. Distally, perfusion of the AChA has to be maintained if trapping is planned. We achieved an aneurysm occlusion rate of 83% (n=10) in ICAsup aneurysms of which the majority were treated with PAO (n=6). Due to flow pattern disruption, the postoperative, intra-aneurysmal residual flow seemed to be weak enough to ultimately lead to total thrombosis in most cases.

Complex ICAbif aneurysms turned out to be the most heterogenous group in our series. For these aneurysms no general rule of occlusion strategy can be given. For proximal occlusion, one has to consider the same principles as with ICAsup aneurysms. It is essential to protect the AChA and lenticulostriatal perforators, which may be embedded in the aneurysm. Concerning the aneurysm outflows at main trunks, perfusion through the Acom may allow the occlusion of the ipsilateral A1, but the origin of artery of Heubner should be protected. Intraluminal aneurysm thrombosis may change the regional flow circumstances and lead to substantial perfusion through external carotid artery (ECA) collaterals. In our series, the aneurysm trapping was possible in two cases. If trapping is not possible, PAO and flow reversal may be a sufficient strategy to trigger aneurysm thrombosis, or change the flow patterns into a more benign one. In aneurysms having multiple outflow branches along the intradural ICA, remodeling and compartmentalization of perfusion with the help of revascularization is a demanding strategy, and it highly depends on the aneurysm morphology. Flow disruption, rather than aneurysm isolation, is often an adequate treatment goal in bilateral ICAbif aneurysms, and is a tradeoff to avoid surgical complications. Disruption may be achieved with partial aneurysm occlusion, or with aneurysm inflow reduction. We do not routinely use electrophysiologic neuromonitoring, but even awake procedures[27] may give extra control for the outcome when dealing with the most critical lesions.

Bypass patency

The cumulative bypass patency rate at the latest follow-up was 68% (n=30). This is relatively low when compared to previous studies showing patency rates from 73-77% (saphenous vein graft [SVG], ELANA) up to 98% (arterial pedicle).[8,9,13,21,28–31] However, clinically relevant strokes were rare in our series.

As observed previously by others[28,29], majority of the bypass occlusions (n=9, 64%; all SVGs) occurred during the first postoperative week. Only some (n=6, 43%) of the early bypass occlusions resulted in ischaemic complications. This would indicate that despite the negative preoperative BTO, there must have been substantial collateral flow.

The long-term patency rate has been reported to be up to 99% for arterial pedicles and SVGs.[28] In our series, four bypasses (9%; SVGs) occluded as collateral perfusion had developed and bypass flow became unnecessary. Categorically, long-term bypass occlusions do not usually result in new ischaemic complications.[29,31]

Ischaemic complications

One-third (n=13) of the patients in our series had symptomatic ischaemic complications. The higher occurrence rate of ischaemic complications with intradural aneurysm cases (50%) when compared to ICAcav subgroup (37%) was likely related to the presence of branching arteries. In previous reports, the rate of ischaemic complications were reported between 0-13%, but patient selection and reporting vary.[6,8,13,20] Only one full hemispheric infarction was diagnosed after early bypass occlusion. In all other cases, the lesions were more limited regardless of the bypass status, and were mostly thromboembolic or local watershed-type of infarctions.

Ischaemic lesions do not automatically mean poor prognosis. In our series, six symptomatic patients (46%) did not show functional decline during long-term follow-up. Only four out of the 13 patients (30%) with ischaemic lesions ended up with poor mRS score.

Hemorrhagic complications

Extra-axial hemorrhagic complications requiring surgical removal were diagnosed only infrequently (n=3, 7%) as seen in previous studies (4-10%)[8,9,13]. We did see small contusions/hemorrhagic complications in seven patients (18%). These were associated with the ELANA technique, which required longer surgery, static retraction[32] and frequent heparinization. Currently, we prefer conventional bypass techniques with more superficial anastomoses which require less brain retraction and manipulation. At present, we use heparinized solution only locally for graft and recipient irrigation.

