



Microsurgical Treatment of Cerebral Aneurysms After Previous Endovascular Therapy: Single-Center Series and Systematic Review

Anil K. Roy, Lucas R. Philipp, Brian M. Howard, C. Michael Cawley III, Jonathan A. Grossberg, Daniel L. Barrow

■ **BACKGROUND:** Since its introduction in the early 1990s, endovascular treatment of cerebral aneurysms has had a steady upward trend and is the primary mode of treatment for most intracranial aneurysms. Concurrently, the need for retreatment of aneurysms after previous endovascular treatment has continued to increase, some of which can only be treated with microsurgical techniques. The factors that dictate outcomes in this group of patients are incompletely understood.

■ **OBJECTIVE:** To study factors contributing to patient outcomes after microsurgical treatment of aneurysms with previous endovascular treatment.

■ **METHODS:** The records of the senior author (D.L.B.) since 2002 were retrospectively reviewed for aneurysms treated after previous endovascular treatment. Demographics, treatment details, and imaging were reviewed for all patients. A systematic review of the literature on microsurgical treatment of aneurysms previously treated by endovascular therapy was also conducted.

■ **RESULTS:** A total of 91 patients were identified from the retrospective review. Mean age at the time of initial treatment was 49 ± 12.68 years. Most patients initially presented with subarachnoid hemorrhage before initial endovascular treatment, with only 11 patients (12%) presenting with incidentally discovered lesions. Modified Rankin Scale score at discharge after initial treatment was good (0–3) in 81.4% of cases. Functional outcomes at the last known follow-up showed a modified Rankin Scale score of 0–3 in 77 patients (84.6%). Only aneurysm neck size was found to be a significant predictor of surgical

complications (Wald $\chi^2 = 10.79$; $P = 0.0010$) with an odds ratio of 2.32 (95% confidence interval, 1.40–3.83) for a 2-mm increase in neck size. Systematic review identified 37 studies who were used to pool data on 370 patients. Although type of surgery was identified as a predictor of poor outcomes, this was significantly confounded by Hunt and Hess grade in the systematic review.

■ **CONCLUSIONS:** Favorable outcomes can be obtained even for highly complex cerebral aneurysms that have failed endovascular treatment at high-volume cerebrovascular centers. Initial presentation grade and aneurysm size are important predictors of final patient outcomes.

INTRODUCTION

Endovascular treatment of cerebral aneurysms is a safe and reliable primary treatment. The proportion of aneurysms treated endovascularly has continued to increase since its introduction more than 25 years ago.^{1–3} The advent of new, clinically proven endovascular methods has augmented this trend, enabling the endovascular treatment of aneurysms, which were previously only amenable to microsurgery.^{4,5} Manifestly, the need for retreatment of endovascularly treated aneurysms has simultaneously increased as patients presenting with recurrence of a previously coiled aneurysm are more frequently encountered.^{1,5,6} Although associated with improved mortality 1 year after initial treatment,³ endovascular embolization also confers higher risk of aneurysm recurrence and rerupture in the setting of incomplete occlusion.^{4,7–11} More than one third of aneurysms treated by endovascular coiling show subtotal occlusion or refilling.^{1,3} Furthermore,

Key words

- Microsurgical clipping
- Recurrent cerebral aneurysm

Abbreviations and Acronyms

- CI: Confidence interval
- GDC: Guglielmi detachable coil
- mRS: Modified Rankin Scale
- OR: Odds ratio
- PAO: Parent artery occlusion
- SAH: Subarachnoid hemorrhage

Department of Neurosurgery, Emory University School of Medicine, Atlanta, Georgia, USA

To whom correspondence should be addressed: Jonathan A. Grossberg, M.D.

[E-mail: jonathan.a.grossberg@emory.edu]

Jonathan A. Grossberg and Daniel L. Barrow contributed equally.

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the CARAT (Cerebral Aneurysm Rerupture After Treatment) study reported annual retreatment rates as high as 13.3%.^{4,12,13}

Treatment of each individual aneurysm is unique and fraught with complexity related to the patient, aneurysm, and associated vascular anatomy; consequently, no universal strategy exists for dealing with recurrences. Options include close observation, additional endovascular treatment, open surgical clip ligation, and parent artery sacrifice with or without bypass. Accordingly, a thorough understanding of the underlying risk factors for poor outcomes associated with clipping after endovascular treatment remains relatively unknown.^{1,4,14-18}

The purpose of this study was to conduct a rigorous examination of the safety and effectiveness of surgical retreatment of aneurysms failing previous endovascular therapy, with a focus on risk factors that predicted poor outcome. We report 2 discrete series for comparison, from which statistical models predicting poor outcomes and complications were produced: first, our single-institution series and second, a pooled series derived from a systematic review of the literature.

METHODS

The study was approved by the local university institutional review board. The surgical records of the senior author (D.L.B.) were retrospectively reviewed for all patients who underwent clip ligation of aneurysms after any previous endovascular treatment since 2002. Clinical data were extracted from the electronic medical record by a single reviewer and verified independently by a second reviewer. Descriptive statistics were determined for patient sex, age at initial presentation, smoking history, initial presentation (incidental or subarachnoid hemorrhage), Hunt and Hess score on admission, aneurysm location, and aneurysm size. Aneurysm location was reduced to a binary classification of being located in either the anterior or the posterior circulation (anterior cerebral artery, middle cerebral artery, internal carotid artery, posterior communicating artery aneurysms—anterior circulation). Aneurysm size was grouped into 4 size ranges. Those <7 mm were categorized as small, 7–14.9 mm were medium, 15–24.9 mm were large, and >25 mm were giant aneurysms.

Initial endovascular treatment, associated complications, and related outcomes were recorded for each patient. Outcomes were classified in 2 ways. First, initial discharge modified Rankin Scale (mRS) score was determined from discharge summaries. An mRS score of 0–3 was defined as a good outcome, whereas 4–6 was considered bad.

The characteristics of each patient's readmission for microsurgical treatment were recorded, including the indication for surgery, interval between treatments (defined as the time in months between the date of discharge from endovascular treatment hospital stay to the date of admission for surgical retreatment), preoperative functional status per mRS, surgery type (clipping only, clipping with coil removal, bypass), length of stay, associated complications, discharge mRS score, and the last known mRS score.

