Microsurgical treatment of arteriovenous malformations in pediatric patients: the Boston Children's Hospital experience

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OBJECT Outcomes of microsurgical treatment of arteriovenous malformations (AVMs) in children are infrequently reported across large cohorts.

METHODS The authors undertook a retrospective review of departmental and hospital databases to obtain the medical data of all patients up to 18 years of age who were diagnosed with cerebral AVMs. Demographic and AVM angioarchitectural characteristics were analyzed, and for the patients who underwent surgery, the authors also analyzed the estimated intraoperative blood loss, postoperative angiographically confirmed obliteration rates, and neurological complications and outcomes classified according to the modified Rankin Scale (mRS).

RESULTS Of 117 children with cerebral AVMs, 94 underwent microsurgical resection (80%). Twenty (21%) of these 94 patients underwent adjunctive preoperative embolization. The overall postoperative angiographically confirmed obliteration rate was 94%. As part of a new protocol, the last 50 patients in this series underwent immediate perioperative angiography, improving the subsequent obliteration rate from 86% to 100% ($p = 0.01$). No other factors, such as a hemorrhagic AVM, size of the AVM, location, drainage, or Spetzler-Martin grade, had a statistically significant impact on the obliteration rate. Perioperative neurological deficits occurred in 17% of the patients, but the vast majority of these (77%) were predictable visual field cuts. Arteriovenous malformations that were hemorrhagic or located in noneloquent regions were each associated with lower rates of postoperative neurological complications ($p = 0.05$ and 0.002 , respectively). In total, 94% of the children had good functional outcomes (mRS Scores 0–2), and these outcomes were significantly influenced by the mRS score on presentation before surgery ($p = 0.01$). A review of 1- and 5-year follow-up data indicated an overall annual hemorrhage rate of 0.3% and a recurrence rate of 0.9%.

CONCLUSIONS Microsurgical resection of AVMs in children is associated with high rates of angiographically confirmed obliteration and low rates of significant neurological complications. Implementation of a protocol using perioperative angiography in this series led to complete radiographically confirmed obliteration of all AVMs, with low annual repeat hemorrhage and recurrence rates.

<http://thejns.org/doi/abs/10.3171/2014.9.PEDS146>

KEY WORDS AVM; arteriovenous malformation; angiography; surgery; microsurgery; embolization; pediatric; vascular disorders

CHILDREN with arteriovenous malformations (AVMs) face a lifetime risk of life-threatening intracranial hemorrhage along with symptoms such as chronic headaches, seizures, and progressive neurological deficits due to focal cerebral steal phenomena.^{5,7,18,33} Effective counseling about treatment options and anticipated results depends on a clear understanding of the procedural morbidity and obliteration rates. Reports of treatment outcome in moderate- to large-size pediatric cohorts are rare.^{2,5,16,18,22,27,31} We reviewed our own surgical experience

with AVMs to elucidate obliteration rates and treatment results in the context of an evolved institutional protocol.

Methods

Patients and Study Design

With the approval of the Boston Children's Hospital Institutional Review Board, we undertook a retrospective review of departmental and hospital databases to identify all patients up to 18 years of age in whom cerebral AVMs

ABBREVIATIONS AVM = arteriovenous malformation; mRS = modified Rankin Scale.

SUBMITTED January 4, 2014. **ACCEPTED** September 22, 2014.

INCLUDE WHEN CITING Published online October 31, 2014; DOI: 10.3171/2014.9.PEDS146.

DISCLOSURE The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper. This study received support from the Stuart and Jane Weitzman Vascular Anomalies Center Fund.

were diagnosed from 1995 through October 2013. For this period, complete radiographic and clinical records were available from all databases. Patients with arteriovenous fistulas, vein of Galen malformations, and spinal vascular malformations of any type were excluded from the analysis. We reviewed the records of the patients to identify the following variables: patient age at presentation, sex, mode of presentation, AVM angioarchitectural characteristics (that is, location, size, venous drainage, and associated aneurysms), embolization procedures, early and late angiographically confirmed obliteration rates, the estimated surgical blood loss, and neurological complications. The neurological conditions at presentation and at last follow-up were classified by the modified Rankin Scale (mRS).³⁹ Statistical analysis for categorical variables was performed with the Fisher exact test, and comparisons between mean values of continuous variables were performed with a 2-sided t-test.