Cranial nerve dysfunctions

There are only a few reports focusing on CND improvement in patients treated with bypass surgery for ICA aneurysms. In our series, the preoperative vision deficits or ophthalmoplegia were common presenting symptoms (n=29, 74%) and only 45% of these patients (n=13) experienced improvement. Motor nerves of the extraocular muscles (CN III, IV and VI) showed low to moderate improvement rates during the follow-up (20-50%), whereas vision disturbance (CN II) improved only seldom (22%). Several other studies have reported improvement rates of 30-85%.[6,8,13]

Outcome

When treating complex aneurysms with bypass procedures, the rate of good functional outcome has been reported to vary between 79-100%.[8,9,13,21] We saw good functional outcome (mRS $\leq$2) in 74% of our patients at the latest follow-up (mean of four years).

Patient selection strongly affects these results so direct comparison between the different series is not possible. Many patients experience postoperative functional decline, but most of them seem to recover to their initial functional status later on. Patients with poor preoperative mRS score are unlikely to achieve independency again, which affects the overall outcome. Major ischaemic complications carry the highest risk for functional decline, but at least in our series these were infrequent. The case fatality rate in our series was 3% (n=1) which is similar to some previous reports (0-8%)[9,13,21].

Future role of bypass in ICA aneurysms

Flow diverters have lately changed the treatment of complex ICA aneurysms, especially for the cavernous segment. It has been estimated that up to 90% of the ICA aneurysms are treatable with flow diverters.[33] However, the likelihood of aneurysm occlusion is reported to be lower in cases of higher complexity and distal location.[34,35] Thromboembolic events[36] or ruptures are known complications of flow diverters, and these may occur also late after the treatment. The need for dual antiplatelet therapy makes flow diverters difficult to combine with bypass surgery, and special devices for endovascular ICA bifurcation reconstruction are currently lacking. In our practice, during the last five years, we have nearly stopped bypass surgery for ICAcav aneurysms. For the more distal segments, bypass still remains as one of the treatment options. Revascularization offers an extra dimension of flexibility to attack the target aneurysm in cases where flow diverters are considered unsuitable, or they fail. At present, flow diversion and conventional, more superficial bypasses cover our need when treating complex ICA aneurysms.

Conclusions

Bypass surgery of complex ICA aneurysms is a feasible treatment method. The treatment strategy depends on the segmental location of the aneurysm. Major complications leading to long-term functional decline are rare. Preoperative cranial nerve dysfunctions recover only in a minority of the patients. Lately, flow diverters have taken over in many complex ICA aneurysms, but there is still need for bypasses in some special cases. The art of bypass treatment should be maintained in dedicated neurovascular centers.

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Figure legends

Figure 1. Illustration of the three aneurysm subgroups (n). ACA = anterior cerebral artery; AChA = anterior choroidal artery; ACP = anterior clinoid process; ICAbif = bifurcation of internal carotid artery; ICAcav = cavernous segment of internal carotid artery; ICAsup = supraclinoid segment of internal carotid artery; MCAbif = bifurcation of middle cerebral artery; OphtA = ophthalmic artery; Pcom = posterior communicating artery.

Figure 2. A: Preoperative antero-posterior DSA image of ICAcav aneurysm [case no. 5] B: Preoperative antero-posterior DSA image of previously treated ICAsup aneurysm [case no. 28] C: Preoperative antero-posterior 3D-CTA image of ICAbif aneurysm [case no. 36]. A1 = A1 segment of anterior cerebral artery; ICAbif = bifurcation of internal carotid artery; M1 = M1 segment of middle cerebral artery; Pcom = posterior communicating artery.

Figure 3. Distribution of the modified Rankin Scale score among the 39 patients.

Table 1 Characteristics of the patients (n).

		n (%)
No. of patients	39	
No. of treated aneurysms	41	
Sex	Female	21 (54%)
	Male	18 (46%)
Age at surgery [yrs]; mean (range)	50 (range 18-74)	
Preoperative modified Rankin Scale score	0 – 2; independent	31 (79%)
	3 – 5; dependent	8 (21%)
Main presenting symptom	Mass effect (e.g. CND)	26 (67%)
	Incidental / co-incidental	5 (13%)
	Ischaemia	3 (8%)
	Headache	2 (5%)
	Previous SAH	2 (5%)
	Epistaxis (ruptured aneurysm)	1 (3%)
Aneurysm	ICA cavernous	23 / 41 (56%)
	ICA supraclinoid	12 / 41 (29%)
	ICA bifurcation	6 / 41 (15%)
	Giant aneurysm (≥ 25 mm)	26 / 41 (63%)
	Multiple aneurysms	12 / 39 (31%)
	→ Bilateral ICA aneurysms	2 / 39 (5%)
Previous treatment	For the ICA aneurysm	10 / 39 (26%)
	For other aneurysm	3 / 39 (8%)