Statistical Analysis

Statistical analyses were conducted using SAS/STAT software, version 9.4 for Windows (SAS Institute Inc., Cary, North Carolina,

USA). The primary exposure of interest was type of surgery, grouped as clipping without coil/stent removal, clipping with coil/stent removal, and bypass/parent artery occlusion (PAO)/other. The primary outcome of interest was the risk of bad outcome, defined as an mRS score ≥ 4 . Secondary outcomes included the risk of surgical complications and the observed change in functional status (mRS) before and after surgery.

Logistic regression analysis was used to construct multivariate models predicting poor outcomes and surgical complications. Automated variable selection methods were used to generate the most optimal prediction models from higher-order models, initially controlling for surgery type, age, sex, size (maximum diameter), neck size, location, anterior versus posterior location, initial post-endovascular therapy outcome, time interval between treatments, multiple aneurysms, Hunt and Hess score on initial admission, length of stay, and smoking status. Forward, backwards, and stepwise selection were used with entry/exit criteria of $\alpha = 0.05$. Predictor variables which produced a >10% change in surgery type β -coefficient estimates were included as meaningful confounders regardless of significance in the model.

Pooled Meta-Analysis

A systematic review of the literature was conducted to identify articles reporting series of patients with recurrent aneurysms after endovascular therapy treated by subsequent microsurgery with patient-level data for secondary analysis. Keywords searched included "Intracranial," "aneurysm," "cerebral," "coil," "embolization," "endovascular," "recurrent," "recurrence," "clipping," "clip," "coil," "compaction," "remnant," "stent," "previously," "reoperation," "incomplete," "surgery," in all iterations of "AND" and "OR" search statements. For example, "Aneurysm AND (intracranial OR cerebral) AND (embolization OR coil OR stent OR endovascular) AND (recurrent OR recurrence OR previously OR reoperation) AND clipping," PubMed, Web of Science, and Ovid were searched. Search results were limited to articles written in English and patients in series treated on or after January 1, 1990. For inclusion, articles must have published patient-level data as lists, including at least patient age, sex, surgery type, initial presentation, aneurysm size, location, interval between treatments, and final outcome. Studies reporting only sample or population-level measures of association or mean descriptive statistics were not included. The references of each identified study were further reviewed for eligible articles for inclusion.

Data from each eligible study was entered into a master spreadsheet. Surgery type was reclassified as previously described. Aneurysm location was reclassified as anterior or posterior. Final outcome was reclassified as good or bad. A bad outcome was defined mRS score ≥ 4 . The resultant data were used to conduct a logistic regression analysis analogous to the one described earlier to determine the association between surgery type and outcome, adjusting for significant covariates and confounders.

RESULTS

We identified 91 patients with a history of an intracranial aneurysm(s) initially treated by endovascular means who underwent microsurgical retreatment. Consistent with demographics reported in the literature, 68.1% of the population was female

(n = 62). Mean age at the time of initial treatment was 49 ± 12.68 years, and half of our population had a history of smoking (Table 1). Most patients initially presented with subarachnoid hemorrhage (SAH) before initial endovascular treatment, with only 11 patients (12%) presenting with incidentally discovered lesions. One third (n = 26) presented with Hunt and Hess grade 1 SAH, another 27 patients with grade 2 or 3 SAH, and 13 patients with grade 4 or 5. Most lesions were located in the anterior circulation (83.5%) (Supplementary Table 3), and 50.5% were small (<7 mm). Most of the remaining aneurysms were medium sized (7–14.9 mm), with only 8 reported as large or giant.

Table 2 shows the characteristics of the initial endovascular treatment of our population. Of cases in our series, 94.2% were initially treated by endovascular coiling only. The remaining patients either underwent stent-assisted coiling or stenting only as their initial treatment. There were 4 endovascular complications after the initial treatment. Two aneurysms had an intraprocedural rupture and 2 patients had an iatrogenic cervical dissection requiring stenting. One of the patients who underwent stenting with a Pipeline Embolization Device (Medtronic, Irvine, California, USA) had a postprocedural bleed requiring emergent decompression and surgical clipping. mRS score at discharge was good (0–3) in 81.4% of cases.

Characteristics of the microsurgical retreatment and preoperative patient characteristics are shown in Table 3. The interval between initial endovascular therapy and microsurgical retreatment was 141 ± 376 months on average. Functional outcomes improved in the interval between initial treatment discharge and readmission for microsurgical retreatment. mRS score of 0–3 improved from 81.4% at the time of discharge from initial treatment to 94.5% at the time of rehospitalization for microsurgical treatment. The indication for microsurgical treatment in all patients was aneurysm recurrence or known residual aneurysm, with the exception of 1 patient who required immediate postcoiling decompression and clipping because of a rehemorrhage (Figure 1). In 7 patients, repeat coiling was performed with continued residual aneurysms. In 3 patients (3.3%), the aneurysm ruptured after discharge, which led to surgical clip ligation.

Most patients were treated by surgical clip ligation alone (78 patients; 85.7%). Bypass was performed in 8 patients (8.8%), whereas 5 patients (5.5%) were treated by wrapping or wrapping with clipping. Removal of coils was performed in 11 patients (12%).

There were no major surgical complications (defined as no new cerebral infarcts or hemorrhage) in 77 patients (84.6%). Postoperative infarcts or hemorrhages were seen in 14 patients (15.3%), with 1 postoperative mortality after withdrawal of care. One patient required postoperative shunting for hydrocephalus and a cerebrospinal fluid leak and 6 patients (6.9%) had cranial nerve III palsies that had either complete or significant improvement at their final clinic follow-up. Intraoperative aneurysm rupture occurred in 17 cases (18.7%). Intraoperative angiography showed complete aneurysm occlusion in 83 patients (91.2%), filling at the neck in 1 patient, and delayed aneurysm filling in 3 patients who had been wrapped or distally occluded. Four patients did not have angiography performed.