Surgical Technique

Prior to incision, we ensured that matched blood products were in the operating room, that the microscope was draped, and that temporary aneurysm clips were selected and loaded. In all cases, a craniotomy was performed, ensuring that the margins of the lesion lay well within the margins of the operative exposure, and the dissection was performed under the operating microscope once the dura was opened. When feasible, an early identified superficial draining vein could be followed proximally to localize the nidus. Easily identifiable and major arterial feeders were then coagulated.²⁴ An anatomical, circumferential cortical and subcortical dissection was performed with serial coagulation of supplying arterial pedicles before disconnecting the venous drainage. Indocyanine green angiography was variably employed to help distinguish arterial feeders from arterialized veins, identify en passage vessels, and to confirm resection. Since 2008, we have adopted a formal protocol in which all patients remain under general anesthesia and are transferred to the dedicated angiography suite (50 patients in this study were treated with this protocol). If a residual AVM is detected, the patient is returned to the operating room for AVM resection; otherwise, anesthesia is reversed, and extubation is performed in the angiography suite.

Embolization Technique

As part of the new protocol, since 2008, all children were evaluated for potential preoperative embolization before microsurgical resection. In most cases, embolization was performed on the day prior to microsurgical resection, with the patient being monitored in the intensive care unit overnight. This timing allowed for a full day and early start for the subsequent resection and was appropriate for most cases; some small AVMs were embolized, followed immediately by resection in the same anesthesia period. All of these procedures were performed under general anesthesia.

The goal of the embolization was to deeply penetrate the nidus with the embolic agent (most commonly Onyx [ev3]) while carefully avoiding occlusion of the venous drainage. Arterial pedicles were chosen on the basis of the

access they provide to the AVM nidus and their location. Deep pedicles that were not expected to be encountered along the surgical track from the periphery to the AVM were systematically embolized if feasible. If resection was scheduled for the following day, a dexmedetomidine drip was initiated during the embolization session and then continued after a “deep” extubation. This procedure ensured strict blood pressure control while allowing for serial neurological examinations until surgery the following morning.

Results

Overall Population and Rationale for Nonoperative Management

Our overall cohort consisted of 117 pediatric patients with cerebral AVMs (Table 1). The cohort displayed no significant bias in the sex ratio (47% male), and presentation included hemorrhage in 52% of the cases, headache without hemorrhage in 20%, seizures in the absence of hemorrhage in 12%, and an asymptomatic/incidental finding in 16%. Four of the children had hereditary hemorrhagic telangiectasia (HHT), and 2 had a family history of cerebral AVMs without a diagnosis of HHT. By mRS score, 68% of patients were functionally independent (that is, their score was 0–2). Two children died as a result of their hemorrhage, 7 were referred for stereotactic radiosurgery because the AVM was located in deep or eloquent cortex, and the remaining 14 patients underwent observation only (because of a high Spetzler-Martin grade or a preference expressed by the family) and/or underwent treatment at other institutions. The remaining 94 patients (80%) were treated with microsurgical resection, 20 of whom (21%) had adjunctive preoperative embolization.

Surgical Population: Clinical and Radiographic Presentation

The surgical cohort also showed no significant bias in the sex ratio (46% male). Mean age at the time of surgery was 10.9 years (SD 4.5 years, range 3 months to 18 years). Most of the patients presented with hemorrhage (56%), and the remaining patients had headaches (18%), seizures (13%), or were asymptomatic (13%). According to the mRS, 69% of the patients were independent (that is, had mRS scores of 0–2). The AVM location was lobar in 82% of the cases, cerebellar in 14%, and deep supratentorial in 4%. Most AVMs (76%) were small (up to 3 cm in diameter), 21% were 3–6 cm, and 3% were larger than 6 cm in diameter. Thirty-five percent of the AVMs had deep venous drainage, and 13% had an aneurysm either on an associated feeding artery or at an intranidal location. Classified by Spetzler-Martin grade,³⁶ 19% of the AVMs were Grade I, 46% were Grade II, 32% were Grade III, and 3% were Grade IV. Demographic and AVM angioarchitectural characteristics did not significantly differ between the surgical cohort and the cohort at large (Table 1).