CND = cranial nerve dysfunction; SAH = subarachnoid hemorrhage.

Table 2 ICAcav aneurysms treated with bypass surgery.

No	Gender; age	Preop. / late mRS	CND	Side; size (mm); morphology	Calcif. / thromb.	Multiple aneurysms	Previous treatment	Bypass type	Anastomosis	Obliteration	Aneurysm filling postop. / late	Bypass occluded	Postop. radiologic ischaemia / contusions
1	M; 42	1/1	III, V, VI	Left; 32; f	- / -	+	Other	STA – MCA distal	Conv.	Prox./endo.	-	-	-
2	F; 45	1/1	II, III, V	Left; 17; s	- / +	+	+ / Other	ECA – SVG – ICAbif	ELANA	Proximal	Slight / -	-	- / +
3	F; 39	1/0	VI	Left; 23; s	- / -	+	-	ECA – SVG – ICAid	ELANA	Proximal	Slight / -	< 7 days	+ / -
4	M; 18 bilateral	3/3	VI	Left; 27; f	+ / +	+	-	ECA – SVG – ICAid	ELANA	Proximal	-	-	-
				Right; 37; f	+ / +			ECA – SVG – ICAid	ELANA	Proximal	Slight / Slight	-	-
5 *	F; 72 reoperation	1/2	III-VI	Left; 30; s	+ / -	-	-	STA – MCA distal	Conv.	Proximal	+ / -	Intraop.	-
								STA – SVG – M2	Conv.	+ Distal		< 7 days	+ / -
6	M; 64 reoperation	2/2	II, III, VI	Right; 25; s	+ / +	-	-	STA – MCA distal, x2	Conv.	Distal	+ / -	-	-
								STA – SVG – M2	Conv.	+ Proximal		-	-
7	F; 70	1/0	-	Right; 32; s	+ / +	+	-	STA – MCA distal, x2	Conv.	Prox./endo.	-	-	-
8	M; 57	1/5	-	Right; 30; traum.	- / +	-	+	ECA – SVG – ICAid	ELANA	Proximal	-	Follow-up	- / +
9	F; 45	1/1	VI	Left; 32; s	- / -	-	-	ECA – SVG – ICAid	ELANA	Proximal	-	Follow-up	-
10	F; 56	1/1	VI	Right; 28; s	- / +	-	-	ECA – SVG – ICAbif	ELANA	Proximal	-	< 7 days	+ / -
11	M; 51	1/1	III, IV, VI	Left; 22; s	- / +	-	-	ECA – SVG – ICAid	ELANA	Proximal	-	-	-
12	F; 55	1/0	-	Right; 23; f	- / -	-	-	STA – M2	Conv.	Prox./endo.	Slight / -	-	-
13	F; 44	1/0	III	Right; 25; s	- / +	-	+	CCA – SVG – MCA distal	Conv.	Prox./endo.	-	Follow-up	-
14	F; 53	1/1	VI	Left; 16; s	+ / +	-	-	ECA – SVG – ICAid	ELANA	Trapping	-	-	- / +
15	F; 46	1/1	VI	Right; 28; s	- / -	-	-	ECA – SVG – ICAid	ELANA	Proximal	-	-	+ / -
16	F; 65	1/0	VI	Left; 35; s	- / -	-	-	STA – MCA distal	Conv.	Prox./endo.	-	-	+ / -
17	M; 54	1/1	VI	Left; 17; s	- / -	-	-	ECA – SVG – ICAbif	ELANA	Proximal	-	< 7 days	+ / +
18	M; 71	1/6	II	Left; 23; s	- / +	-	-	ECA – SVG – ICAbif	ELANA	Prox. + endo.	Slight / -	< 7 days	+ / -
19	M; 24	1/0	VI	Right; 32; s	+ / +	-	-	STA – MCA distal	Conv.	Distal	-	-	-
20	F; 62	3/3	V, VI	Right; 25; s	+ / -	-	+	ECA – SVG – MCA distal	Conv.	Crutchfield	+ / +	< 7 days	-
21	F; 59	1/2	III	Right; 16; s	- / +	+	-	ECA – SVG – ICAid	ELANA	Proximal	Slight / -	< 7 days	+ / +
22	F; 58	1/1	III	Right; 16; s	- / +	+	-	ECA – SVG – ICAid	ELANA	Proximal	-	Follow-up	-

