Original research

Combined standard bypass and parent artery occlusion for management of giant and complex internal carotid artery aneurysms

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ABSTRACT

Background Complex aneurysms do not have a standard protocol for treatment. In this study, we investigate the safety and efficacy of microsurgical revascularization combined with parent artery occlusion (PAO) in giant and complex internal carotid artery (ICA) aneurysms.

Methods Between 1998 and 2017, 41 patients with 47 giant and complex ICA aneurysms were treated by an a priori planned combined treatment strategy. Clinical and radiological outcomes were stratified according to mRS and Raymond classification. Bypass patency was assessed. Median follow-up time was 3.9 years.

Results After successful STA–MCA bypass, staged endovascular (n=37) or surgical (n=1) PAO was executed in 38 patients following a negative balloon occlusion test. Intolerance to PAO led to stent/coil treatments in two patients. Perioperative bypass patency was confirmed in 100% of completed STA–MCA bypass procedures. Long-term overall bypass patency rate was 99%. Raymond 1 occlusion and good outcome were achieved in 95% and 97% (mRS 0–2) of cases, respectively. No procedure-related mortality was encountered. Eighty-four percent of patients with preoperative cranial nerve compression syndromes improved during follow-up.

Conclusions The combined approach of STA-MCA bypass surgery followed by parent artery occlusion achieves high aneurysm occlusion and low morbidity rates in the management of giant and complex ICA aneurysms. This combined indirect approach represents a viable alternative to flow diversion in patients with cranial nerve compression syndromes or matricidal aneurysms, and may serve as a backup strategy in cases of peri-interventional complications or lack of suitable endovascular access.

INTRODUCTION

The grave natural history of giant and complex aneurysms, with reported 5-year rupture rates of up to 50%, necessitates an effective form of therapy.[1] Microsurgical clipping as the gold standard allows preservation of the parent artery. However, feasibility of this therapy depends on aneurysm location and factors such as wall calcification, intraluminal thrombus, and involvement of important vessels. Combined surgical morbidity and mortality for complex aneurysms are not negligible and may range from 10% to 45%.[1–3]

Hunterian ligation had been introduced as an alternative treatment for otherwise unclippable aneurysms. In selected cases, this technique was supported by microsurgical revascularization to protect the depending vascular territory from ischemia.[2–6] With the refinement of endovascular therapy (EVT), combining both methods was regarded as a logical progression, especially by endovascular and hybrid neurosurgeons.[5–10] A growing body of evidence supports their preferential use of high-flow grafts.[2 11] Few centers only opt to proceed with the "low-flow" bypass technique prior to parent artery occlusion (PAO).[12]

We reviewed our experience with standard superficial temporal artery–middle cerebral artery (STA–MCA) revascularization combined with predominantly endovascular PAO in the management of complex internal carotid artery (ICA) aneurysms. To the best of our knowledge, this series represents one of the largest cohort of patients treated in such a way to date.

PATIENTS AND METHODS

Study cohort

Between 1998 and 2017, 2779 aneurysms were treated at our neurosurgical department. Medical records and imaging data were retrospectively analyzed. The study population included patients with giant and complex ICA aneurysms with an a priori planned deconstructive strategy of combined standard STA–MCA revascularization and PAO. Inclusion criteria were age above 18 years and no subarachnoid hemorrhage within 60 days prior to treatment. After exclusion of treatments involving pure endovascular PAO, surgical clipping, and high-flow bypasses, 41 patients harboring 47 complex ICA aneurysms were included in the study (table 1 and online supplemental table 1).

Due to the retrospective study design, the need for informed consent was waived. The study was approved by our institutional ethical review committee. The reporting adheres to the STROBE statement.

Aneurysm characteristics and indications

Complex aneurysms were defined as unclippable or difficult to clip after reviewing imaging data

Table 1 Baseline characteristics of target aneurysm

Aneurysm baseline characteristics	Total
Aneurysms treated per patient (n, %)	
Single aneurysm	36 (88%)
Multiple aneurysms	5 (12%)
Aneurysm size (main aneurysm, n, %)	
Small <10 mm	4 (10%)
Large 10–19 mm	8 (19%)
Very large 20–24 mm	9 (22%)
Giant ≥25 mm	20 (49%)
Median (mm)	24
Range	5–79
Aneurysm neck (in mm, n, %)	
Wide	27 (66%)
Short	1 (2%)
Fusiform (no neck)	13 (32%)
Median (mm)	7
Range	2–20
Aneurysm morphology and complexity (n, %)	
Saccular	20 (49%)
Fusiform	15 (36%)
Dysplastic	6 (15%)
Complex[8]	41 (100%)
Partially thrombosed	20 (49%)
Calcified	13 (32%)
Parent artery location (n, %)	
Carotid bifurcation	1 (3%)
Communicating segment	3 (7%)
Ophthalmic segment	8 (20%)
Cavernous segment	5 (12%)
Petrous segment	4 (10%)
Prepetrous segment	3 (7%)
Multisegmental	17 (41%)

according to the following criteria: location, neck dimension, extension into the cavernous sinus, fusiform parent artery configuration, excessive wall calcification, intra-luminal thrombus formation, and/or previous coil treatment.[8] In line with the pertinent literature, our institutional selection criteria for the combined indirect treatment have been modified over the past two decades (online supplemental table 2).[2 13–19]

Multimodal treatment and BTO technique

Our bypass technique has been established for several decades and has been slightly modified since its introduction.[9] We recently reported on an improved planning workflow for EC-IC revascularization combined with transdural indocyanine green videoangiography (tICG-VA).[20] Moreover, online supplemental figure 1 provides a step-by-step description of our institutional double-barrel bypass technique. Intraoperative heparinization was not performed except in one patient with repeated intraoperative donor occlusion. Continuous monitoring was achieved by electroencephalography and somatosensory evoked potential tests in all patients.[6 7]

Bypass patency was confirmed intraoperatively by micro-Doppler ultrasonography, indocyanine green video-angiography (since 2007), and ultrasonic flow probe (Transonic Systems Inc., since 2014).[7] Intraoperative digital subtraction angiography (DSA) was performed exceptionally.