Surgical Outcomes

The surgical outcomes are summarized in Table 2. Of 87 patients undergoing formal postoperative angiography, 82 showed obliteration of the AVM (94%). In the most recent 50 cases, angiography was performed according to

TABLE 1. Characteristics of all patients and of those undergoing surgery*

Variable	All Patients (%)	Surgical Cohort (%)
No. of patients	117 (100)	94 (100)
Male sex	55 (47)	43 (46)
Presentation		
Incidental	19 (16)	12 (13)
Headache (no hemorrhage)	23 (20)	17 (18)
Seizure (no hemorrhage)	14 (12)	12 (13)
Hemorrhage	61 (52)	53 (56)
Presenting mRS score		
0	19 (16)	12 (13)
1	49 (42)	44 (47)
2	12 (10)	9 (10)
0–2 combined	80 (68)	65 (69)
3	12 (10)	9 (10)
4	9 (8)	9 (10)
5	14 (12)	11 (12)
6	2 (2)	0 (0)
Location		
Lobar	92 (79)	77 (82)
Deep supratentorial	11 (9)	4 (4)
Cerebellar	14 (12)	13 (14)
AVM diameter†		
Up to 3 cm	60 (70)	52 (76)
3–6 cm	21 (24)	14 (21)
>6 cm	5 (6)	2 (3)
Deep venous drainage‡	45 (42)	31 (35)
Spetzler-Martin grade†		
I	13 (15)	13 (19)
II	36 (42)	31 (46)
III	27 (31)	22 (32)
IV	7 (8)	2 (3)
V	3 (3)	0 (0)
Associated aneurysm§	12 (13)	9 (13)

* All values indicate number (%) of patients; in cases in which the number of patients in subgroups differs from the total numbers in the main groups (that is, all patients and the surgical cohort), the total number in each subgroup is indicated.

† The total numbers of patients assessed for this variable were 86 for all patients and 68 for the surgical cohort; percentages were calculated with these totals.

‡ The total numbers of patients assessed for this variable were 108 for all patients and 88 for the surgical cohort; percentages were calculated with these totals.

§ The total numbers of patients assessed for this variable were 91 for all patients and 72 for the surgical cohort; percentages were calculated with these totals.

the protocol described above, that is, immediately after wound closure. This immediate postoperative angiography clearly improved obliteration rates, which increased from 86% to 100% after initiation of this protocol ($p = 0.01$) (Table 3). Preoperative embolization, hemorrhagic presentation, larger AVM size, AVM location in eloquent regions, deep venous drainage, and Spetzler-Martin grades of III or IV did not significantly affect obliteration

TABLE 2. Overall surgical outcomes

Parameter	Relative Rate (%)
Obliteration rate	82/87 (94)
Preop embolization	20/94 (21)
Periop angiography	50/94 (53)
Neurological complications	
Total	16/94 (17)
Visual field deficit	12/94 (13)
Hemiparesis/hemiplegia	3/94 (3)
New seizures	3/94 (3)
Neurological complication by Spetzler-Martin grade	
I	0/13 (0)
II	5/31 (16)
III–IV	7/24 (29)
Neurological outcome by mRS score	
0	45/94 (48)
1	30/94 (32)
0–2	88/94 (94)

rates in this study, but deep venous drainage tended to be associated with a higher rate of nonobliteration ($p = 0.11$).

Overall, the mean estimated blood loss during AVM surgery was 212 ml (median 150 ml). Surgery on hemorrhagic ($p = 0.02$) and smaller ($p = 0.0001$) AVMs was associated with lower operative blood loss, while preoperative embolization, AVM location, deep venous drainage, and Spetzler-Martin grade did not appear to significantly influence operative blood loss (Table 4).