*Later endovascular proximal occlusion obliterated the aneurysm. CND = cranial nerve dysfunction; ELANA = Excimer Laser-Assisted Non-occlusive Anastomosis; endo. = endovascular occlusion; f = fusiform; ICAbif = bifurcation of internal carotid artery; ICAid = intradural internal carotid artery; mRS = modified Ranking Scale; s = saccular; STA = superficial temporal artery; SVG = saphenous vein graft; traum. = traumatic.

Table 3 ICAsup aneurysms treated with bypass surgery.

	Gender; age	Preop. / late mRS	CND	Side; size (mm); morphology	Calcif. / thromb.	Multiple aneurysms	Previous treatment	Bypass type	Anastomosis	Obliteration	Aneurysm filling postop. / late	Bypass occluded	Postop. radiologic ischaemia / contusions
23 *	F; 68	2/3	II	Left; 32; f	+ / +	-	+	STA – MCA distal	Conv.	Pcom/endo.	Slight / -	-	+ / -
24	M; 56	5/5	III	Left; 79; s	+ / +	+	-	STA – MCA distal	Conv.	Proximal	Slight / -	-	-
25 †	M; 55	0/1	-	Right; 9; f	- / -	-	-	ECA – SVG – M2	Conv.	Prox./endo.	Slight / Foreign	-	+ / -
26 *	F; 61	1/2	III	Left; 25; f	+ / +	+	+	STA – MCA distal	Conv.	Pcom/endo.	-	-	+ / -
27	F; 47	4/3	-	Right; 15; s	- / -	+	Other	ECA – SVG – M1	ELANA	Proximal	Slight / -	-	- / +
28	M; 74	4/4	-	Left; 30; s	+ / +	+	+ / Other	STA – SVG – M2	Conv.	Proximal	Slight / -	-	-
29	F; 30	0/0	-	Right; 17; f	- / -	-	-	STA – MCA distal	Conv.	Prox./endo.	Slight / Slight	-	-
30	F; 52	1/1	V	Left; 40; s	+ / -	-	-	ECA – SVG – M2	Conv.	Trapping	-	-	+ / +
31	F; 29	1/1	II	Left; 19; s	- / -	-	-	STA – M2	Conv.	Clipping	-	-	+ / -
32	M; 25 reoperation	1/1	II	Left; 18; f	- / -	-	+	thyroid A – SVG – M2	ELANA	None	+ / -	Intraop.	-
								ECA – SVG – M2	Conv.	Proximal		Follow-up	-
33	M; 24	1/2	VI	Left; 30; f	+ / +	-	-	ECA – SVG – MCA distal	Conv.	Proximal	Slight / -	-	+ / -
34	M; 53	5/2	-	Left; 2; s	- / -	-	+	STA – MCA distal	Conv.	Prox./endo.	-	-	-

*Remaining retrograde filling through the Pcom was occluded with endovascular means. †The ELANA arteriotomy failed and bypass was converted to a conventional type. CND = cranial nerve dysfunction; endo. = endovascular occlusion; f = fusiform; mRS = modified Ranking Scale; s = saccular; STA = superficial temporal artery; SVG = saphenous vein graft.
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Table 4 ICAbif aneurysms treated with bypass surgery.