After surgery, patients were closely monitored in our ICU, with blood pressure maintained at normotension. Neither heparin nor aspirin was used except for the administration of low-dose heparin to prevent deep venous thrombosis. Due to the anticipated heparinization during planned endovascular PAO, a dry operative field was considered critical throughout surgery.

Staged, predominantly endovascular PAO was performed at a biplane flat-panel angiographic suite (Axiom Artis, Siemens), usually 48–72 hours after surgery. Generally, patients were embolized under local anesthesia without sedation under anesthesiologic monitoring.

Prior to PAO, a balloon test occlusion (BTO) of the diseased ICA was performed. The venous phase BTO technique has been traditionally applied at our center since the 1990s as initially described by Vasquez-Anon.[21] As the endovascular technique and materials evolved over time, our set-up was adapted to meet the internationally accepted standard operating procedures.[22] A balloon catheter (Magic B1, Balt; Hyperglide, Medtronic; or Scepter XC balloon, Microvention) was positioned in coaxial fashion via a guiding catheter (Envoy or Vista Brite; Cordis) proximally adjacent to the aneurysm. Prior to balloon inflation, 4000–5000 IU of heparin (bodyweight-dependent) was administered. Contrast medium injection confirmed sufficient inflation and flow arrest. Patients were continuously monitored and tested for a total duration of 25–30 min with simple motor and language tasks and examined for neurocognitive impairment. If a hypotensive challenge test was deemed necessary, a decrease in systolic blood pressure of approximately 20 mmHg was targeted for a short duration of time (5 min).[23 24] Once stable neurology was documented, loose coiling of the aneurysm sac and endovascular PAO were performed with detachable balloons, coils, or a combination of both. Recently, flow-blocking vascular plugs were also placed (UNO, neurovascular embolization system, Reverse Medical) below the petrous ICA after coiling the diseased segment. In the ICU, heparin was continued for 24 hours (aPTT of 60–80 s). Blood pressure was titrated to the desired level and hemodynamics optimized.[10 15]

Outcome assessment

Immediate bypass patency and aneurysm occlusion grades were determined postoperatively by DSA. Radiological follow-up was routinely performed at 6–12 months. The post-treatment MR protocol for investigation for delayed silent infarctions or signal abnormalities due to chronic hypoperfusion, thromboembolic stroke, or perforator stroke consisted of T2, proton-density-weighted spin-echo, and FLAIR sequences. A neuroradiologist and a neurosurgeon evaluated all imaging data blinded to the results. Aneurysm occlusion was assessed according to the Raymond classification.[25] Baseline and follow-up neurological data were rated according to the modified Rankin Scale (mRS). We performed an official death-register comparison. Complications were evaluated postoperatively, post-interventionally, and at follow-up. Procedure-related morbidity was defined as any permanent deficit related to treatment (mRS >2). Severe adverse events were defined as major ischemic or hemorrhagic stroke leading to significant neurological deficits (mRS >3). Temporary neurological deficits that resolved completely by discharge or final follow-up were regarded as minor adverse events. Wound-healing problems and non-neurological adverse effects were also documented. Median follow-up time was 3.9 years (range: 0.3–14.8) with a total observation period of 263.7 years.

Statistical analysis

Statistical calculations were performed using descriptive analyses, including median and range and total number and percentage. The Mann-Whitney *U* test and Fishers' exact test were used to assess the differences between the successful BTO and failed BTO groups of patients. Clinical outcome was evaluated by the Wilcoxon test for paired samples. Two-sided P-values<0.05 were considered statistically significant. SPSS Statistics (Version 25.0, IBM Corp.) was used for data administration and statistical calculations.

RESULTS

Aneurysm characteristics and indications

Our study comprised 41 patients with 47 giant or complex ICA aneurysms, which were not amenable to conventional treatments. Aneurysm characteristics are detailed in table 1. Fusiform and dysplastic configurations were seen in 21 patients (21/41, 51%). A total of 90% of target aneurysms were large or giant in size (37/41). Infraclinoidal neck extension was noticed in 15 patients. Indications for indirect combined treatment for complex ICA aneurysms included failed prior coiling attempts (8/41, 20%), lack of endovascular access due to tortuous vascular anatomy (9/41, 22%), and symptomatic patients with cranial nerve (CN) compression syndromes demanding a deconstructive procedure to rapidly diminish mass effect (24/41, 58%).

Surgical results

Of the 41 intended STA–MCA bypass surgeries, one procedure (1/41, 2%) was aborted due to thrombosis of the donor vessel, possibly related to vessel injury during preparation. In the remaining 40 cases, a double-barrel STA–MCA bypass was constructed in the majority of cases (33/40, 83%). Median temporary occlusion time of the recipient artery was 30 min (range: 10–45 min). Micro-Doppler ultrasound, indocyanine green video-angiography, or DSA confirmed intraoperative patency in 100% of completed procedures.