Sixteen patients (17%) had new and lasting neurological deficits after surgery, but in 12 of these patients (75%), these deficits were anticipated visual field cuts, given that these 12 AVMs were located close to optic radiations, the calcarine cortex, or both. Three patients (3%) had new-onset seizures requiring antiepileptic medication for long-term seizure control, and 3 had new postoperative hemiparesis due to proximity of the AVMs to the motor/premotor cortex in 2 cases and to the internal capsule in 1 case. Evaluating the impact of Spetzler-Martin grade on neurological complications, we noted that none of the patients with Grade I, 16% with Grade II, and 29% with Grade III or IV AVMs had neurological complications. Arteriovenous malformations in noneloquent regions ($p = 0.002$) and hemorrhagic AVMs ($p = 0.05$) were associated with lower postoperative rates of neurological complications (Table 5).

Long-Term Follow-Up

The mean clinical follow-up duration in this series was 3.6 years. In total, 54% of the patients were asymptomatic (that is, had an mRS score of 0) at the follow-up, compared with 13% before the surgery. Ninety-four percent of patients were clinically independent at the follow-up (mRS Score 0–2), an improvement from a rate of 69% prior to surgery; a higher mRS score before surgery significantly predisposed patients to a higher mRS score after surgery ($p = 0.01$) (Table 6). Seventy-six patients had at least 1 year of clinical follow-up; 24 patients had at least 5 years

TABLE 3. Factors for complete AVM obliteration rates*

Characteristic/Risk Factor	Obliteration Rate (%)		p Value
	Yes	No	
Preop embolization	19/19 (100)	63/68 (93)	0.58
Hemorrhagic presentation	49/53 (92)	33/34 (97)	0.64
Larger AVM size (≥ 3 cm)	16/16 (100)	47/48 (98)	1.0
AVM in eloquent region	48/51 (94)	34/36 (94)	1.0
Deep venous drainage	25/28 (89)	53/54 (98)	0.11
Spetzler-Martin Grade III or IV	22/22 (100)	41/42 (98)	1.0
Use of early postop angiography/new protocol	50/50 (100)	32/37 (86)	0.01

* The table compares the obliteration rates in the presence or absence of the 7 different factors and AVM characteristics.

of follow-up; and both of these groups had similar rates of clinical independence (that is, an mRS score < 3 in 93% and 88% of patients, respectively).

Over a combined 337.3 patient-years of clinical follow-up, 3 postoperative hemorrhages were observed in 3 patients (equivalent to a 0.9% annualized rate). Two hemorrhages occurred from known residual postoperative AVMs and 1 from a recurrent AVM. Of note, none of these 3 patients underwent perioperative angiography. In all 3 cases, the patient was returned to the operating room and the residual or recurrent AVM was resected. Considering only the 82 initially angiographically confirmed and obliterated AVMs, 1 postoperative hemorrhage originated from a recurrent AVM, corresponding to an annualized hemorrhage rate of 0.3% over 288.3 patient-years of clinical follow-up.

Including both postoperative MRI and MR angiography in these 82 cases, a total of 212.1 patient-years of imaging follow-up (mean 2.6 years) was recorded, during which 2 radiographic recurrences of AVMs were observed (corresponding to a 0.9% annualized recurrence rate). In both cases, the recurrent AVM was resected. Of the 82 patients, 55 had repeated formal digital subtraction angiography 1–2 years after the surgery, with a total of 66.6 patient-years of formal angiographic follow-up over which 2 recurrences were found. Fourteen patients had MRI follow-up at least 5 years after surgery and no recurrences of AVMs were observed in these cases.

TABLE 4. Mean intraoperative blood loss*

Characteristic/Risk Factor	Mean Estimated Blood Loss (ml)		p Value
	Yes	No	
Preop embolization	280	191	0.16
Hemorrhagic presentation	147	315	0.002
Larger size (≥ 3 cm)	453	160	0.0001
AVM in eloquent region	202	228	0.65
Deep venous drainage	160	242	0.18
Spetzler-Martin Grade III or IV	263	210	0.46

* The mean estimated blood loss in all procedures was 212 ml (median 150 ml). The table compares the blood loss in the presence or absence of the 6 different factors and AVM characteristics.