Functional outcomes at the last known follow-up showed an mRS score of 0–3 in 77 patients (84.6%). Comparing preoperative

Table 1. Patient Characteristics and Population Demographics

Characteristic	All Patients (n = 91)	
	n	%
Sex		
Male	29	31.87
Female	62	68.13
Age (years), mean \pm standard deviation	49	\pm 12.68
Smoking history		
Yes	39	50.65
No	38	49.35
	Missing = 14	
Initial presentation/Hunt and Hess grade		
0 (incidental)	11	12.09
1	26	33.77
2	3	3.90
3	24	31.17
4	12	15.58
5	1	1.30
	Subarachnoid hemorrhage NOS = 14	
Aneurysm location		
Anterior	76	83.52
Posterior	15	16.48
Aneurysm size (mm)		
Small (<7)	46	50.55
Medium (7–14.9)	37	40.66
Large (15–24.9)	4	4.40
Giant (>25)	4	4.40
NOS, not otherwise specified.		

with postoperative functional status, surgery resulted in a worsened status in 12 patients (13.2%). Within this group, final mRS score was 6 in 1 patient, 5 in 6 patients, and 4 in 5 patients. There were no recurrences after surgical treatment.

Multivariate analysis predicting poor outcomes after microsurgical retreatment identified 5 variables of interest from logistic regression analysis, including surgery type, age, having a bad outcome after initial endovascular therapy, aneurysm size (maximum diameter), and aneurysm neck size (Table 4). In the univariate unadjusted model, statistically significant increased odds of poor outcome (mRS score \geq 4) were associated with surgery type when comparing bypass with clipping without coil removal (odds ratio [OR], 6.67; 95% confidence interval [CI], 1.65–26.93). No significant difference was observed between coil removal versus no coil removal, although the overall trend seems to suggest that coil removal is associated with a worse

Table 2. Initial Admission, Discharge, and Endovascular Treatment Outcomes

Characteristic	All Patients (n = 91)	
	n	%
Initial endovascular therapy		
Coil only	85	93.40
Stent only	3	3.30
Stent + coil	3	3.30
Length of stay (days), mean \pm standard deviation	17	\pm 8.92
Initial endovascular procedural complications		
None	87	95.60
Procedural complications		
Intraoperative rupture	2	2.20
Cervical dissection (1 postoperative rupture)	2	2.20
Initial discharge modified Rankin Scale score		
0	2	2.20
1	34	37.36
2	18	19.78
3	20	21.98
4	14	15.38
5	3	3.30

outcome. When adding age to the model (model 2), the predicted odds of poor outcome associated with surgery type substantially change, indicating a significant confounding effect of age on surgery type. Initial bad outcome was similarly a significant confounder. Adjusting for aneurysm size and neck, although they were not significant as predictors themselves, resulted in a substantial change in parameter estimates already in the model. Addition of these confounders to the model caused the comparison of bypass with clipping without coil removal to weaken, although statistical significance was retained.

Logistic regression analysis predicting surgical and postoperative complications determined that no multivariate model outperformed univariate associations. Selecting from all possible models, only the size of the aneurysm neck was found to be a significant predictor of surgical complications (Wald $\chi^2 = 10.79$; $P = 0.0010$) with an OR of 2.32 (95% CI, 1.40–3.83) for a 2-mm increase in neck size. Major complications were best predicted by maximum aneurysm diameter in a univariate model (Wald $\chi^2 = 0.68$; $P = 0.0011$) with an OR of 2.36 (95% CI, 1.41–3.93) for a 5-mm increase in diameter. Aneurysm neck size was also associated in univariate analysis (Wald $\chi^2 = 0.23$; $P = 0.0014$) and confounded the relationship between maximum diameter and complications in a multivariate model. No other variables were found to be significant predictors of complications or confounders of these associations. Size of recurrence was also not found to be a significant predictor of complications.

The second population for analysis was the pooled data of patients reported in the literature (Figure 2). Fifty-one potential studies were identified reporting on outcomes of patients undergoing microsurgical retreatment of intracranial aneurysms previously treated by endovascular means. Of these studies, 5 were excluded for nontopical data reported, and 9 were excluded for reporting only mean/average measures of overall results without consideration for patient-level data. Thirty-seven studies were used to pool data on 370 total patients for analysis (Supplementary Table 1). Logistic regression analysis analogous to that shown in Table 4 determined a similar relationship between surgery type and the risk of poor outcome (Table 5). Bypass/PAO/other surgery type was initially associated with significantly increased odds of poor outcome (OR, 2.32; 95% CI, 1.16–4.66); however, this was confounded by patient age. More substantially, this effect was also confounded by initial Hunt and Hess grade. Although not significant itself as a predictor of poor outcome after surgical retreatment (OR, 1.24; 95% CI, 0.95–1.61), addition of Hunt and Hess to the model resulted in a large change in the B coefficients of surgery type, resulting in a loss of significance predicting overall poor outcome in the final model.

Examining the pooled subset of patients who had an initial endovascular treatment other than Guglielmi detachable coil (GDC) coiling determined that 23/30 non-GDC patients had good outcomes (Supplementary Table 2). Factors associated with a bad outcome were multiple previous treatments and attempted removal of well-incorporated stent material. Examining only patients who were stented, 9/14 had a good outcome (64.3%).

DISCUSSION

Endovascular treatment of aneurysms has significantly improved since its introduction in the early 1990s as a result of constant technological developments. Nevertheless, endovascular treatment of aneurysms also comes with a higher rate of retreatment as has been identified by multiple studies (BRAT [Barrow Ruptured Aneurysm Trial]¹⁹ and ISAT [International Subarachnoid Aneurysm Trial]³). The primary modality of retreatment after initial endovascular treatment remains endovascular therapy. The patients listed in the current series underwent discussion by a multidisciplinary team with open and endovascular expertise. Given the lengthy period encompassed by this series and the continued evolution of endovascular technology, it is reasonable to postulate that some of the earlier patients could have been treated by the modern generation of stents, flow diverters, distal access catheters, and microcatheters.