BTO was performed in a median of 2 days (range: 1–57 days) after bypass in 36 patients (36/40, 90%). Of these, BTO was well tolerated by 89% of patients (32/36) and was followed by permanent ICA occlusion. Four patients (4/36, 11%) developed neurological symptoms and BTO was immediately aborted in the first attempt (figure 1). In two of them, the ICA was successfully occluded after negative BTO at a second attempt, 24 hours and 21 days later. PAO without BTO was successfully performed under general anesthesia in the remaining four patients with luxuriant bypass flow (4/40, 10%). In three of them, occlusion was achieved by endovascular means, and in one, surgically (Hunterian clip ligation, 1/40, 2%), due to difficult vascular access. PAO was performed by EVT in all other cases (37/40, 92%). Hence, a combined treatment was executed, as planned, in 38 patients (38/40, 95%). In the remaining two patients, successful EVT with a stent/coil construct was used after poor bypass filling in one and after speech arrest during BTO in another.

Overall, information regarding bypass patency was available for 39 patients at the last follow-up, including both failed BTO cases with subsequent treatment modification. Patency was confirmed in 92% of patients (36/39) or 93% of all anastomoses (66/71). Notably, initial bypass patency of the failed BTO patients had been demonstrated angiographically before abort of the PAO procedure. However, a significant difference

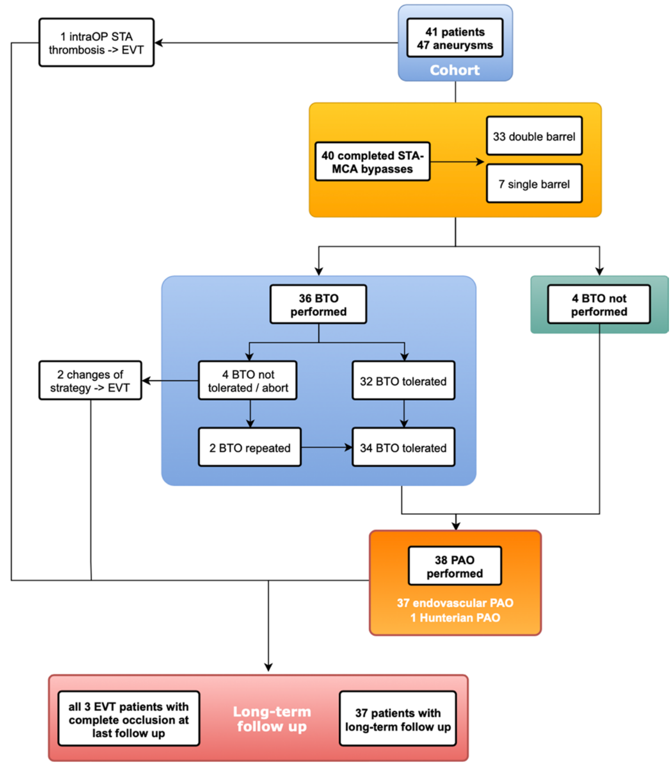

Figure 1 Treatment protocol and long-term (≥1 year) follow-up status of 41 patients with 47 complex ICA aneurysms. One procedure (1/41, 2%) was aborted due to thrombosis of the donor vessel during anastomosis. The patient was later treated by stent-assisted coil embolization and was not included in the outcome analysis. 38/40 patients underwent successful PAO. In 2/36 patients (6%), successful stent-assisted coiling was performed later due to failed BTO. Clinical and radiological parameters were available for all patients at baseline and for 37 of the 38 patients (97%) at last follow-up.

was found in long-term patency rates between the successful and failed first-attempt BTO groups at the last follow-up (P=0.029, n=35). Of the patients who had completed bypass surgery and successful PAO, long-term follow-up was available for 37 patients (figure 1). The patency rate in this group was 99% (66/67 bypass grafts in 36/37 patients) at last follow-up.

Long-term aneurysm occlusion

Long-term (≥1 year) aneurysm obliteration rates were available for 37 patients (figure 1). Complete occlusion (Raymond I) was documented in 95% of patients (35/37) at the last follow-up (figure 2). Residual filling was evident on control-angiography in two patients only (2/37, 5%). In one patient (1/37, 3%) a recanalized ICA was diagnosed 2 months after PAO. Retreatment by surgical ICA ligation led to total aneurysm obliteration. Hence, the efficacy of a combined strategy for giant or complex ICA aneurysms was evident with a first-attempt success rate of 89% (33/37 patients, Raymond I). It rose to 95% after retreatment and at the last follow-up. No aneurysmal ruptures were observed during the follow-up period.

Clinical outcome and complications

At last follow-up, 97% of patients (36/37) presented with excellent or good clinical outcomes (median mRS: 0, range: 0–2). A statistically significant improvement compared with their preoperative status (median mRS 2) was clinically evident (P<0.001). In one patient, poor outcome was attributed to watershed

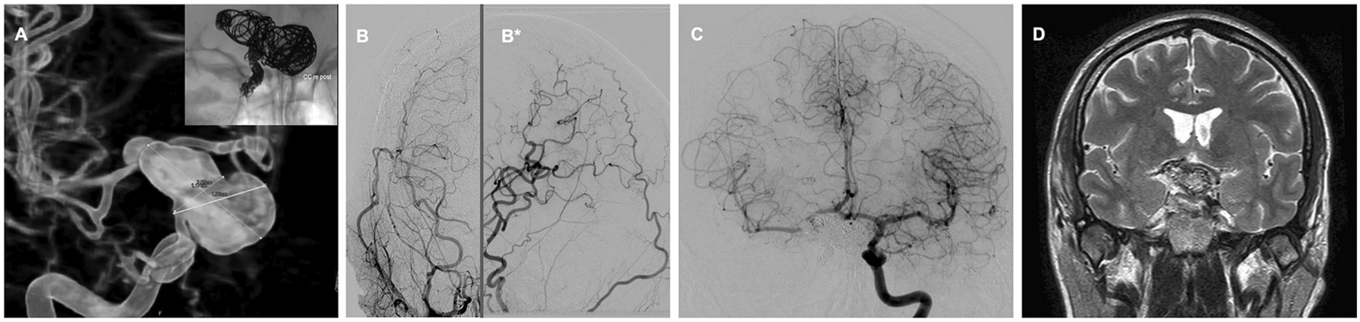

Figure 2 Three-dimensional-digital subtraction angiography image of a patient in their 40s complaining of headaches and right-sided progressive impairment of visual acuity caused by a right-sided supraclinoidal fusiform aneurysm (A). Insert shows coil-occluded internal carotid artery aneurysm. Vision recovered completely within 7 months. (B) robust bypass filling of the right middle cerebral artery territory (anteroposterior and lateral view). (C) cross flow from the left side. (D). follow-up MRI demonstrating the thrombosed aneurysm.

infarction and postoperative hemiparesis further complicated by severe cardiac disease (table 2). At last follow-up, a complete remission of CN compression syndromes was documented in 10 patients and a marked improvement in a further 10 patients. Thus, 84% (20/24) of patients with CN symptoms responded well to the deconstructive strategy. In four patients (4/24 patients, 16%) symptoms remained unchanged.

At last follow-up, we observed two non-procedure-related deaths 2.7 and 4.9 years after flow replacement surgery (in the first case due to oncological progression of a bronchial carcinoma and in the second due to a traumatic acute subdural hematoma).

DISCUSSION

We analyzed one of the largest patient series to date of complex ICA aneurysms, otherwise not amenable to conventional reconstructive methods, who were thus managed by combined microsurgical and endovascular treatment.[5 12] Our cohort comprised 41 patients with 47 complex ICA aneurysms with 90% being large or giant in size. Fifteen aneurysms showed infraclinoidal neck extension into the cavernous sinus. All but one patient were treated by standard STA–MCA bypass surgery followed by staged endovascular PAO. With a 99% long-term bypass patency rate, 95% complete aneurysm occlusion, and 97% excellent and good clinical outcome at last follow-up, our results were well within the range reported by other groups.[8 12] Careful patient selection may be one of the leading factors resulting in the overall good outcome in this series.

Table 2 Summary of peri-operative and delayed complications

Complications	N (%)	N (%) requiring revision surgery
Peri-operative complications (<30 days) n=41		
Periprocedural hygroma	1 (2%)	1 (2%)
Donor occlusion (STA branch, abort of bypass procedure)	1 (2%)	
Ischemic events	4 (10%)	
Permanent stroke	1	
Transient neurological deficits (TIA)	2	
Asymptomatic perforator infarction	1	
Pulmonary embolism (PE) and deep-vein thrombosis (DVT)	2 (5%)	
Neurologic death	0 (0%)	
Non-neurologic death	0 (0%)	
Delayed complications (n=37)		
Ischemic events		
Delayed coil permeation, ICA repermeation, TIA	1 (3%)	1 (3%)
Wound necrosis	2 (6%)	
Neurologic death	0 (0%)	
Non-neurologic death	2 (6%)	

Patient selection and evolution of the concept

Before 1996, every patient harboring an unclippable or uncoilable ICA aneurysm was evaluated by a BTO protocol that relied purely on clinical and angiographic testing, including a hypotensive challenge test.[13] Although our BTO protocol had low complication rates, we were at an early stage aware of patients developing delayed ischemic symptoms due to hemispheric hypoperfusion the day following successful testing and uneventful PAO.[6 10 13–15] In fact, the introduction of a cumbersome and expensive cerebral perfusion assessment protocol using Xenon-enhanced CT during testing could not adequately predict the risk of stroke after ICA sacrifice. Several patients classified as low risk according to their cerebral bloodflow state during BTO still suffered strokes after PAO.[6 12–15] Since up to 22% of patients experienced ischemic symptoms after uneventful BTO and completed PAO, pointing toward a high rate of false-negative test results, our institutional workflow was consequently modified.[13–15] Moreover, de-novo aneurysm formation or enlargement of preexisting contralateral aneurysms after sole PAO have been frequently reported and also observed by the senior authors.[10 13] To detect these potential long-term sequelae, our neuroradiological follow-up recommendations include a MRA follow-up after 6 and DSA after 12 months. After confirmed aneurysm occlusion and bypass patency, further radiological follow-up including MRA is recommended every 3–5 years.

Currently, only those patients meeting strict criteria undergo BTO directly in our institution. Patients with robust collaterals including well-developed AComA and A1-segments or PComA – as seen on CTA and evaluated by manual compression of the involved ICA during angiography – are now regarded as having the anatomical prerequisites for PAO alone. Chen et al reported 11 cases where failed clinical BTO were associated with absent or hypoplastic AComA and A1-segments.[13] Their overall infarction rate after PAO was 20%, probably due to paradoxical blood pressure elevation during BTO. Individual patient characteristics such as age, comorbidities, multiple aneurysms, and additional steno-occlusive diseases are now integrated into our decision process as well.[13] All patients who are found likely to develop ischemic symptoms according to published criteria will receive STA–MCA bypass surgery before BTO and PAO.[13 15 26]

Since the introduction of Hunterian ligation, treatment modalities and outcomes for these pathologies have changed significantly.[4 27] With the development of modern EVT, it became imperative to combine both methods to improve radiological and clinical results.[5–7 10 12] The concept seemed especially attractive for dually-trained neurosurgeons.[5 10 13] Several publications emphasized the value of integrating modern endovascular techniques with neurosurgical management with the aim of enhancing therapeutic options and reducing technical complication rates.[5–7 10 12 15 25 26 28]

In one report on 13 complex ICA aneurysms treated by combined bypass surgery and PAO, complications arose in two patients after high-flow bypass beside thromboembolic events after ICA balloon occlusion.[6] The latter was attributed to the technically more demanding balloon occlusion technique, but the resulting 15% complication rate attributed to high-flow bypasses, may question this concept.