TABLE 5. Rates of postoperative neurological complications*

Characteristic/Factor	Neurological Complications (%)		p Value
	Yes	No	
Preop embolization	3/20 (15)	13/74 (18)	1.0
Hemorrhagic presentation	6/57 (11)	10/37 (27)	0.05
Larger AVM size (≥ 3 cm)	5/16 (31)	7/52 (13)	0.14
AVM in eloquent region	15/55 (27)	1/39 (3)	0.002
Deep venous drainage	6/31 (19)	10/57 (18)	1.0
Spetzler-Martin Grade III or IV	7/24 (29)	5/44 (11)	0.10
Use of early postop angiography/new protocol	7/50 (14)	9/44 (20)	0.43

* The table compares neurological complications in the presence or absence of the 7 different factors and AVM characteristics.

Discussion

Cerebral AVMs have been proposed to form as a result of the failure of primitive vascular channels to differentiate into arteries, interposed capillaries, or veins. Although their natural history has not been prospectively studied in pediatric cohorts, a recent retrospective analysis of 120 pediatric patients with AVMs reported an annual hemorrhage rate of 4%.⁵ Assuming that in our surgical cohort the AVMs were present since birth, the retrospective annual hemorrhage rate in this series was 5.5% (that is, 57 events during 1026 patient-years). However, because this rate was derived from a surgical cohort, this estimate was potentially biased toward an increased representation of more aggressive malformations. Nonetheless, these rates are similar to or slightly higher than those reported for adults.^{4,11,37}

The overall mortality rate due to AVM rupture in children is as high as 21% in some series.¹⁸ Furthermore, AVMs may undergo dynamic changes in morphology and develop associated arterial and venous aneurysms and venous stenoses as the patient ages. Young women must also anticipate an elevated risk of hemorrhage during pregnancy,¹⁰ and all children with an AVM must bear the psychological burden of possessing a lesion that may cause neurological devastation or even death at any time in their life. Thus, regardless of rupture status, in our opinion all AVMs in children should be evaluated for potential treatment.

Patient Selection

Of the AVMs in our series, 80% were managed surgically. Our “surgery-first” approach is based on the surgical advantages of immediate therapeutic cure and high obliteration rates. This approach is in contradistinction to the unknown long-term impact of cranial radiosurgery in children, both in regard to obliteration rate and other long-term complications of this treatment. Immediate therapeutic management is particularly advantageous in cases of ruptured AVMs, as such patients face a greater risk of rerupture,^{4,11,37} particularly in the first year.¹² In children presenting with clinical and/or radiographic signs of herniation from an acute hemorrhage, we prefer to evacuate the clot without attempting a resection of the AVM. If feasible, after the administration of mannitol, we perform

TABLE 6. Rates of poor neurological outcome for various AVM characteristics and surgical procedures*

Characteristic/factor	Neurological Outcome (%)		p Value
	Yes	No	
mRS score >2 before surgery	5/29 (17)	1/60 (2)	0.01
Preop embolization	1/20 (5)	5/74 (7)	1.0
Hemorrhagic presentation	5/57 (9)	1/37 (3)	0.40
Larger AVM size (≥ 3 cm)	1/16 (6)	2/52 (4)	0.56
AVM in eloquent region	3/55 (5)	3/39 (8)	0.69
Deep venous drainage	4/31 (13)	2/57 (4)	0.18
Spetzler-Martin Grade III or IV	2/24 (8)	1/44 (2)	0.28
Use of early postop angiography/new protocol	2/50 (4)	4/44 (9)	0.41

* Poor neurological outcome was defined as an mRS score > 2.

a preoperative CT angiogram en route to the operating room to help delineate a safe route to the clot without disrupting the AVM. Formal digital subtraction angiography and AVM treatment are performed after evacuation of the clot along an individualized treatment course based on the child's recovery.

It is interesting to note that in our series, microsurgical resection of hemorrhagic AVMs was associated with significantly lower postoperative neurological complication rates as well as lower intraoperative blood loss than resection of nonhemorrhagic AVMs. The lower neurological complication rate after surgery for ruptured AVMs is consistent with previous studies^{13,23} and has in fact been incorporated in a recently published AVM grading scale that includes an older patient age, nonhemorrhagic presentation, and diffuse nidus morphology as significant risk factors for surgical morbidity.²³ Importantly, although new neurological deficits were noted in 17% of the patients at follow-up in this series, the vast majority—over three-quarters (77%)—of these deficits were relatively minor and were anticipated visual field deficits after resection of AVMs. Unanticipated neurological complications were observed in 4 patients (4%)—2 having new weakness and seizures requiring antiepileptic medication, 1 having a new seizure disorder, and another having a new weakness. As expected, in our study, Spetzler-Martin grade³⁶ did correlate with surgical morbidity; however, location in an eloquent brain region emerged independently as a statistically significant factor that had the greatest impact on postoperative complications, consistent with our experience with other vascular malformations.¹⁵