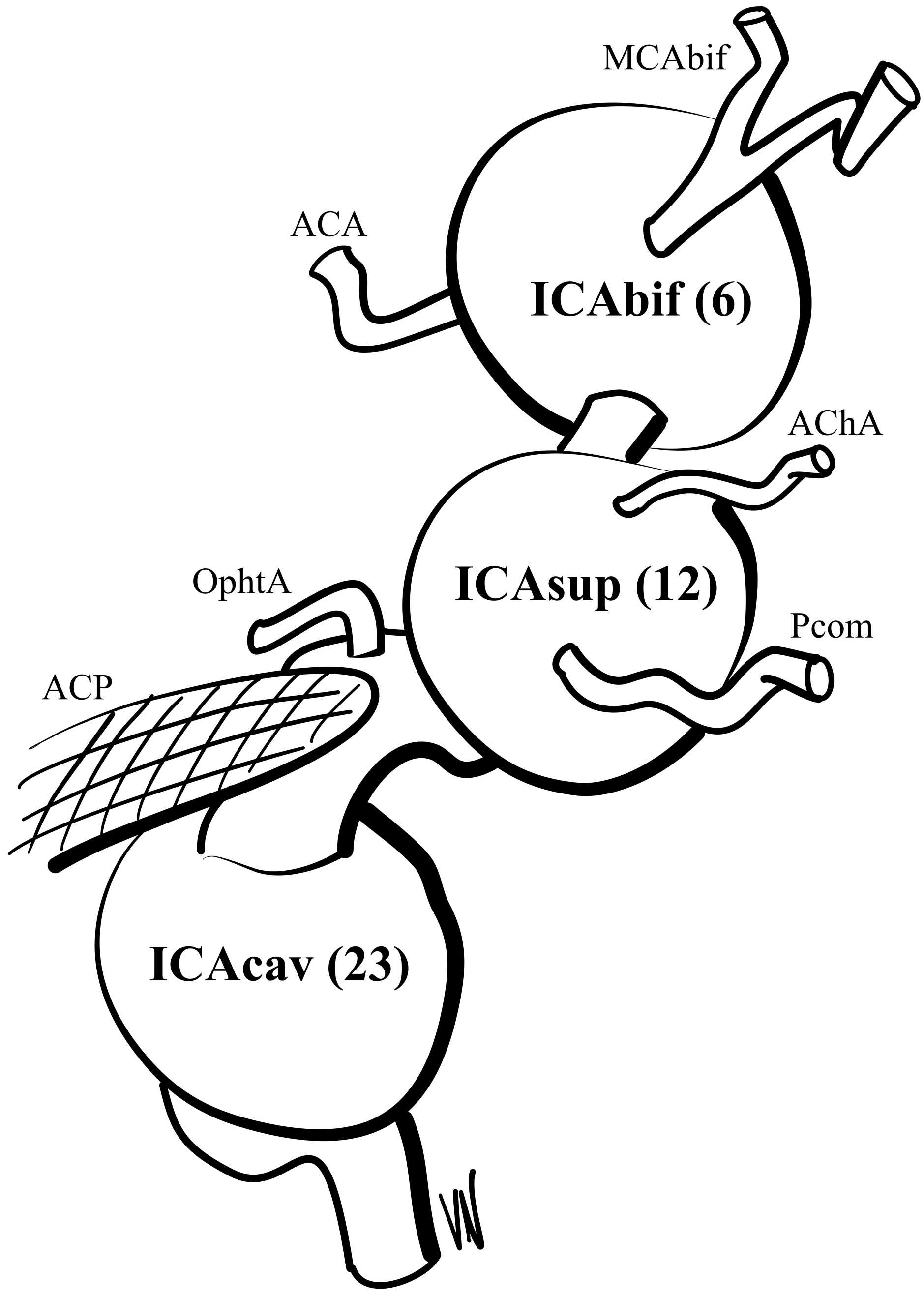
	Gender; age	Preop. / late mRS	CND	Side; size (mm); morphology	Calcif. / thromb.	Multiple aneurysms	Previous treatment	Bypass type	Anastomosis	Obliteration	Aneurysm filling postop. / late	Bypass occluded	Postop. radiologic ischaemia / contusions
35 *	F; 65	1/1	II	Right; 38; f	- / -	-	-	ECA – RAG – M2; STA – M3	Conv.	Remodeling	Small residual	-	+ / -
36	M; 18	3/3	-	Right; 25; f	- / -	-	-	STA – MCA distal, x2	Conv.	Trapping	-	-	+ / -
37	M; 14	4/2	-	Right; 70; s	+ / +	-	-	STA – MCA distal, x2	Conv.	Trapping	-	-	-
38 †	F; 57	1/4	II	Left; 50; s	+ / +	-	+	STA – MCA distal	Conv.	Proximal	-	-	+ / -
39 ‡	M; 50 bilateral	1/2	II	Right; 30; f	+ / +	+	-	ECA – SVG – MCA distal	Conv.	Crutchfield	Slight / Slight	-	-
				Left; 30; f	+ / +			STA – SVG – MCA distal	Conv.	Crutchfield	+ / +	-	-