Standard STA–MCA bypass vs high-flow grafts

Various bypass types have been proposed.[2 3 6 9] For years, specialized cerebrovascular units emphasized the application of large grafts (radial artery or saphenous vein) with the intention of substituting entire territories.[2 11]

Although high-flow anastomoses have large flow capacities, microsurgery is associated with complication rates reaching 16%.[2 11] Even the innovation of non-occlusive techniques, specifically invented to avoid longer occlusion times, could not lower this rate. Van Doormal et al reported a combined mortality and morbidity rate of 16.8% in 34 patients treated non-occlusively.[11]

However, studies expressing a balanced view, comparing different revascularization concepts, are limited.[12 29 30] Few groups that relied on “low-flow” STA-MCA bypass techniques before PAO reported patency rates up to 99% and low morbidity.[5 9 12 29 30] Ponce et al. performed eight STA–MCA bypasses followed by PAO with good clinical outcome.[29] Nussbaum et al presented their STA–MCA bypass experience for 30 ICA aneurysms, demonstrating high patency and low complication rates of 98.8% and 4.8%, respectively.[12]

Cherian et al described a significantly higher flow rate of up to 120 cc/min when using double-barrel bypasses compared with single-barrel bypasses.[30] The observed flow rates match those delivered by radial artery grafts and, thus, question the term “low-flow” bypass. Since the majority of our patients received a double-barrel STA–MCA bypass, Cherian’s findings and our clinical results validate our treatment concept, provided that highest quality standards are followed.[30] We summarized our institutional technique and recommendations in online supplemental figure 1. Of note, we encountered 6% (two cases) of wound-healing complications in our long-term follow-up cohort. These complications, while being rare, were only observed among double-barrel cases but were all managed conservatively without long-term sequelae.[12]

Our series also includes two patients who failed the initial BTO but went on to be treated successfully by PAO. It may be explained by the ability of grafts to mature and rapidly adapt to the demand by increasing their caliber over short time periods.[5 9 30] Consequently, we prefer the term “standard” rather than “low-flow” for double-barrel STA–MCA bypasses.[9 12 30]

In our experience, PAO is best performed within 1 week of bypass construction. However, in one patient, endovascular PAO was finalized 57 days after bypass surgery. In contrast to high-flow conduits, requiring immediate performance of PAO, EVT can be postponed and has the advantage of examining the patient while awake during BTO as well as having the opportunity to optimize hemodynamics.[6 10 11 25 26 28 29]

Our long-term outcome data are also evidence of the safety and reliability of STA–MCA anastomosis when compared with high-flow conduits.[2 11]

Long-term outcomes and comparison with modern endovascular treatment

EVT techniques evolved at an impressive pace.[8 10 31–33] Coil embolization emerged as a treatment of choice for small-necked, saccular aneurysms.[31 32] However, large and giant aneurysms demonstrated unsatisfactory long-term results with high recurrences, rebleeding rates of up to 1.9% per year, and M&M rates of 24% and 9%, respectively.[33 34]

Our earlier experience with coiling large and giant aneurysms are proof of the challenges surrounding unimodal treatments.[33] Later, stent- and balloon-assisted methods resulted in improved radio-anatomical outcomes.[7] A recent multicenter analysis reported complete occlusion rates between 67% and 84% after stent-assisted embolization of 670 aneurysms, depending on the used device.[35]

Next, flow diverting devices (FDDs) were introduced with the intention of treating giant aneurysms.[17 36–40] Short-term safety and efficacy of FDD-induced endoluminal vessel reconstruction with progressive aneurysm occlusion have been demonstrated in several studies, including ours.[8 17 36–40] We previously demonstrated complete or near-complete long-term occlusion in 95% cases, comparable to the final PUFS trial occlusion rates that increased from 87% to 95% over time with a retreatment rate of 6% after 5 years.[8 40]

Thus, flow diversion undoubtedly represents a major advancement. We also obtained a low-flow diverter-associated complication rate of 5% in a highly preselected cohort.[8] A meta-analysis summarizing 1451 patients treated with FDDs reported M&M rates of 5% and 4%, respectively.[36] The analysis expressed uncertainty about the safety and risks of FDDs in large and giant aneurysms and did not allow for a clear recommendation. Another important point to be stressed is the complication rate in complex aneurysms after FDD, as addressed by the IntrePED study group.[37] They published M&M rates of 13% and 5% for large and 28% and 9% for giant aneurysms, respectively. Notably, the rates for post-operative aneurysm rupture (5, 8%), intraparenchymal hemorrhage (5, 8%), and ischemic stroke (13, 5%) were not negligible, with three of five ruptures occurring in giant aneurysms. In our previous flow diversion series, one of two severe complications arose in a giant lesion.[8] In a multicenter study of second-generation FDDs, a potential relationship between size and 30-day mRS was found,

Impact of modality on cranial nerve compression syndromes

Patients with CN compressions require longer recovery times after flow diversion due to delayed aneurysmal obliteration and persisting inflow, which may be too long for re-establishing severely compromised visual function.[39] While Szikora et al. reported on the improvement of mass effect in most patients presenting with CN deficits (12/16), they also observed visual deterioration after flow diversion.[39] Clinical symptoms started to improve as late as 8 months' post-intervention. Another study reported an improvement in 15/28 patients with CN compression.[17] In both studies, most patients presented with ophthalmoparesis only and in aneurysms < 20 mm in size. Ultimately, both giant aneurysms in the latter study ended up with bypass-supplemented ICA occlusions, since the deployment of six FDDs failed to relieve the mass effect.[17] These data suggest that size is definitively a complicating factor for a quick resolution of CN compression, and giant aneurysms more frequently require multiple FDDs to achieve satisfactory occlusion. Both factors might result in critically long recovery times.[8 17 39] In contrast, we observed no deterioration in CN function but saw a resolution or marked improvement in 84% of cases (online supplemental figure 1–3). Microsurgical debulking, while principally feasible after PAO but not after FDD due to long-term double antiplatelet therapy, was not necessary to achieve these results.[4 5 8 10 12 15 25 26 28] Marked functional improvement occurred by the cessation of arterial pulsations and administration of dexamethasone alone.[26 29]

Recently, giant cavernous carotid aneurysms causing external compression and, hence, stenosis of the ICA have been termed “matricidal”. These complex pathologies, associated with CN compression syndromes in 75% of presented cases, are linked with a 30% failed FDD treatment rate. In this study, the authors concluded that parent artery occlusion (with or without bypass) might represent a sound treatment alternative.[18]

Consequently, we reason that insecurities concerning FDD as a newer technique remain. A future series of novel endovascular devices should be compared with the reported combined approach herein, which represents an immediate curative approach with an aneurysm obliteration rate of 95% and is associated with low long-term morbidity.

Limitations, outlook, and conclusion

The limitations of our study are its retrospective and center-based nature, the relatively small sample size, and the selection of patients based on experience alone. In our opinion, both flow diversion and combined STA–MCA bypass and PAO, are equally safe treatment options in experienced hands. Although the balance has shifted in favor of FDDs recently, our long-term outcome data allow us to carefully select patients and tailor the treatment for each patient.

Although nowadays more centers are opting for the flow-diversion technique alone, the combined indirect approach represents a viable alternative to flow diversion in patients with cranial nerve compression syndromes or matricidal aneurysms, and may serve as a backup strategy in cases of peri-interventional complications or lack of suitable endovascular access.

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Data availability statement All data relevant to the study are included in the article or uploaded as supplementary information. Individual de-identified participant data will not be shared due to the general Data Protection regulation which came into effect on May 25 2018 in Austria. The study protocol in the German language will be available on request.

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Supplemental File

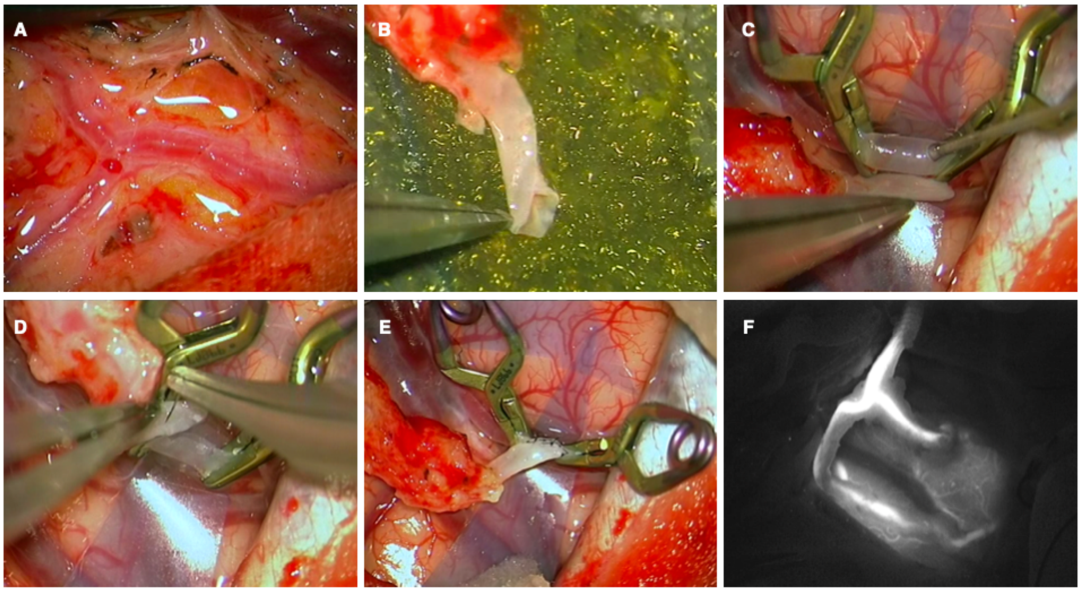
Patient Baseline characteristics	**Total**
Number of patients treated (n)	41
Mean age (y)	
Median	57
Range	(19-73)
Female : male (n)	*30 : 11*
Clinical presentation (n, %)	
Incidental / unrelated symptoms	8 (20%)
Cranial nerve palsy	24 (58%)
II	*8*
III	*4*
VI	*7*
Multiple (incl. Horner)	*5*
Previous SAH	1 (2%)
TIA / stroke	4 (10%)
Other	4 (10%)
Medical history (n; yes : no)	
Arterial hypertension	*26 : 15*
TIA / stroke	*4 : 37*
Neoplastic disease	*3 : 38*
Smoker	*12 : 29*
Patients with multiple aneurysms (n, %)	
Single aneurysm	25 (61%)
Multiple aneurysms	16 (39%)
Multifocal	*11*
Same parent artery	*5*
Prior treatments (n, %)	
Of target aneurysm	8 (19%)
Endovascular treatment	*5*
Endovascular attempt	*3*
No prior treatment	33 (81%)

Supplemental Table I: Clinical characterization of included patients (n=41)

The vast majority of patients (51%) presented with cranial nerve palsy (in several cases with multiple cranial nerves involved). One patient experienced previous aneurysmal rupture. However, SAH occurred more than 60 days before treatment. Eight patients underwent EVT or EVT attempt of the target aneurysm prior to bypass surgery and parent artery occlusion.

Literature overview of selection criteria for combined STA-MCA Bypass and PAO
a) Inadequate collateral capacity of the Circle of Willis A CT-A and DSA based assessment of the anatomical characteristics of the Circle of Willis may display the absence (or significant hypoplasia) of one or more collateral vessels. The ACoA was considered as anatomically robust, if symmetrical non-hypoplastic well developed A1-segments were identified. The PCoA was regarded as substantial, if the entire segment including the P1-segment was well developed.[13,15] Early studies described a manual compression test of the affected ICA in the neck to determine the tolerance for PAO without preliminary bypass.[14] More recent studies performed the manual compression test of the ipsilateral cervical ICA during angiographic work-up to visualize the crossflow but also to decide between low-flow and high-flow bypass techniques.[16]
b) Coexisting ipsilateral and contralateral aneurysms as well as a stenosis or an occlusive disease located on potential collateral vessels with anticipated enhanced hemodynamic aneurysmal stress or reduced collateral flow capacity were seen as a contraindication to sole PAO.[2,13,15]
c) Cranial nerve compression syndromes due to local mass effect observed in large and giant aneurysms have been identified as excellent indications for deconstructive treatment strategies. Moon et al. described patients with cranial nerve compression syndromes who ended up with bypass-supplemented ICA occlusions, since the deployment of six FDDs failed to relieve the mass effect.[17]
d) Matricidal cavernous aneurysms have recently been described as a suitable deconstructive treatment indication.[18] Here, these large and giant aneurysms exert direct compression of the parent ICA, causing ICA stenosis and ischemia.
e) Patient age Young-aged patients (< 50 years) facing a high lifetime rupture risk were seen as candidates for a bypass in several studies e.g. Barnett et al. 1994.[19] In contrast, Chen et al. described elderly patients as more likely to develop ischemic complications after carotid artery sacrifice without preliminary bypass.
f) The inability to achieve a pharmacologically induced hypotension during BTO before bypass surgery (hypotensive challenge) and/or the occurrence of a paradoxical elevation of blood pressure (which is regarded as a regulatory response to a compromised cerebrovascular reserve) pointed to the need for revascularization in some studies.[13,15]

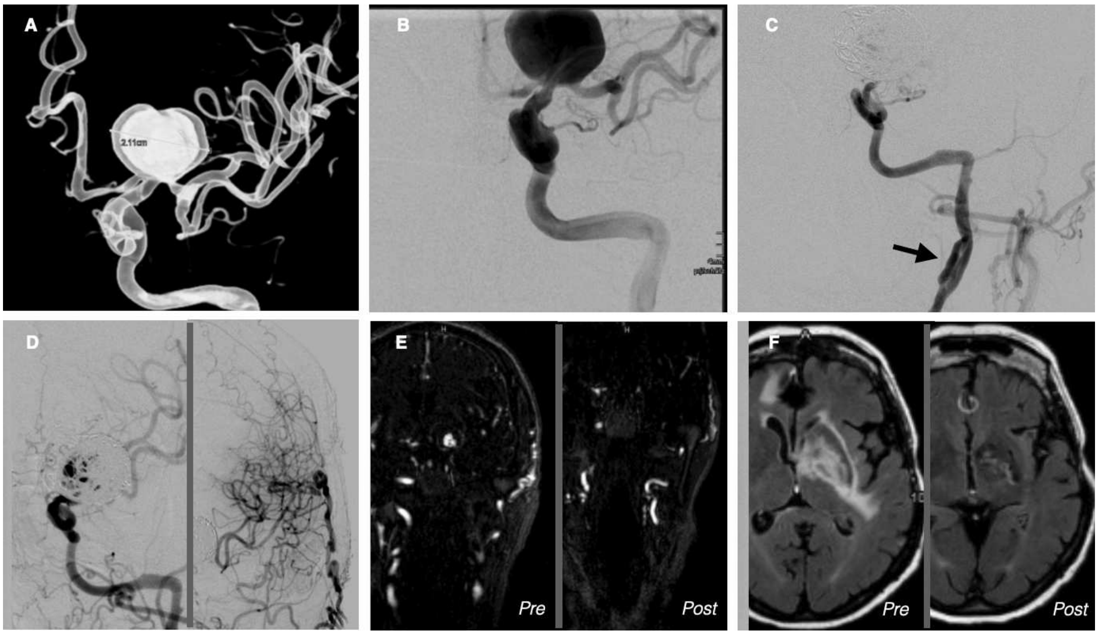
Supplemental Table II: Literature overview of selection criteria for combined STA-MCA bypass and PAO.



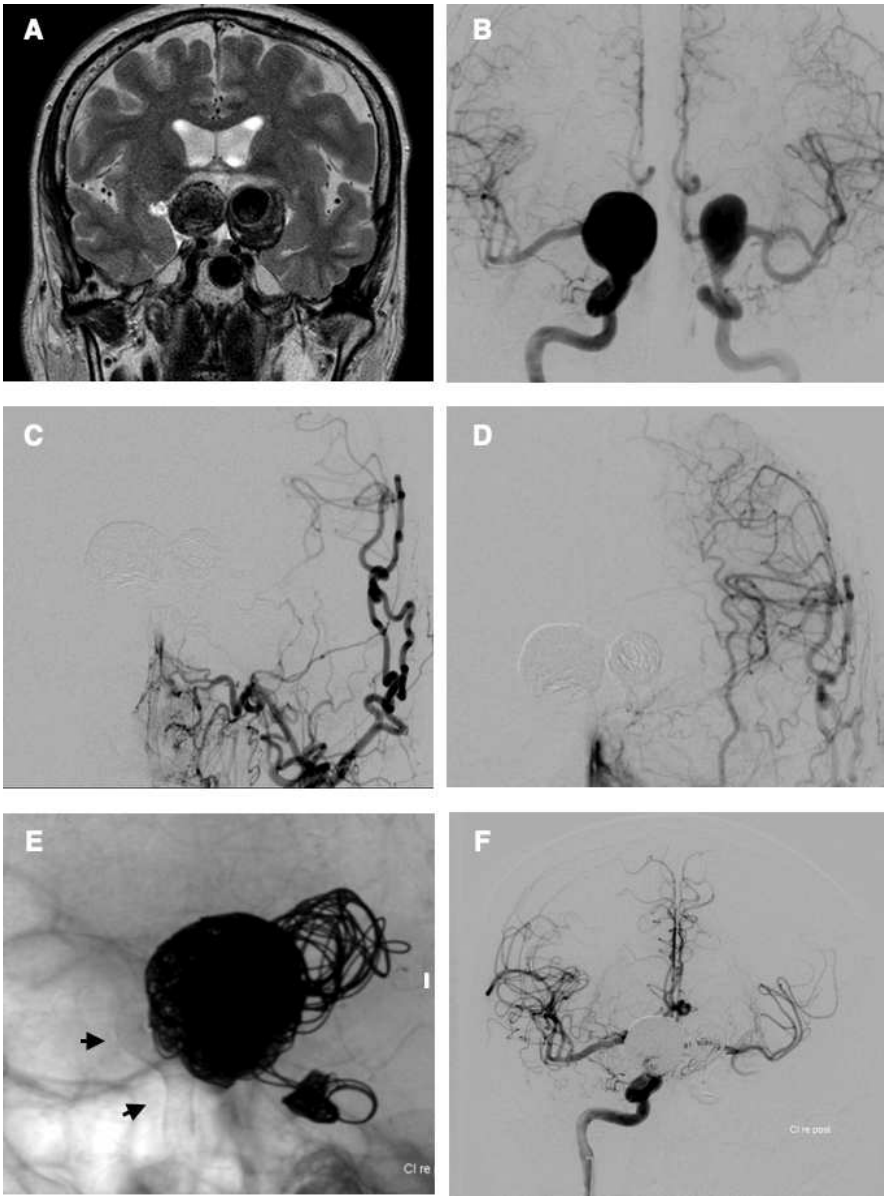
Supplemental Figure I. Step-by-step illustration of a double-barrel STA-MCA bypass in end-to-side technique, acute angle (Department of Neurosurgery, Medical University of Vienna). The most important prerequisite / requirement for cerebrovascular neurosurgeons to perform under optimal circumstances is the regular practice in the microsurgical laboratory.

A. Meticulous preparation of both donor branches, the frontal and parietal superficial temporal arteries (STA*)*. We strongly believe in the fastidious acquisition and analysis of complete sets of angiographical imaging to visualize the course of STA donor grafts and to assess their robustness preoperatively. Intraoperatively, a meticulous dissection of both grafts (min. of 6 cm) is performed under continuous irrigation and a conservative application of coagulation. We recommend the use of two separate micro-bipolar forceps, with one adjusted to low diathermy current (4 watts) to be applied to side-branches only without causing thermal damage to the graft; **B.** Enlargement of the orifice of the graft in fish-mouth technique; **C.** Circumferential mobilization of recipient artery (M4 branch of MCA), temporary proximal and distal clamping and arteriotomy, followed by flushing of the lumen*.* We recommend the use of the highest magnification and light intensity of the surgical microscope (and more recently, of the exoscope); **D.** First heel suturing ('anchoring suture'). Regarding the anastomosis technique, we pay utmost attention to avoid extensive tension on both donor and recipient grafts. **E.** Final result demonstrating the completed anastomosis before removal of temporal clips. We have achieved good results by using interrupted sutures. In our opinion, this technique provides the possibility to correct each suture individually without the risk to compromise the entire anastomosis. While not supported by sufficient scientific evidence, we hypothesize that the frequently observed growth of donor vessel diameter over time might have been associated with the ability of the anastomosis site to enlarge and adapt to perfusion demand; **F.** ICG angiography confirming the patency of both bypasses.

The most important prerequisite / requirement for cerebrovascular neurosurgeons to perform under optimal circumstances is the regular practice in the microsurgical laboratory.



Supplemental Figure II. A/B. patient in their 60s experienced a left-sided TIA and was treated by coiling of a giant left ICA bifurcation aneurysm. The patient was referred after clipping of multiple contralateral aneurysms and unsuccessful trial of FDD placement, which resulted in cervical ICA dissection and aneurysm recanalization . **C.** DSA image shows the dissected ICA. **D.** The left image depicts the recanalized, growing aneurysm before combined treatment. The right image demonstrates the well-developed bypass filling the left MCA-territory, immediately prior to PAO. **E./F.** Long-term-CE-angio MRI with contrast medium depicts a diminishing aneurysm rest over 7 years and disappearance of the perilesional edema on MRI.



Supplemental Figure III. A/B. Coronal T2-weighted MRI image and digital subtraction angiography of a patient in their 50s with bilateral partially thrombosed giant paraophthalmic aneurysms (our series included bilateral giant aneurysms in 5 out of 41 patients). The patient presented with bilateral progressive visual loss. First, the larger left-sided aneurysm was deconstructed after a double barrel STA–MCA bypass procedure. **C.** Luxuriant bypass flow to the left middle cerebral artery territory is seen after 12 months with significant caliber enlargement. **D/E.**The right-sided aneurysm showed minimal reperfusion after primary coiling and was subsequently stabilized by implanting two flow diverting devices (arrows, anteroposterior view). The final visual outcome was excellent, with only a minimal defect in the right upper quadrant. Although anticipated, surgical debulking of the aneurysmal mass was not necessary. **F.** Post-interventional angiogram depicts the final result *(right internal carotid artery injection, anteroposterior view).*