We do recommend radiosurgery for AVMs of appropriate size that are located in eloquent areas, such as the motor cortex, functional speech cortex, the basal ganglia, thalamus, and brainstem. It is intriguing that an extensive number of studies have reported using radiosurgery to manage AVMs in children.^{1,3,5,6,20,25,28,30,34,40} By comparison, reports of surgical AVM series, summarized in Table 7,^{2,5,8,9,16–18,21,22,27,31} are sparse and contain fewer patients, but some describe better results after resection of AVMs in children than in adults.³¹ Furthermore, as most pediatric AVMs in nearly all series are hemorrhagic,^{2,8,9,16–18,22} a more aggressive, expedient therapy via microsurgery, as

TABLE 7. Literature reports of surgical treatment for AVMs in children

Authors & Year	No. of Patients	Obliteration Rate (%)	Complication Rate (%)
Bristol et al. 2006	64*	65	19
Darsaut et al. 2011	NS†	67	10
Fong & Chan 1988	27	NS	15
Garza-Mercado et al. 1987	12	83	33
Hladky et al. 1994	52	90	19
Hoh et al. 2000	21	95	5
Humphreys et al. 1996	125	85	NS
Kiriş et al. 2005	20	89	10
Klimo et al. 2007	35	76	14
Nair et al. 2012	36	100	14
Sanchez-Mejia et al. 2006	32	97	6
Current series	94	94	17

NS = not specified.

* From a series of 82 children undergoing any treatment modality.

† From a series of 120 children who underwent 104 surgical procedures; procedures included attempts at AVM obliteration and those aimed at only treating associated aneurysms.

opposed to radiosurgery, should be sought in such cases. It is interesting to note that in the most recent iteration of radiosurgical grading schemes, hemorrhage was considered an adverse factor for radiosurgical success,³⁸ an assessment that differs from the observed impact of hemorrhage on the outcomes of microsurgery.²³ We did not observe significant operative blood loss, a potential limitation of microsurgery relative to radiosurgery, and our obliteration rates were high. As underscored by our data and by those of previous series, immediate perioperative angiography appears crucial in achieving total AVM obliteration.² Radiosurgical series may rely on noninvasive imaging modalities to reach conclusions about obliteration status of AVMs,^{3,25,34} and potentially delayed radiosurgical complications are of particular concern in pediatric patients.^{14,19,29,32}

Although the management of unruptured AVMs has come under considerable scrutiny as a result of the ARUBA study ("A Randomized trial of Unruptured Brain Arteriovenous malformations"),²⁶ the observations in that study have little relevance to pediatric patients, given that children were excluded from the ARUBA study and that the length of its clinical follow-up was shorter (the mean length of follow-up was < 3 years). Furthermore, although 76 of the 114 AVMs in the ARUBA interventional group (68%) were of Spetzler-Martin Grades I or II, only 5 were treated with microsurgery (4%) and 12 with microsurgery and embolization (11%). This makes it difficult to draw any conclusions from the ARUBA study about the impact of microsurgical resection on unruptured AVMs compared with that of observation only. Nonetheless, a review of the ARUBA study is relevant, as its data reveal an annual stroke rate of approximately 4% for untreated AVMs.

The data reported here are important, as the natural history of untreated AVMs in children incorporates an annual hemorrhage rate of 4%–5.5%. These percentages contrast sharply with our postsurgery annual hemorrhage

rate of 0.3%, representing a marked reduction in bleeding risk that is directly attributable to the surgical treatment. Consequently, the data of others, coupled with our experience reported here, support the practice of employing resection to improve the natural history and outcomes in children with intracranial AVMs.

Rationale for AVM Embolization

Although our results did not indicate greater obliteration rates and lower estimated blood loss after preoperative embolization, the absence of these improvements was likely an artifact of selection bias. We did not embolize all AVMs but rather only larger AVMs and those with deep arterial feeders. This selective embolization had the goal of reducing anticipated blood loss, of lowering the risk of perfusion pressure breakthrough, and of providing an Onyx-marked intraoperative guide to the lesion. Our surgical preference for Onyx stems not only from the roadmap it provides to feeding vessels at surgery, but also from the relative ease of coagulating and handling vessels embolized with Onyx as compared with *N*-butyl cyanoacrylate. In our cohort, 1 child had a postembolization hemorrhage (corresponding to a complication rate of 4.8%); however, the child recovered well and had no long-term neurological sequelae. A recent study of 25 children undergoing 38 procedures for Onyx embolization of AVMs reported an overall obliteration rate of 12%, with a procedural complication rate of 26.3% and no permanent neurological morbidity.³⁵

Given the potential for long-term AVM recurrence in children, even if complete angiographically confirmed obliteration is serendipitously achieved, we would proceed to resection, wherever feasible, regardless of the postembolization angiographic appearance. Complete obliteration is not the primary goal of our embolization sessions. Our low embolization-related morbidity, coupled with our low total periprocedural morbidity and high AVM obliteration rates, highlights the potential advantages of adjunctive embolization used selectively in cases where an additional procedure provides a clear advantage.

Utility of Perioperative Angiography

In 2008, our institution developed a standardized protocol for the treatment of children with intracranial AVMs. An important component of this protocol is the inclusion of high-quality perioperative catheter angiography to confirm resection of the AVM prior to the conclusion of anesthesia. We observed no complications from the additional angiography. After the introduction of this protocol, the postoperative angiographically confirmed obliteration rates significantly improved from 86% to 100% ($p = 0.01$; Table 3). These results support the continued use of perioperative angiography. It is critical to emphasize that we use high-quality, biplane angiography, in contrast to the lower-quality portable units in the operating room. This markedly improves the resolution of the images and enhances the likelihood of identifying small residual AVMs.

Long-Term Results

Importantly, our series included both unruptured and ruptured AVMs with comparable results in both cohorts. Although AVMs that presented with hemorrhage did have

lower volumes of operative blood loss and lower rates of perioperative neurological deficits (Tables 4 and 5), it is important to note that the presence or absence of a hemorrhage neither had a significant impact on the rate of surgical obliteration (Table 3) nor influenced the likelihood of long-term poor neurological outcomes (Table 6).

Considering a reported natural history of AVMs that includes a 4%–5.5% annual hemorrhage rate and an up to 20% mortality rate from each hemorrhage, we demonstrated that resection of AVMs confers a 0.3% annual hemorrhage rate and is associated with a 0.9% recurrence rate. Perioperative angiography significantly improved resection rates. Over a long period of follow-up (mean length 3.6 years), outcomes were excellent, with similar, durable 1- and 5-year rates of clinical independence (93% and 88%, respectively).

Conclusions

This series of pediatric patients with AVMs who underwent microsurgery demonstrates high obliteration rates (94% overall), acceptable rates of blood loss (mean blood loss 212 ml), and low rates of neurological complications, which were anticipated and manifested primarily as visual field deficits. Blood loss during surgery was lower for smaller and hemorrhagic AVMs. Surgeries on hemorrhagic AVMs and on AVMs in noneloquent locations were associated with lower rates of neurological complications. Long-term outcome, as measured by the mRS, was significantly influenced by the patient's mRS score at presentation. Rates of AVM obliteration improved as a result of a protocol modification mandating the use of perioperative angiography during the same anesthesia period. Surgical treatment markedly reduced the annual hemorrhage rate of AVMs compared with the rates reported from the natural history of untreated lesions. In aggregate, these data strongly support the use of resection in selected pediatric patients with intracranial AVMs.

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Conception and design: Gross, Scott, Smith. Acquisition of data: Gross, Storey. Analysis and interpretation of data: all authors. Drafting the article: Gross. Critically revising the article: Gross, Orbach, Scott, Smith. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Gross. Statistical analysis: Gross. Administrative/technical/material support: Scott, Smith. Study supervision: Scott, Smith.

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