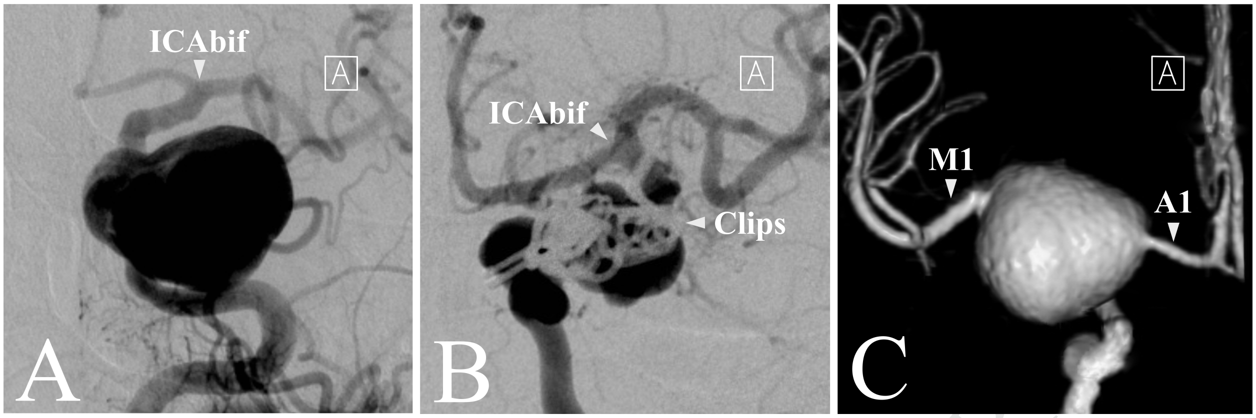
*Aneurysm was remodeled with clips and the bypasses provided perfusion to isolated ACA and MCA regions. †Previous unsuccessful treatment with a middle meningeal artery – MCA -bypass in another department. ‡The left-sided Crutchfield apparatus was purposefully left slightly open to allow diminished arterial flow to the aneurysm and periphery. CND = cranial nerve dysfunction; f = fusiform; mRS = modified Ranking Scale; RAG = radial artery graft; s = saccular; STA = superficial temporal artery; SVG = saphenous vein graft.

Table 5 The outcome scores on the modified Rankin Scale (n).

	mRS score	
	0-2	**3-5 (6)**
ICAcav (22)		
Preoperative	20	2
Latest	18	3 (1)
ICAsup (12)		
Preoperative	8	4
Latest	8	4
ICAbif (5)		
Preoperative	3	2
Latest	3	2
ICA aneurysm treated before (10)		
Preoperative	7	3
Latest	6	4
Postoperative ischaemia or contusions (21)		
Preoperative	19	2
Latest	15	5 (1)
Multiple aneurysms (12)		
Preoperative	8	4
Latest	8	4
Giant aneurysms (24)		
Preoperative	18	6
Latest	16	8

ICAbif = bifurcation of internal carotid artery; ICAcav = cavernous segment of internal carotid artery; ICAsup = supraclinoid segment of internal carotid artery.