With the addition of previous results from our center by Zhang et al.,⁵ our results represent the largest published series of patients (129 patients) treated by microsurgical techniques after previous endovascular treatment. Our initial retrospective analysis on these data showed a major complication rate of 15.4%. This finding shows that good outcomes can be achieved at high-volume cerebrovascular centers in patients with high-risk aneurysms. Our univariate and multivariate analysis shows that although an increased odds of poor outcomes was seen with the need for bypass surgery, the relationships were confounded by age, aneurysm size, and sentinel event outcomes. Aneurysm

Table 3. Microsurgical Treatment Details and Outcomes

Characteristic	All Patients (n = 91)	
	n	%
Indication for surgery		
Aneurysm recurrence	64	70.33
Recurrence after repeat coiling	8	8.79
Known residual	19	20.88
Preoperative modified Rankin Scale score		
1	60	65.93
2	19	20.88
3	6	6.59
4	4	4.40
5	2	2.20
Surgery type		
Clipping alone	67	73.63
Clipping with coil removal	11	12.08
Clipping with wrapping	3	3.30
Wrapping alone	2	2.20
Bypass/parent artery occlusion/other	8	8.79
Length of stay (days), mean \pm standard deviation	7	\pm 6.4
Complications of surgery		
None	69	75.82
Cerebral infarction or hemorrhage	14	15.38
Cranial nerve III palsy (temporary)	6	6.59
Frontalis palsy	1	1.10
Cerebrospinal fluid leak—ventriculoperitoneal shunt	1	1.10
Last known modified Rankin Scale score		
1	41	45.05
2	23	25.27
3	13	14.29
4	8	8.79
5	5	5.49
6	1	1.10

maximal diameter and neck size were also predictive of surgical complications.

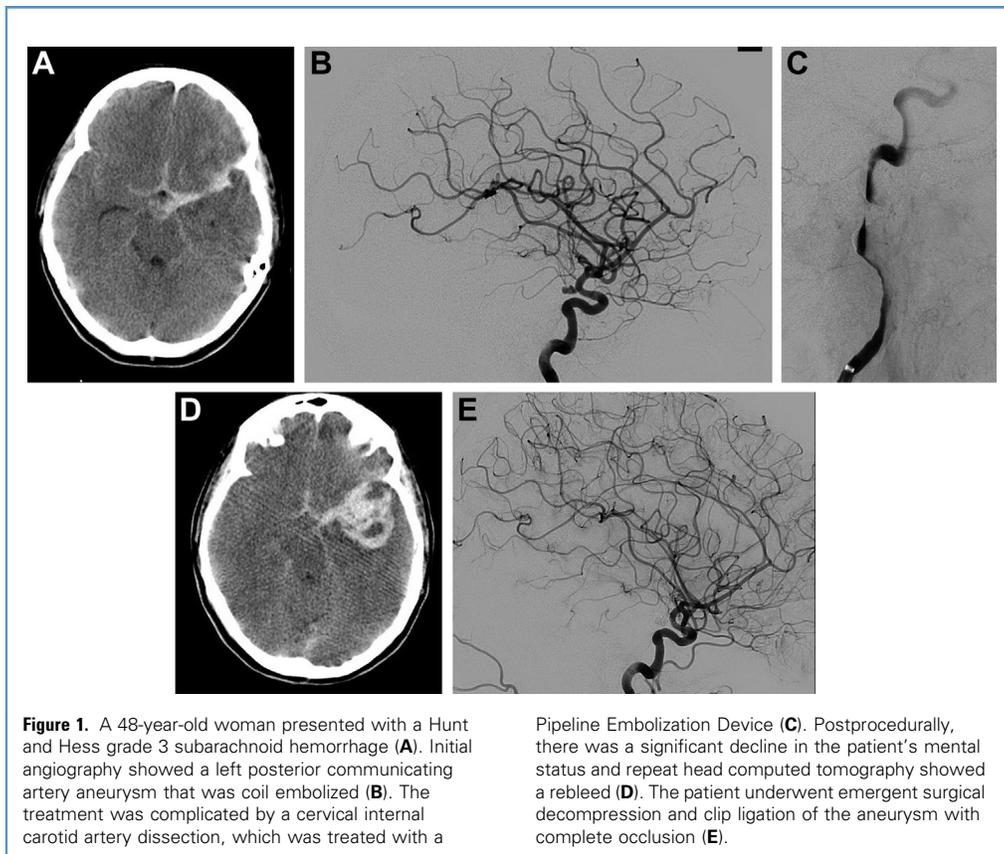
The 2 other large published series on surgical treatment of aneurysms after previous coiling include a study by Daou et al.² that looked at 111 patients and one by Romani et al.¹⁷ that reported on 81 patients. All other studies identified in our literature search were smaller single-center case series. In a meta-analysis conducted by Petr et al.,²⁰ 466 patients were analyzed. Long-term good neurologic outcomes defined as an mRS score <3 or a Glasgow Outcome Scale score of 4 or 5 were seen in 88.1% of patients. The

study by Romani et al.¹⁷ showed surgical outcomes to be the same or better than preoperative status in 87.8% of patients. Daou et al.² showed good outcomes in 90% of patients at the last visit as defined by an mRS score <3 . Our previous results showed good recovery in 86.8% of patients. These findings are all in line with our current results that showed surgery resulting in a worsening status in 13.2% of patients. Despite the increasing complexity of aneurysms requiring surgical treatment after endovascular techniques, the surgical outcomes have remained good, highlighting the need for these cases to be performed at high-volume cerebrovascular centers.

Our analysis showed that PAO was associated with worse outcomes consistent with previous reports²⁰; however, this was confounded by patient age and initial Hunt and Hess grade. Patient outcomes after treatment by endovascular means other than coiling were slightly limited by low numbers, given a total of 30 patients. Our pooled analysis model did not identify this group of patients to be predictors for poor outcomes despite the intuitive notion that clipping after stent-assisted coiling in particular would portend significantly increased risk. Within this population, outcomes were good in 76.7% of patients. Restricting analysis to a sample population of only patients who initially underwent stenting determined that only 64.3% of patients had a final good outcome. Although these patients seem to have worse outcomes, these aneurysms usually require adjunctive techniques for surgical clipping, including the possible use of bypass and PAO. Only 1 of the patients in the current series who underwent previous stenting required temporary parent artery clipping, which was tolerated.

Outcomes associated with microsurgical treatment of previously coiled recurrent aneurysms may be largely dependent on particular surgical technique. Previous single-institution series have typically been small, and heterogeneous with respect to patient selection, reported outcomes, and safety of coil removal.^{4,5,14,15,17,18,20-28} In our series, as well as in our secondary pooled analysis, coil retention versus removal as surgery type was not a significant predictor of outcome or complication rate. The only significant association with surgery type in our analysis seems to be an increased risk of poor outcome and complications among patients undergoing bypass or PAO, which is likely reflective of the inherent challenges of these techniques and other patient-specific and clinical factors.

There are several limitations to the present study, largely because of its retrospective nature and the inherent weaknesses associated with analysis of data collected from chart review. Of particular note is the variable follow-up time at both the post-endovascular and the postsurgical periods. We have attempted to mitigate the inequality in treatment timelines by comparing the immediate discharge outcomes as a means of standardization in addition to reporting preoperative to last known postoperative outcomes. In addition, although not significant in multivariate analysis, the variable between-procedure time interval and the specific indications explaining each patient's treatment timeline may serve as important confounders for which we were not able to control. Our pooled analysis is limited in that many of these patients are drawn from case reports/case series and may have a strong reporting bias. Furthermore, comparing across studies, there was considerable heterogeneity in the reporting of study data and predictor variables to be considered, thereby limited our



ability to construct a comprehensive data set for thorough analysis.

Although pooled analysis may be criticized as inferior to a formal analysis for comparing across studies, we believe that this

secondary analysis has value. First, pooling the data allows for multivariate regression analysis and for specific delineation of potential predictors of poor outcome in line with our study objectives. Second, a formal meta-analysis has already been

Table 4. Logistic Regression from Current Series Data of 91 Patients

Predictor Variables	Model											
	1		2			3			4			
	OR	95% CI	OR	95% CI	OR	95% CI	OR	95% CI	OR	95% CI		
Surgery type												
Clipping without coil/stent removal	1.00	Referent	1.00	Referent	1.00	Referent	1.00	Referent	1.00	Referent		
Clipping with coil/stent removal	1.33	0.14 12.54	1.96	0.17 23.37	1.80	0.12 27.04	1.78	0.10 32.41				
Bypass/parent artery occlusion/other	6.67	1.65 26.93	14.08	2.12 93.39	19.55	2.50 152.81	13.13	1.32 130.21				
Age (10 year difference)			5.23	1.99 13.79	5.46	1.93 15.58	4.73	1.61 13.79				
Initial bad outcome					3.79	0.75 19.07	5.37	0.93 31.18				
Aneurysm size (5 mm difference)							1.60	0.62 4.19				
Aneurysm neck (2 mm difference)							0.96	0.36 2.58				

OR, odds ratio; CI, confidence interval.

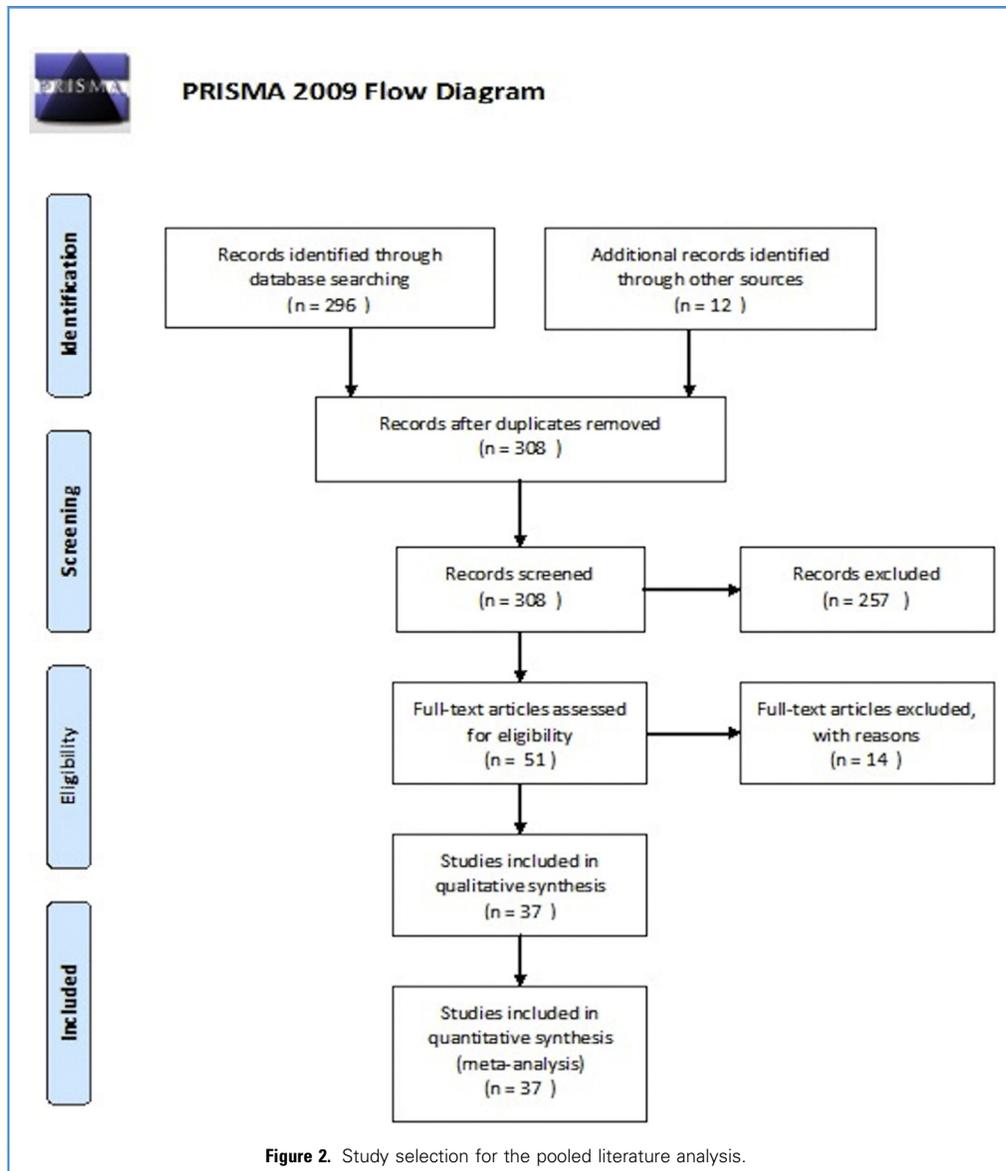


Table 5. Logistic regression from pooled literature analysis

Predictor Variables	Model								
	1			2			3		
	OR	95% CI		OR	95% CI		OR	95% CI	
Surgery type									
Clipping without coil/stent removal	1.00	Referent		1.00	Referent		1.00	Referent	
Clipping with coil/stent removal	1.78	0.94	3.36	1.75	0.92	3.32	1.95	0.88	4.30
Bypass/parent artery occlusion/other	2.32	1.16	4.66	2.19	1.09	4.42	1.98	0.84	4.65
Age (10 year difference)				1.20	0.97	1.49	1.15	0.89	1.48
Initial Hunt and Hess grade							1.24	0.95	1.61

OR, odds ratio; CI, confidence interval.

conducted with a similar, albeit smaller, body of literature.²⁰ The primary analysis of the present study is also valuable in that it represents the largest single-center series investigating these clinical issues. Furthermore, we have conducted a rigorous statistical analysis to control for other clinical factors, which has previously not been attempted. Perhaps most unique to our study is the restricted analysis of patients who initially underwent non-GDC endovascular treatments and the determination that microsurgical retreatment of aneurysms in this population is safe.

CONCLUSIONS

Favorable outcomes can be obtained even for highly complex cerebral aneurysms that have failed endovascular treatment at high-volume cerebrovascular centers. Initial presentation grade, age, and aneurysm size are important predictors of final patient outcomes. We must strive to maintain expertise in treating this small subset of aneurysms to maintain good outcomes.

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22. Conrad MD, Pelissou-Guyotat I, Morel C, Madarassy G, Schonauer C, Deruty R. Regrowth of residual ruptured aneurysms treated by Guglielmi's detachable coils which demanded further treatment by surgical clipping: report of 7 cases and review of the literature. *Acta Neurochir (Wien).* 2002;144:419-426.
23. Lejeune JP, Thines L, Taschner C, Bourgeois P, Henon H, Leclerc X. Neurosurgical treatment for aneurysm remnants or recurrences after coil occlusion. *Neurosurgery.* 2008;63:684-691 [discussion 691-682].
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SUPPLEMENTARY DATA

Supplementary Table 1. List of Studies and Patients Included Per Study in the Pooled Analysis	
Study	Patients Included (n)
Al-Schameri AR, Lunzer M, Daller C, Kral M, Killer M. Middle cerebral artery aneurysm surgery after stent misplacement: a case report. <i>Interv Neuroradiol</i> . 2016;22:49-52 ¹	1
Aoun SG, Rahme RJ, El Ahmadih TY, Bendok BR, Hunt Batjer H. Incorporation of extruded coils into the third nerve in association with third nerve palsy. <i>J Clin Neurosci</i> . 2013;20:1299-1302 ²	1
Asgari S, Doerfler A, Wanke I, Schoch B, Forsting M, Stolke D. Complementary management of partially occluded aneurysms by using surgical or endovascular therapy. <i>J Neurosurg</i> . 2002;97:843-850 ³	5
Boet R, Poon WS, Yu SC. The management of residual and recurrent intracranial aneurysms after previous endovascular or surgical treatment—a report of eighteen cases. <i>Acta Neurochir (Wien)</i> . 2001;143:1093-1101 ⁴	10
Bowers CA, Taussky P, Park MS, Neil JA, Couldwell WT. Rescue microsurgery with bypass and stent removal following Pipeline treatment of a giant internal carotid artery terminus aneurysm. <i>Acta Neurochir (Wien)</i> . 2015;157:2071-2075 ⁵	1
Chung J, Lim YC, Kim B, Lee D, Lee K-S, Shin YS. Early and late microsurgical clipping for initially coiled intracranial aneurysms. <i>Neuroradiology</i> . 2010;52:1143-1151 ⁶	29
Civit T, Auque J, Marchal JC, Bracard S, Picard L, Hepner H. Aneurysm clipping after endovascular treatment with coils: a report of eight patients. <i>Neurosurgery</i> . 1996;38:955-960 [discussion 960-961] ⁷	7
Conrad MD, Pelissou-Guyotat I, Morel C, Madarassy G, Schonauer C, Deruty R. Regrowth of residual ruptured aneurysms treated by Guglielmi's detachable coils which demanded further treatment by surgical clipping: report of 7 cases and review of the literature. <i>Acta Neurochir (Wien)</i> . 2002;144:419-426 ³	7
Deinsberger W, Mewes H, Traupe H, Boeker DK. Surgical management of previously coiled intracranial aneurysms. <i>Br J Neurosurg</i> . 2003;17:149-154 ⁹	7
Deshmukh VR, Hott JS, Dumont T, Nakaji P, Spetzler RF. Treatment of recurrent previously coiled anterior circulation aneurysm with minimally invasive keyhole craniotomy: report of two cases. <i>Minim Invasive Neurosurg</i> . 2006;49:70-73 ¹⁰	2
Ding D, Starke RM, Liu KC. Microsurgical strategies following failed endovascular treatment with the Pipeline Embolization Device: case of a giant posterior cerebral artery aneurysm. <i>J Cerebrovasc Endovasc Neurosurg</i> . 2014;16:26 ¹¹	1
Grasso G, Alafaci C, Passalacqua M, et al. Aneurysm clipping following endovascular coil embolization: a report of two cases. <i>Med Sci Monit</i> . 2009;15:CS63-66 ¹²	2
Gurian JH, Martin NA, King WA, Duckwiler GR, Guglielmi G, Viñuela F. Neurosurgical management of cerebral aneurysms following unsuccessful or incomplete endovascular embolization. <i>J Neurosurg</i> . 1995;83:843-853 ¹³	21
Horowitz M, Purdy P, Kopitnik T, Dutton K, Samson D. Aneurysm retreatment after Guglielmi detachable coil and nondetachable coil embolization: report of nine cases and review of the literature. <i>Neurosurgery</i> . 1999;44:712-719 [discussion 719-720] ¹⁴	5
Izumo T, Matsuo T, Morofuji Y, et al. Microsurgical clipping for recurrent aneurysms after initial endovascular coil embolization. <i>World Neurosurg</i> . 2015;83:211-218 ¹⁵	7
Kim YB, Lee KC, Lee JW, Huh SK, Yoon PH, Kim DI. Rescue microsurgery in coil herniation causing thromboembolic occlusion of parent artery. <i>Acta Neurochir (Wien)</i> . 2009;151:1609-1616 ¹⁶	6
Klein O, Colnat-Coulbois S, Civit T, et al. Aneurysm clipping after endovascular treatment with coils: a report of 13 cases. <i>Neurosurg Rev</i> . 2008;31:403-410 [discussion 410-411] ¹⁷	13
König RW, Kretschmer T, Antoniadis G, et al. Neurosurgical management of previously coiled recurrent intracranial aneurysms. <i>Zentralbl Neurochir</i> . 2007;68:8-13 ¹⁸	9
Kumar R, Deopujari CE, Shah R, Luhana R. Surgical management of intracranial aneurysms previously treated with endovascular therapy. <i>Neurol India</i> . 2010;58:292-297 ¹⁹	5
Ladouceur DL. Transcranial clipping of recurrent cerebral aneurysms after endovascular treatment. <i>Stroke</i> . 1993;24:1087-1089 ²⁰	2
Lejeune J-P, Thines L, Taschner C, Bourgeois P, Henon H, Leclerc X. Neurosurgical treatment for aneurysm remnants or recurrences after coil occlusion. <i>Neurosurgery</i> . 2008;63:684-691 [discussion 691-692] ²¹	21
Makoui AS, Smith DA, Evans AJ, Cahill DW. Early aneurysm recurrence after technically satisfactory Guglielmi detachable coil therapy: is early surveillance needed? Case report. <i>J Neurosurg</i> . 2000;92:355-358 ²²	1

Continues

Supplementary Table 1. Continued

Study	Patients Included (n)
Minh T, Hwang PYK, Nguyen KC, Ng I. Neurosurgical management of intracranial aneurysms following unsuccessful or incomplete endovascular therapy. <i>Br J Neurosurg.</i> 2006;20:306-311 ²³	7
Nakamura M, Montibeller GR, Götz F, Krauss JK. Microsurgical clipping of previously coiled intracranial aneurysms. <i>Clin Neurol Neurosurg.</i> 2013;115:1343-1349 ²⁴	15
Nomura M, Kida S, Uchiyama N, et al. Aneurysm clipping after partial endovascular embolization for ruptured cerebral aneurysms. <i>Interv Neuroradiol.</i> 2000;6(1 suppl):49-58 ²⁵	6
Pillai P, Karim A, Nanda A. Technical challenges to surgical clipping of aneurysmal regrowth with coil herniation following endovascular treatment—a case report. <i>J Med Case Rep.</i> 2007;1:168 ²⁶	1
Raftopoulos C, Vaz G, Docquier M, Goffette P, Interventional Cerebrovascular Group, Université Catholique de Louvain. Neurosurgical management of inadequately embolized intracranial aneurysms: a series of 17 consecutive cases. <i>Acta Neurochir (Wien).</i> 2007;149:11-19 [discussion 18-19] ²⁷	17
Rubino PA, Mura J, Kitroser M, et al. Microsurgical clipping of previously coiled aneurysms. <i>World Neurosurg.</i> 2014;82:e203-208 ²⁸	20
Thomas JA, Watson VE, McGrail KM. Surgical management of a paraclinoid aneurysm containing a displaced neuroform microstent: technical case report. <i>Neurosurgery.</i> 2008;63:E817 [discussion E817-818] ²⁹	1
Thornton J, Dovey Z, Alazzaz A, et al. Surgery following endovascular coiling of intracranial aneurysms. <i>Surg Neurol.</i> 2000;54:352-360 ³⁰	11
Tirakotai W, Sure U, Yin Y, et al. Surgery of intracranial aneurysms previously treated endovascularly. <i>Clin Neurol Neurosurg.</i> 2007;109:744-752 ³¹	8
Toyota S, Taki T, Wakayama A, Yoshimine T. Retreatment of recurrent internal carotid-posterior communicating artery aneurysm after coil embolization. <i>Neural Med Chir (Tokyo).</i> 2015;55:838-847 ³²	7
Vezenadaroglu E, Benitez RP, Rosenwasser RH. Surgically treated aneurysms previously coiled: lessons learned. <i>Neurosurgery.</i> 2008;62(6 suppl 3):1516-1524 ³³	10
Waldron JS, Halbach VV, Lawton MT. Microsurgical management of incompletely coiled and recurrent aneurysms: trends, techniques, and observations on coil extrusion. <i>Neurosurgery.</i> 2009;64(5 suppl 2):301-315 [discussion 315-317] ³⁴	43
Wang H-W, Sun Z-H, Wu C, Xue Z, Yu X-G. Surgical management of recurrent aneurysms after coiling treatment. <i>Br J Neurosurg.</i> 2017;31:96-100 ³⁵	21
Yoshida K, Wataya T, Hojo M, Doi D, Yamagata S. Surgical clipping of a recurrent small saccular aneurysm after repeated coil embolization. <i>Neural Med Chir (Tokyo).</i> 2005;45:356-359 ³⁶	1
Zhang YJ, Barrow DL, Cawley CM, Dion JE. Neurosurgical management of intracranial aneurysms previously treated with endovascular therapy. <i>Neurosurgery.</i> 2003;52:283-293 [discussion 293-295] ³⁷	39

Supplementary Table 2. List of Patients Included Per Study for the Pooled Non–Guglielmi Detachable Coil Analysis

Study	Age	Sex	Presentation/ Hunt and Hess	Aneurysm Location	Aneurysm Size	Endovascular Therapy Type	Endovascular Outcome	Endovascular Complications	Treatment Interval (m)	Surgery Type	Surgery Complications	Final Outcome
Current study	15	M	Incidental	Basilar tip	Large	Stent + coil	Bad	Two previous endovascular procedures; second one with iatrogenic SAH	76	SC	Quadripareisis from aneurysm thrombosis	Bad
Current study	67	F	Incidental	L OA	Large	Stent + coil	Good	Failed coiling, stent left in place	2	SC	None	Good
Current study	53	M	1	L PICA	Medium	Stent + coil	Bad	Left cerebellar infarct	27	Bypass	None	Good
Current study	29	M	Incidental	L distal anterior cerebral artery	Medium	Stent only	Good	None	5	SC	None	Good
Current study	50	M	4	ACoMA	Medium	Stent + coil	Good	Multiple recurrences and retreatment (coiling + stent revisions)	7	SC	None	Good
Current study	56	F	Incidental	L MCA	Giant	Stent only	Good	Multiple recurrences and retreatment (coiling + stent revisions)	76	Bypass ×2	L MCA infarction, intraoperative rupture	Bad
Current study	70	F	Incidental	R PComA + MCA	Medium	Stent only	Good	Failed stent deployment, initially coiled. Repeated stent attempt ×3. Recoiled. Two stents left in place	7	SC + removal	R MCA PCA watershed area infarction	Bad
Zhang et al. ³⁷	27	F	Incidental	Vertebral artery	Medium	Balloon occlusion	–	–	0	SC		Good
Zhang et al. ³⁷	58	M	Incidental	VBJ	Giant	Balloon occlusion	–	–	1	PAO		Good
Zhang et al. ³⁷	25	M	2	ICA	Giant	Balloon occlusion	–	–	24	PAO		Good
Zhang et al. ³⁷	51	F	Incidental	ICA	Giant	Balloon occlusion	–	–	4	Bypass		Good
Zhang et al. ³⁷	62	F	Incidental	ICA	Giant	Balloon occlusion	–	–	3	PAO		Good
Raftopoulos et al. ²⁷	61	F	2	ICA	Large	Stent only	–	–	72	SC		Good
Raftopoulos et al. ²⁷	56	M	1	PICA	Medium	Stent only	–	–	12	SC		Good
Kim et al. ¹⁶	46	F	Incidental	M2	Small	Balloon occlusion	–	–	0	SC + removal		Good
Kim et al. ¹⁶	55	F	4	ACoMA	Small	Balloon occlusion	–	–	0	SC + removal		Good
Ladouceur ²⁰	46	F	Incidental	PComA	Medium	Balloon occlusion	–	–	24	SC		Good
Ladouceur ²⁰	52	F	2	PComA	Medium	Balloon occlusion	–	–	18	SC		Good
Thomas et al. ²⁹	63	F	Incidental	ICA	Large	Stent only	–	–	3	SC		Good
Bowers et al. ⁵	58	F	Incidental	ICA	Giant	Pipeline embolization	–	–	0.5	Bypass		Good

M, male; SC, simple clipping; F, female; L, left; OA, ophthalmic artery; PICA, posterior inferior cerebellar artery; ACoMA, anterior communicating artery; MCA, middle cerebral artery; R, right; PCA, posterior cerebral artery; PAO, parent artery occlusion; ICA, internal carotid artery; PComA, posterior communicating artery; VBJ, vertebrobasilar junction.

Continues

Supplementary Table 2. Continued

Study	Age	Sex	Presentation/ Hunt and Hess	Aneurysm Location	Aneurysm Size	Endovascular Therapy Type	Endovascular Outcome	Endovascular Complications	Treatment Interval (m)	Surgery Type	Surgery Complications	Final Outcome
Al-Schameri et al. ¹	56	F	3	M2	Medium	Stent only	–	–	0	SC		Good
Gurian et al. ¹³	65	F	2	ICA	Giant	Balloon occlusion	–	–	0	Bypass		Good
Gurian et al. ¹³	63	F	3	ICA	Giant	Balloon occlusion	–	–	0	Bypass		Good
Gurian et al. ¹³	50	F	4	PCoMA	Small	Balloon occlusion	–	–	3	SC		Good
Gurian et al. ¹³	75	F	2	ICA	Large	Balloon occlusion	–	–	0	Bypass		Good
Gurian et al. ¹³	73	F	2	ICA	Giant	Balloon occlusion	–	–	0	Bypass		Good
Minh et al. ²³	40	F	1	PCoMA	Small	Stent only	–	–	0	SC		Bad
Ding et al. ¹¹	51	M	Incidental	PCA	Giant	Pipeline embolization	–	–	3	SC + removal		Bad
Gurian et al. ¹³	52	F	2	PCoMA	Small	Balloon occlusion	–	–	0	PAO		Bad
Gurian et al. ¹³	74	F	1	PCoMA	Medium	Balloon occlusion	–	–	1	SC + removal		Bad

M, male; SC, simple clipping; F, female; L, left; OA, ophthalmic artery; PICA, posterior inferior cerebellar artery; ACoMA, anterior communicating artery; MCA, middle cerebral artery; R, right; PCA, posterior cerebral artery; PAO, parent artery occlusion; ICA, internal carotid artery; PCoMA, posterior communicating artery; VBJ, vertebrobasilar junction.

Supplementary Table 3. Location of Aneurysms

Aneurysm Location	n
Middle cerebral artery	12
Anterior communicating complex	31
Distal anterior cerebral artery	8
Internal carotid artery—communicating segment	14
Internal carotid artery—ophthalmic segment	4
Internal carotid artery—anterior choroidal	2
Internal carotid artery—superior hypophyseal artery	4
Internal carotid artery—terminus	1
Basilar apex	8
Basilar trunk	1
Posterior inferior cerebellar artery	6

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- Raftopoulos C, Vaz G, Docquier M, Goffette P. Interventional Cerebrovascular Group Université Catholique de Louvain. Neurosurgical management of inadequately embolized intracranial aneurysms: a series of 17 consecutive cases. *Acta Neurochir (Wien)*. 2007;149:11-19 [discussion 18-19].
- Rubino PA, Mura J, Kitroser M, Botta JS, Salas E, Lambre J, et al. Microsurgical clipping of previously coiled aneurysms. *World Neurosurg*. 2014;82:e203-208.
- Thomas JA, Watson VE, McGrail KM. Surgical management of a paraclinoid aneurysm containing a displaced neuroform microstent: technical case report. *Neurosurgery*. 2008;63:E817 [discussion E817-E818].
- Thornton J, Dovey Z, Alazzaz A, Misra M, Aletich VA, Debrun GM, et al. Surgery following endovascular coiling of intracranial aneurysms. *Surg Neurol*. 2000;54:352-360.
- Tirakotai W, Sure U, Yin Y, Benes L, Schulte DM, Bien S, et al. Surgery of intracranial aneurysms previously treated endovascularly. *Clin Neurol Neurosurg*. 2007;109:744-752.
- Toyota S, Taki T, Wakayama A, Yoshimine T. Retreatment of recurrent internal carotid—posterior communicating artery aneurysm after coil embolization. *Neurol Med Chir (Tokyo)*. 2015;55:838-847.
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- Yoshida K, Wataya T, Hojo M, Doi D, Yamagata S. Surgical clipping of a recurrent small saccular aneurysm after repeated coil embolization. *Neurol Med Chir (Tokyo)*. 2005;45:356-359.
- Zhang YJ, Barrow DL, Cawley CM, Dion JE. Neurosurgical management of intracranial aneurysms previously treated with endovascular therapy. *Neurosurgery*. 2003;52:283-293 [discussion 293-285].