MCAbif
ACA
ICAbif (6)
AChA
OphtA
ICAsup (12)
Pcom
ACP
ICAcav (23)


ICAbif
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ICAbif
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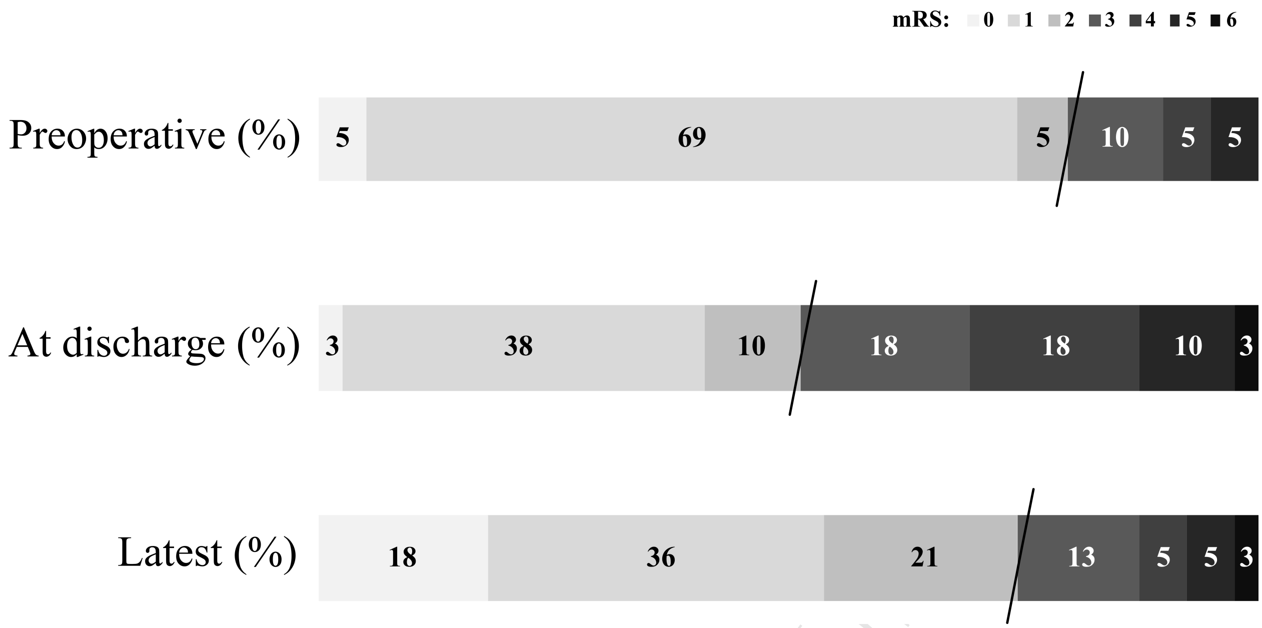
M1
A1
C


mRS: 0 1 2 3 4 5 6
Preoperative (%)
5
69
5
10
5
5
At discharge (%)
3
38
10
18
18
10
3
Latest (%)
18
36
21
13
5
5
3

Abbreviations

A1, A1 segment of anterior cerebral artery; ACA, anterior cerebral artery; AChA, anterior choroidal artery; Acom, anterior communicating artery; ASA, asetylsalicylic acid; BTO, balloon test occlusion; CN, cranial nerve; CND, cranial nerve dysfunction; CT, computed tomography; CTA, computed tomography angiography; DSA, digital subtraction angiography; ECA, external carotid artery; EC-IC, extracranial-intracranial; ELANA, Excimer Laser-Assisted Non-occlusive Anastomosis; HUS, Helsinki University Hospital; ICA, internal carotid artery; ICAbif, bifurcation of internal carotid artery; ICAcav, cavernous segment of internal carotid artery; ICAsup, supraclinoid segment of internal carotid artery; LMWH, low-molecular-weight heparin; M1, M1 segment of middle cerebral artery; MCA, middle cerebral artery; MRI, magnetic resonance imaging; mRS, modified Rankin Scale; OphtA, ophthalmic artery; PACS, Picture Archiving and Communicating System; PAO, parent artery occlusion; PCA, posterior cerebral artery; Pcom, posterior communicating artery; RAG, radial artery graft; SAH, subarachnoid hemorrhage; SHA, superior hypophyseal artery; SVG, saphenous vein graft.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: