BrainPath Tubular Retractor System for Subcortical Hemorrhagic Vascular Lesions: A Case Series of Technique and Outcomes

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BACKGROUND AND OBJECTIVES: Hemorrhagic subcortical vascular lesions such as cavernous malformations (CM) and arteriovenous malformations (AVM) can be neurologically devastating. Conventional open surgical resection is often associated with additional morbidity. The BrainPath® (NICO Corp.) transsulcal tubular retractor system offers a less-invasive corridor to deep-seated lesions. Our objective was to describe a single-center experience with the resection of subcortical hemorrhagic vascular lesions in adult and pediatric patients using the BrainPath® system.

METHODS: The departmental database was queried for patients who underwent resection of a hemorrhagic CM, AVM, or cerebral aneurysm through the BrainPath® tubular retractor system between January 2017 and September 2021. All patients underwent either postoperative MRI (for patients with CM) or digital subtraction angiography (for patients with AVM or aneurysm). Demographic and clinical characteristics, preoperative and postoperative imaging features, operative details, and surgical and clinical outcomes were extracted through a retrospective review of the medical records.

RESULTS: Fourteen patients (mean [SD] age 32.3 [23.9] years; 7 (50%) female) underwent BrainPath®-based resection of a deeply seated CM (n = 7), AVM (n = 6), or ruptured cerebral aneurysm (n = 1). The mean maximal lesion diameter was 21.5 (12.6) mm. The mean operative time was 134 (53) minutes. Residual lesion was present in 2 patients, both of which underwent repeat BrainPath®-assisted surgery for complete resection. All lesions were completely resected or obliterated on postoperative MRI or digital subtraction angiography. At a mean follow-up of 4.1 (1.1) years, the median modified Rankin Scale score was 1 (range 0-6).

CONCLUSION: In a well-selected cohort, we show the effective use of BrainPath® tubular retractors for resection or obliteration of subcortical hemorrhagic vascular lesions. This report further exemplifies the expanded role of the endoport system beyond that of intracerebral hemorrhage and tumor. Further study will elucidate the impact of this less-invasive brain retraction technique on clinical outcome in patients with vascular lesions.

KEY WORDS: Arteriovenous malformation, BrainPath, Case series, MIPS, Subcortical cavernous malformation

Deep-seated cavernous malformations (CMs) and arteriovenous malformations (AVMs) pose unique surgical challenges. Acute rupture of these lesions causes intracranial and intraventricular hemorrhage, leading to potentially devastating neurologic injury.[1,2] In addition, the required brain retraction, tissue manipulation, and traversing of eloquent fiber tracts in conventional open surgery for these lesions often leads to accrual of additional neurologic deficits.[3] Therefore, selection of a safe and minimally disruptive operative corridor to these deep lesions can be a barrier to achieving an optimal surgical result.

ABBREVIATIONS: CM, cavernous malformation; **SRS,** stereotactic radiosurgery.

To mitigate these barriers, tubular retractor or endoport systems have been introduced over the past years. These less-invasive

TABLE 1. Descriptive Characteristics of Patients With a CM

Characteristic	Summary statistic (n = 7)
Age (y), mean (SD)	27.9 (21.2)
Female, n (%)	4 (57)
Presenting symptoms, n (%)	
Headache	2 (29)
Nausea/emesis	2 (29)
Seizure	3 (43)
Speech/language difficulty	2 (29)
Weakness	1 (14)
Numbness/tingling	2 (29)
Fall	2 (29)
Neurological deficits at presentation, n (%)	
Nonfocal	2 (29)
Speech/language deficit	3 (43)
Lethargy/confusion	1 (14)
Focal cranial nerve deficit	0
Unilateral motor/coordination deficit	3 (43)
Stuporous/coma	0
Location of CM on initial head CT, n (%)	
Frontal	1 (14)
Parieto-occipital	1 (14)
Thalamic	3 (43)
Intraventricular	2 (29)
Side of lesion, n (%)	
Left	4 (57)
Right	3 (43)
Maximal diameter (mm) of CM, mean (SD)	32.3 (7.8)
Duration from presentation to surgery (d), mean (SD)	9.7 (12.3)
Operative time (min), mean (SD)	153.1 (66.5)
BrainPath® length, n (%)	
60 mm	5 (71)
75 mm	2 (29)
Intraoperative complication, n (%)	0
Need to convert to open microsurgery, n (%)	0
Presence of new postoperative deficit, n (%)	2 (29)
Need for postoperative CSF diversion, n (%)	3 (43)[a]
Duration of clinical follow up (mo), mean (SD)	29.9 (8.3)
Residual CM on follow-up MRI, n (%)	1 (14)
ICU length of stay (d), mean (SD)	3.3 (3.8)
Hospital length of stay (d), mean (SD)	8.6 (5.3)
Disposition at hospital discharge, n (%)	
Home	3 (43)
Acute rehabilitation	4 (57)
Need for rehospitalization related to CM, n (%)	1 (14)[b]
Mortality, n (%)	0
Current modified Rankin Scale score, n (%)	
0	4 (57)
1	2 (29)
2	0
3	1 (14)
4	0
5	0
6	0

CM, cavernous malformation; CT, computed tomography; CSF, cerebrospinal fluid; ICU, intensive care unit.
[a]Three patients had an EVD inserted intraoperatively for 6, 3, and 2 days postoperatively. None required permanent CSF shunting.
[b]One patient required 2 hospitalizations and 3 subsequent surgeries for wound revision and re-resection of CM.

techniques provide access to deeply seated lesions by minimizing frank brain retraction and consequent tissue injury. The BrainPath® (NICO Corp) is a minimally invasive parafascicular surgery system containing a navigable inner obturator with a beveled tapered tip and an outer, transparent tubular retractor of various diameters and lengths.[4,5] The obturator tip was designed for minimally traumatic displacement, rather than transection, of sulcal gray and underlying white matter as the retractor is advanced to the target lesion. The BrainPath® system has been largely used for subcortical tumors[6,7] and spontaneous intracranial hemorrhages.[7-10]

There have been reports on the use of tubular retractors for resection of deep-seated CMs and AVMs.[11-15] However, there remains a paucity of published experience with the BrainPath® system for surgical treatment of vascular lesions, and to date, there are no reports on the clip ligation of a cerebral aneurysm through a tubular retractor.

TABLE 2. Descriptive Characteristics of Patients With an Arteriovenous Malformation (n = 6) or Cerebral Aneurysm (n = 1)

Characteristic	Summary statistic (n = 7)
Age (y), mean (SD)	32.3 (23.9)
Female, n (%)	3 (43)
Presenting symptoms, n (%)	
Headache	4 (57)
Nausea/emesis	5 (71)
Altered consciousness	5 (71)
Weakness	1 (14)
Fall	2 (29)
Neurological deficits at presentation, n (%)	
Alteration in consciousness	
Mild	2 (29)
Moderate	2 (29)
Severe	3 (43)
Focal cranial nerve deficit	2 (29)
Paresis/plegia	2 (29)
Posturing	2 (29)
Spetzler-Martin Grade, n (%)[a]	
I	1 (14)
II	1 (14)
III	3 (43)
IV	1 (14)
V	0
Hunt-Hess score, n (%)[b]	
I	0
II	0
III	0
IV	0
V	1 (14)
Location of AVM on initial head CT, n (%)	
Frontal	1 (14)
Temporal	0
Parieto-occipital	1 (14)
Thalamic	2 (29)
Intraventricular	3 (43)
Side of lesion, n (%)	
Left	4 (57)
Right	3 (43)
Maximal diameter (mm) of AVM, mean (SD)	10.7 (3.4)
Duration from presentation to surgery (d), mean (SD)	5.9 (3.4)
Preoperative CSF diversion with EVD, n (%)	5 (71)
Preoperative embolization, n (%)	2 (29)
Operative time (min), mean (SD)	114.6 (27.5)
BrainPath® length, n (%)	
50 mm	2 (29)
60 mm	3 (43)
75 mm	1 (14)
Intraoperative complication, n (%)	0
Need to convert to open microsurgery, n (%)	0
Postoperative angiogram findings	
Presence of residual vascular lesion	1 (14)[c]
Presence of new postoperative deficit, n (%)	1 (14)
Need for permanent CSF diversion, n (%)	0
Duration of clinical follow-up (mo), mean (SD)	49.2 (13.5)
ICU length of stay (d), mean (SD)	13.1 (8.8)
Hospital length of stay (d), mean (SD)	15.3 (8.4)
Disposition at hospital discharge, n (%)	
Home	2 (29)
Acute rehabilitation	4 (57)
Mortality	1 (14)
Need for rehospitalization related to AVM/aneurysm, n (%)	0[d]
Mortality, n (%)	1 (14)
Current modified Rankin Scale score, n (%)	
0	2 (29)
1	3 (43)
2	1 (14)

TABLE 2. Continued.

Characteristic	Summary statistic (n = 7)
3	0
4	0
5	0
6	1 (14)

AVM, arteriovenous malformation; CT, computerized tomography; CSF, cerebrospinal fluid; EVD, eternal ventricular drain; ICU, intensive care unit.
[a]Spetzler-Martin grade for n = 6 patients with an AVM.
[b]Hunt-Hess score for n = 1 patient with ruptured cerebral aneurysm.
[c]Postoperative angiogram showed residual filling of anterior choroidal artery aneurysm.
[d]One patient with a ruptured aneurysm with residual filling on postoperative angiogram underwent repeat craniotomy the subsequent day for clipping of residual aneurysm.

We describe our single-center, fourteen-patient experience with a stereotactically navigated endoport retractor system for resection of ruptured CM, AVM, and cerebral aneurysm.

METHODS

Cohort and Data Collection

This was a single-center, retrospective case series approved by our hospital institutional review board. The pediatric and adult neurosurgical departmental databases were queried for all patients who underwent BrainPath® -assisted resection or obliteration of a ruptured vascular lesion between 2017 and 2021.

Relevant clinical, demographic, and radiographic data were collected from the hospital electronic medical records and picture archiving and communication system. Data collected included age, sex, presenting neurologic deficits, use of antithrombotic therapy, MRI or digital subtraction angiography (DSA) findings including lesion location and size, and whether preoperative embolization was performed. For AVMs and aneurysms, the Spetzler-Martin grade, Hunt-Hess score, and modified Fisher Scale score, as appropriate, were collected. Operative characteristics collected included operative approach or trajectory, BrainPath® endoport length (mm), operative duration (minutes), need to convert to open microsurgery, and intraoperative complications.

Postsurgical outcomes captured included the presence of residual lesion on postoperative MRI or DSA and need for reoperation, presence of new postoperative deficits, need for postoperative cerebrospinal fluid diversion, intensive care unit and hospital length of stay (days), disposition at hospital discharge, rehospitalization, mortality, and modified Rankin Scale (mRS) score.

Surgical Technique

The surgical procedure, including the use of a stereotactic tubular retractor system, was discussed as part of the consent process with all patients or their surrogate. The surgical procedures were performed under general anesthesia by a neurosurgeon trained on the BrainPath® system (PM, CM, MMB, JAS). Patients were positioned in the appropriate position according to lesion location and surgical trajectory, in a three-point head holder. A preoperative volumetric MRI or CT angiogram was obtained, to which the patient was registered intraoperatively using the StealthStation S8 (Medtronic). A BrainPath® trajectory was planned on the Stealth (Medtronic) workstation. Trajectory entries were transsulcal, and were intentionally chosen to respect standard surgical corridors parallel to known fiber tracts, and minimize disruption to known eloquent topographic regions. The target point was defined as the nidus of the AVM or the peripheral border of the CM. BrainPath® length was chosen based on the distance from the calvarial surface to the target point. A mini-craniotomy was fashioned, typically approximately 3 cm in diameter. The dura was incised linearly. The cannulated BrainPath® retractor was introduced to the target under navigation. Using standard microsurgical technique with a Zeiss Kinevo 900 microscope, the lesion was resected or obliterated. Bayonetted, low-profile keyhole instruments were used to dissect and coagulate coaxially through the BrainPath®. Bimanual technique was used to sequentially toggle the tubular retractor around the CM or AVM to obtain circumferential dissection. Once the lesion was resected (or aneurysm ligated), hemostasis was achieved, a synthetic dural onlay was placed, the craniotomy was plated into the native position, and incision was closed in multiple layers.

Statistical Analysis

Summary statistics were computed as frequencies, and measures of central tendency and dispersion, as appropriate. Statistical analyses were performed using StataBE 18.0 (StataCorp).

This case series has been reported in line with the PROCESS guideline.

RESULTS

Fourteen patients underwent navigated tubular retractor-based resection or obliteration of a deep-seated ruptured vascular lesion (CM, n = 7; AVM, n = 6; cerebral aneurysm, n = 1) between January 2017 and September 2021. Preoperative and postoperative imaging for 4 illustrative cases are shown in Figures 1-4. Baseline demographic and presenting clinical and imaging characteristics are presented in Tables 1 and 2. The mean (SD) age was 32.3 (23.9, range 4-73) years, and 7 (50%) were female. Symptoms and neurological deficits at the time of presentation are summarized in Tables 1 and 2. For patients with an AVM or CM, the most common sites of hemorrhage on initial CT were thalamic (5, 36%) and intraventricular (5, 36%). In 8 patients (57%), the hemorrhagic lesion was left sided. The mean lesion diameter was 32.3 (7.8) mm for patients with a cavernoma and 10.7 (3.4) mm for those with an AVM. Five patients (83%) with an AVM underwent preoperative external ventricular drain (EVD) placement. For patients with an AVM, the median (range) Spetzler-Martin grade was 3 (1-4). The Hunt-Hess score for the 1 patient with a ruptured aneurysm was 5.

The mean (SD) duration from presentation to surgery was 9.7 (12.3) days for patients with a CM and 5.9 (3.4) for those with an AVM. Two (29%) of the patients with an AVM underwent

TABLE 3. Individual Patient Case Clinical Features and Operative Details

Patient #	Vascular lesion	Age (y)	Sex	Examination findings at presentation	Antithrombotics	Severity score*	Angiogram or MRI findings	Lesion maximal diameter (mm)	Lesion location	Preoperative embolization	Operative approach	BrainPath® tube length (mm)
1	Aneurysm	73	M	Comatose	ASA, Plavix	HH 5, mFS IV	Fusiform AChA aneurysm of temporal horn	5	R temporal horn	No	R temporal	50
2	AVM	49	F	Disorientation, R ptosis	None	SM II	L mesial frontal AVM w/ACA feeder	10.6	L frontal	No	L eyebrow	60
3	AVM	9	M	right lower extremity > right upper extremity paresis, lethargy	None	SM II	L parietal AVM w/ PCA feeder	12	L parietal	No	L parietal	50
4	AVM	28	F	L paresis, L homonymous hemianopia	None	SM III	R posterior AVM w/distal PCA feeders and nidal aneurysm	12	R peri-thalamic	Yes	R occipital	50
5	AVM	12	M	Disorientation, lethargy	None	SM III	R posterior AVM w/PCA feeders	10	R peri-thalamic	No	R parieto-occipital	60
6	AVM	12	M	Stuporous, localizing movement	None	SM III	L intraventricular AVM w/PChA feeders and nidal aneurysm	16	L intraventricular	Yes	Contralateral R frontal	60
7	AVM	43	F	Stuporous, localizing movement	None	SM III	R intraventricular AVM w/PChA feeders	9	R intraventricular	No	R parieto-occipital	75
8	CM	4	F	Nonfocal	None	n/a	L thalamic hemorrhage/ cyst	33	L thalamic	n/a	Contralateral R frontal	60
9	CM	8	M	Nonfocal	None	n/a	Giant L parietal hemorrhage	41	L mesial parieto-occipital	n/a	L parieto-occipital	60
10	CM	26	F	R numbness, paresis	None	n/a	L frontal hemorrhage, multiple cavernomas	36	L frontal	n/a	L frontal	75
11	CM	15	F	Drowsiness, disorientation	None	n/a	R frontal horn cavernoma, punctate traumatic ICH	26	R frontal intraventricular	n/a	Awake R frontal	60

TABLE 3. Continued.

Patient #	Vascular lesion	Age (y)	Sex	Examination findings at presentation	Antithrombotics	Severity score*	Angiogram or MRI findings	Lesion maximal diameter (mm)	Lesion location	Preoperative embolization	Operative approach	BrainPath® tube length (mm)
12	CM	64	M	Aphasia	None	n/a	L frontal horn cavernoma	38	L frontal intraventricular	n/a	Awake L frontal	60
13	CM	36	M	L face and UE paresis	Eliquis	n/a	R thalamic and cerebral peduncle cavernoma	34	R thalamic	n/a	Contralateral L frontal	75
14	CM	42	F	L altered sensation	None	n/a	R thalamic cavernoma	18	R thalamic	n/a	R posterior temporal	60

AChA, anterior choroidal artery; ASA, aspirin; AVM, arteriovenous malformations; CM, cavernous malformation; F, female; ICH, intracerebral hemorrhage; *HH, Hunt Hess score; L, left; LE, lower extremity; M, male; *mFS, modified Fisher Scale; PCA, posterior cerebral artery; PChA, posterior choroidal artery; R, right; *SM, Spetzler-Martin grade; UE, upper extremity.

preoperative embolization. The mean operative time was 153.1 (66.5) minutes for those with a CM and 114.5 (27.5) for those with an AVM. The 60-mm BrainPath® sheath was most frequently used. There were no intraoperative complications nor was there a requirement to convert to open microsurgery. Tables 3 and 4 provides clinical, radiographic, surgical, and postoperative details of each patient.

New postoperative deficits were present in 3 patients (Table 4): 1 child with a right perithalamic AVM who underwent resection through a right parieto-occipital trajectory developed a left homonymous hemianopia; 1 adult patient with a left frontal horn intraventricular cavernoma and 1 with a right thalamic cavernoma both developed short-term memory deficits postoperatively. The patient with a ruptured anterior choroidal aneurysm (Figure 1) had residual filling on postoperative DSA, and 1 patient with a CM (Figure 2) had residual lesion on postoperative MRI; both underwent repeat tubular retractor–assisted resection or obliteration. The mean hospital length of stay was 8.6 (5.3) days for patients with a CM and 15.3 (8.4) days for those with an AVM. There was 1 mortality in the cohort, specifically, the patient with a ruptured anterior choroidal aneurysm who succumbed to respiratory complications. For the thirteen patients who survived and were followed clinically, at a mean follow-up duration of 29.9 (8.3) months for those with a CM and 49.2 (13.5) months for those with an AVM, the median mRS was 1 (range 0-3).

DISCUSSION

We present our center's pediatric and adult patients' experience to date with BrainPath® -assisted resection of deep-seated hemorrhagic vascular lesions, including cavernoma, arteriovenous malformation, and cerebral aneurysm. In our highly selected cohort, we suggest that stereotactic, tubular retractor–assisted resection of subcortical vascular lesions is technically achievable, safe, and performed with acceptable perioperative morbidity. Larger, multicentered, and comparative cohort studies will further elucidate the effectiveness of this technique and outcomes of these patients.

For vascular lesions requiring intervention, microsurgical ligation or resection is mainstay, lending itself to immediate radiographic resolution, compared with endovascular embolization (for AVMs and aneurysms) and stereotactic radiosurgery (SRS, for AVMs), which require ongoing monitoring and potentially additional sequential interventions. When associated with an acute hemorrhage and when superficially located in noneloquent brain regions, open microsurgical intervention is often the prevailing treatment strategy. Open surgical treatment of deeply seated vascular lesions or those located in eloquent brain regions can be associated with complications and morbidity due to fixed or dynamic cortical retraction and injury to subcortical white matter tracts. Less-invasive microsurgical approaches for ligation or resection of deep-seated vascular lesions carry the conceivable benefit of decreasing iatrogenic neurologic deficit due to surgery.[15] It is

TABLE 4. Individual Patient Case Intraoperative Details and Postoperative Outcomes

Patient #	Vascular lesion	Operative duration (min)	Need to convert to open microsurgery	Residual lesion on postoperative angiogram or MRI	Reoperation	New postoperative deficits	ICU LOS	Hospital LOS	Mortality	mRS at last follow-up
1	Aneurysm	86	No	Yes	Repeat clipping through BrainPath®	No	29	29	Yes	6
2	AVM	73	No	No	No	No	3	8	No	0
3	AVM	126	No	No	No	No	8	9	No	1
4	AVM	137	No	No	No	No	11	15	No	1
5	AVM	147	No	No	No	L homonymous hemianopia	9	10	No	1
6	AVM	129	No	No	No	No	11	11	No	0
7	AVM	104	No	No	No	No	21	25	No	2
8	CM	197	No	Yes	Once for wound revision and twice via BrainPath® for resection of residual cavernoma	No	3	9	No	0
9	CM	175	No	No	No	No	5	7	No	0
10	CM	75	No	No	No	No	1	3	No	1
11	CM	243	No	No	No	No	1	11	No	0
12	CM	195	No	No	No	Mild STM deficit and R foot weakness	2	6	No	1
13	CM	117	No	No	No	Mild STM deficit	11	19	No	3
14	CM	70	No	No	No	No	0	5	No	0

AVM, arteriovenous malformation; CM, cavernous malformation; ICU, intensive care unit; L, Left; LOS, length of stay; mRS, modified Rankin Scale; R, right; STM, short-term memory.

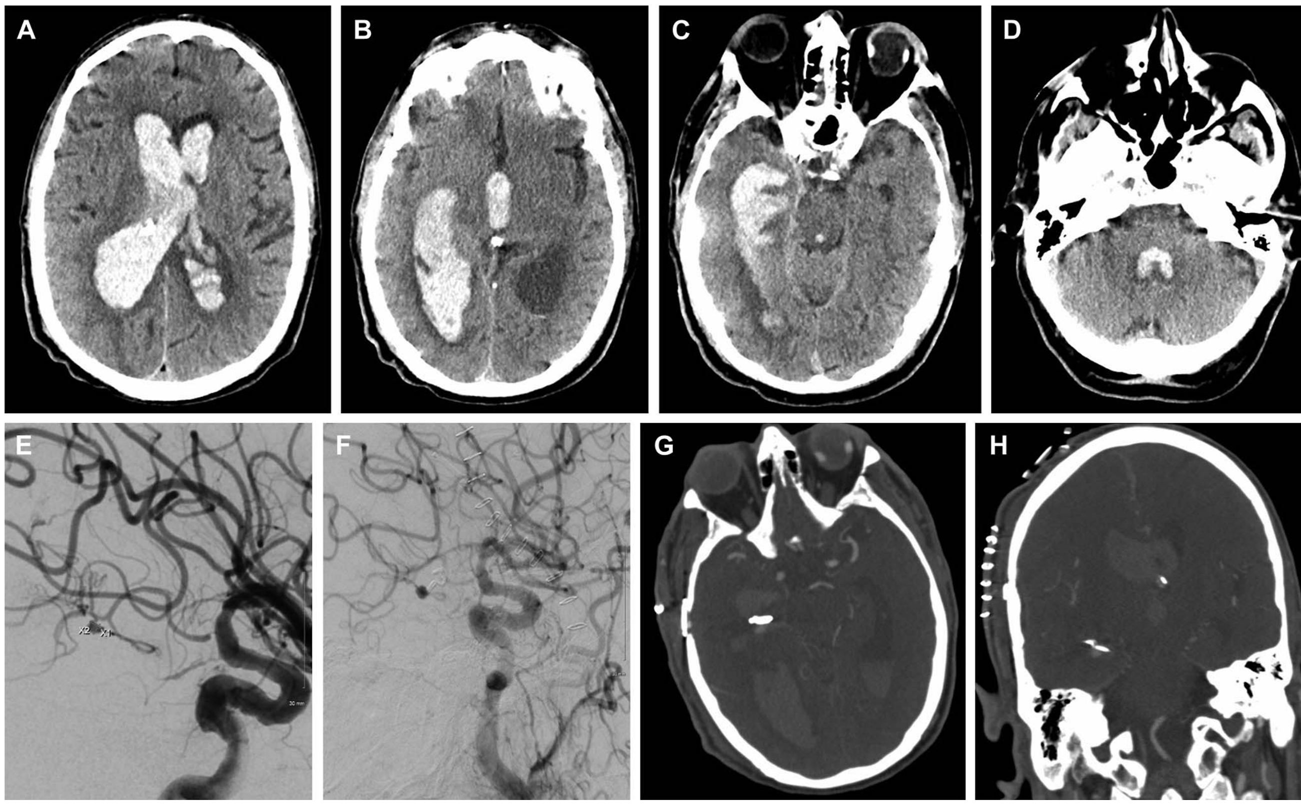

FIGURE 1. *A 73-year-old man with ruptured right anterior choroidal artery aneurysm.* **A-D**, *Axial head CT demonstrating intraventricular hemorrhage with acute ventriculomegaly and right temporal subarachnoid hemorrhage.* **E**, *Preoperative lateral DSA of the right internal carotid injection demonstrating a 2-mm anterior choroidal artery aneurysm.* **F**, *Initial postoperative DSA demonstrating residual aneurysmal filling.* **G** *and* **H**, *Axial and coronal CT angiogram of the head after taken back to the operating room demonstrating complete obliteration of the aneurysm. CT, computed tomography; DSA, digital subtraction angiography.*

important to note that alternatives to surgical AVM resection were discussed with each of our patients, namely stereotactic radiosurgery and embolization. Although SRS is a viable option, each of our patients presented with an AVM rupture and required surgical evacuation of the hematoma to relieve symptoms of mass effect. Obviously, SRS does not have an immediate impact on the hemorrhagic component of the AVM, and obliteration takes upward of 2 years. The goal for these low-moderate grade AVMs was to provide the patients, granted their consent, with a definitive cure.

Our series uniquely includes a case of clip ligation of a ruptured intraventricular anterior choroidal aneurysm. Other reports of tubular retractor–assisted resection of deep AVMs.[6,11,12,16] and cavernomas[5,14,17] have been recently published. Since 2018, the BrainPath® tubular retractor system has been used at our center, initially for the surgical management of intracerebral hemorrhages and deep-seated tumors. With experience gained, we have applied this system to selected deep-seated hemorrhagic vascular lesions. There are several features of these lesions that guided our decision to pursue tubular retractor–assisted resection. Regarding AVMs, smaller size was deemed favorable. All AVMs were less than 2 cm in maximal diameter, which permitted visualization of the entire lesion through the tube. This is a key to adhere to the surgical tenant of arterial disconnection, circumferential dissection, and terminal ligation of the draining vein. Each of the AVMs had a single draining vein. The ruptured status of the AVM provided a hematoma capsule, which facilitated circumferential dissection through the endoport. Regarding cavernomas, these lesions were up to 4 cm in maximal diameter and had all acutely hemorrhaged causing symptoms. They were deep seated, within the ventricle, thalamus, or brainstem most commonly. Finally, the ruptured anterior choroidal artery aneurysm, which was ligated through the tubular retractor, was a 5-mm saccular aneurysm that was intraventricular and accessed through a temporal trajectory.

In our experience to date, the BrainPath® tubular retractor is a safe and technically favorable approach for highly selected, deep-seated hemorrhagic vascular lesions. We did not convert to conventional open microsurgery in any of the 14 cases. Reoperation was required in 2 patients, both of whom had residual lesion on postoperative imaging. The first was an 86-year-old man who presented with Hunt-Hess 5 subarachnoid and

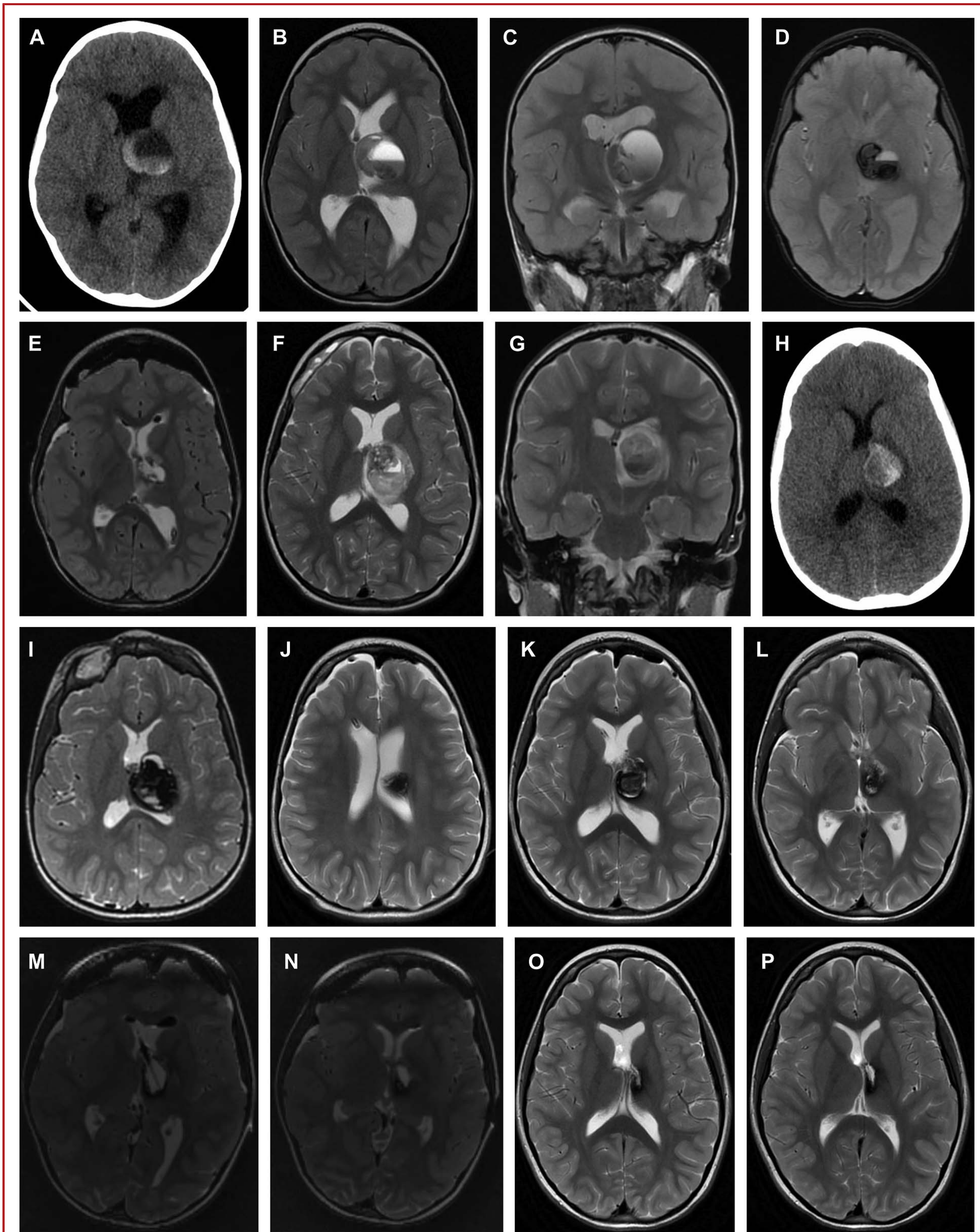
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FIGURE 2. *A 4-year-old girl with a hemorrhagic left thalamic cavernous malformation.* **A**, *Axial head CT,* **B** *and* **C**, *axial and coronal T2-weighted, and* **D**, *axial gradient echo images at the time of clinical presentation.* **E**, *Postoperative axial T2-weighted MRI demonstrating resection cavity.* **F** *and* **G**, *Routine surveillance axial and coronal T2-weighted MRI at 1 month after surgery demonstrating recurrent hemorrhage and mass effect.* **H** *and* **I**, *Axial head CT and T2-weighted MRI 10 months after initial craniotomy when patient returned with acute headache and vomiting, demonstrating acute left thalamic hemorrhage with perilesional edema and mass effect.* **J**-**L**, *Axial T2-weighted MRI obtained postoperatively (ie, after second resection) demonstrating interval debulking but residual cavernoma in the left thalamic region. The patient was taken back to the operating room 5 days later for complete resection of residual cavernoma, as demonstrated in intraoperative axial T2-weighted images in* **M** *and* **N**. **O** *and* **P**, *Last available surveillance scan obtained 18 months after initial presentation continues to demonstrate no residual lesion on axial T2-weighted MRI. The patient's guardians consented to the publishing of these deidentified radiographic images. CT, computed tomography.*

intraventricular hemorrhage due to a ruptured intraventricular temporal horn anterior choroidal artery aneurysm. He was taken to the operating room for stereotactic tubular retractor–assisted clip ligation of the aneurysm through a right temporal corridor using a 50-mm tube. The decision to pursue this tubular retractor–based approach was based on the complicated aneurysm morphology, its distinct intraventricular location, and the intent to preserve the parent artery. On DSA obtained immediately after surgery, there was residual aneurysm. Decision was made to reopen the right temporal craniotomy, and using precisely the same 50-mm tubular retractor approach, modify the clip ligation. Postoperative DSA then demonstrated complete obliteration of the aneurysm and maintained patency of the parent vessel. Although ultimately a successful surgical result was achieved, the patient did succumb to respiratory complications, as he was unable to be liberalized from the ventilator and family wished to pursue hospice. His significant baseline medical comorbidities and Hunt-Hess 5 presentation were factors contributing to his overall poor clinical outcome. The second patient was a 4-year-old girl who presented with acute headache, emesis, and lethargy, and was found to have a left thalamic 33-mm hemorrhagic cavernoma. She underwent 60 mm BrainPath® -assisted resection through a

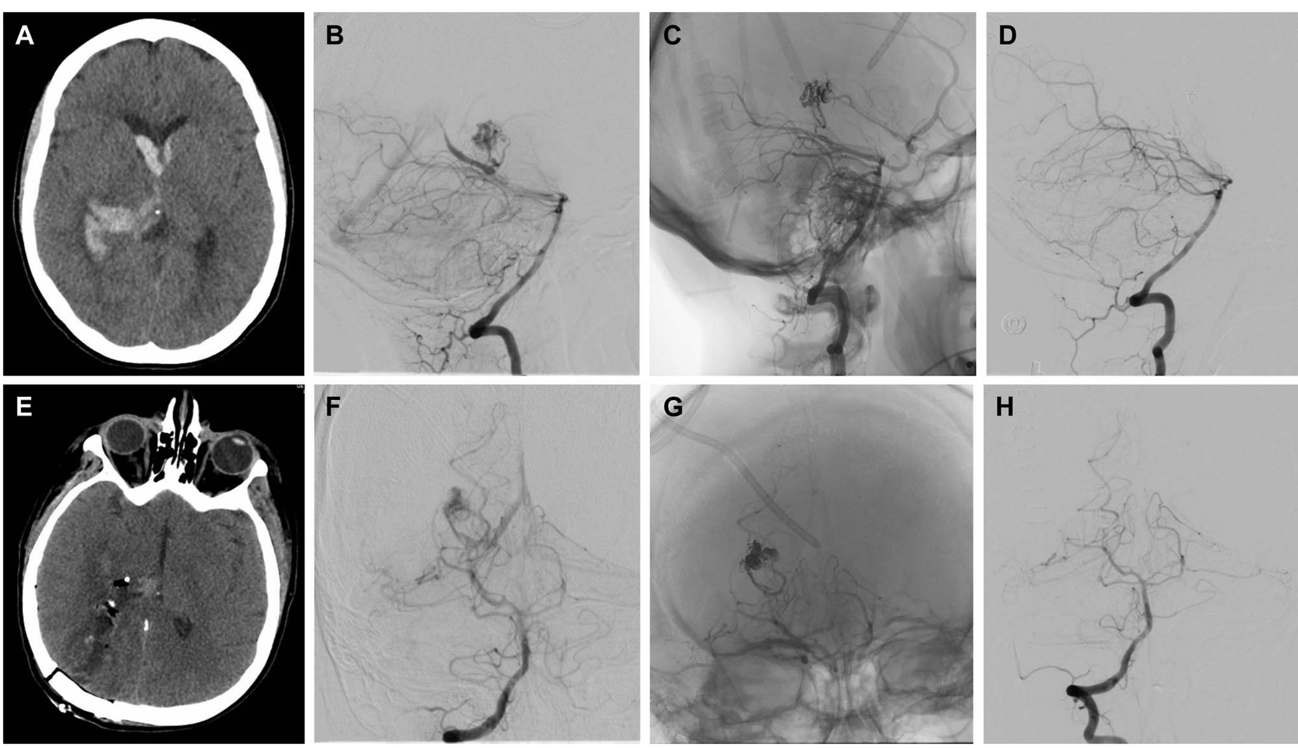

FIGURE 3. *A 28-eight-year old woman with a hemorrhagic Spetzler-Martin grade III arteriovenous malformation.* **A**, *Axial head CT at the time of presentation with sudden onset headache, nausea, and vomiting demonstrates right thalamic region intracerebral hemorrhage with associated intraventricular hemorrhage and mass effect.* **B** *and* **F**, *Preoperative lateral and A-P digital subtraction angiography demonstrates an AVM arising from the right P3 branch with a nidus measuring 11 × 9 mm and with associated early deep venous drainage into the vein of Galen complex.* **C** *and* **G**, *Lateral and A-P projections after Onyx embolization of the nidus through 2 pedicle feeders by a right posterior cerebral artery microcatheterization.* **E**, *Axial head CT obtained postoperatively demonstrating a right occipital trajectory to the AVM.* **D** *and* **H**, *Lateral and A-P projections obtained after craniotomy for AVM resection demonstrating no residual early venous drainage and no residual AVM nidus. AVM, arteriovenous malformation; CT, computed tomography.*

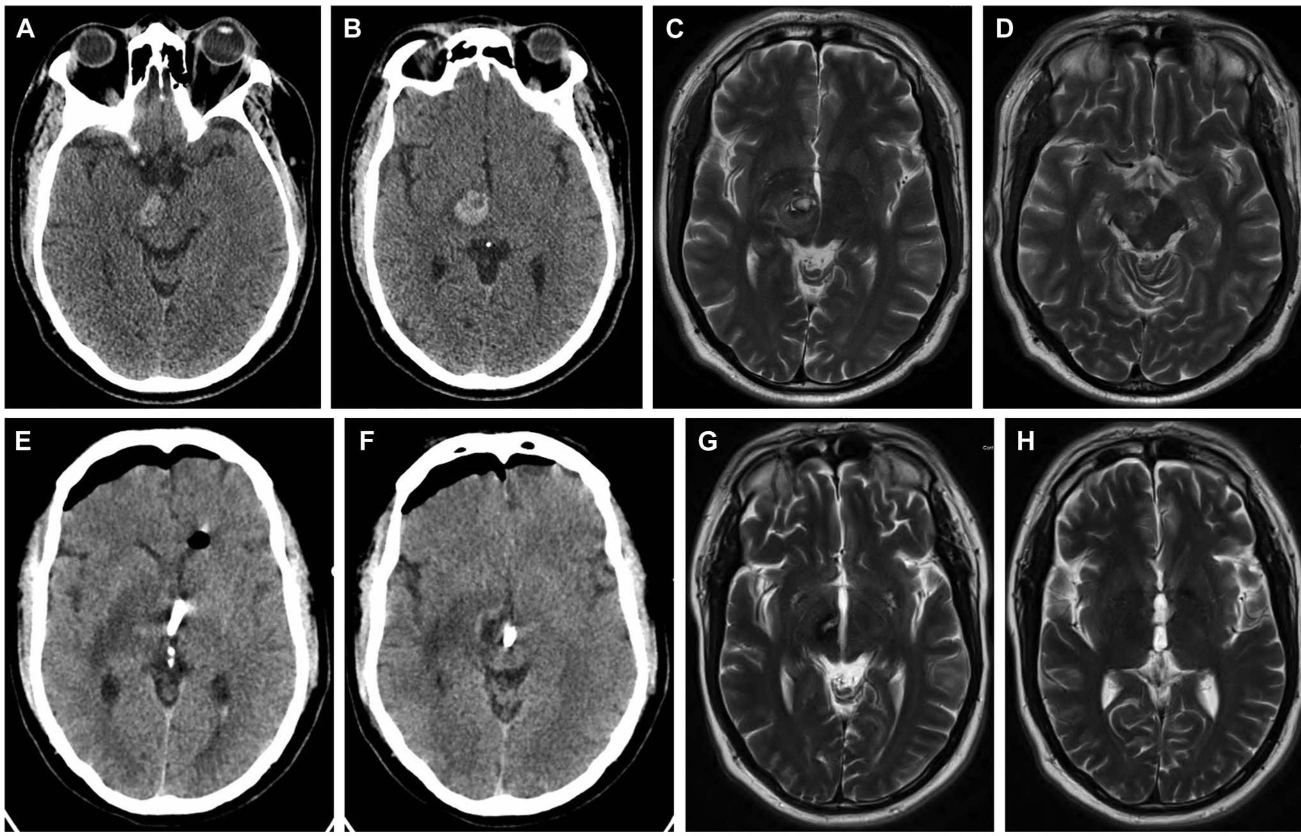

FIGURE 4. *A 36-year-old man with hemorrhagic cavernoma in the right thalamus and midbrain.* **A** *and* **B**, *Axial head CT obtained at the time of presentation with acute left hemiparesis and dysarthria, demonstrating an intracerebral hemorrhage in the right thalamus and extending into the right cerebral peduncle with surrounding edema and regional mass effect.* **C** *and* **D**, *Axial T2-weighted MRI through the thalamus and midbrain demonstrating a mixed intensity well-circumscribed lesion with intralesional fluid-fluid levels and surrounding edema.* **E** *and* **F**, *Axial head CT obtained after left frontal craniotomy demonstrating interval resection of hemorrhagic lesion with an external ventricular drain after the surgical trajectory.* **G** *and* **H**, *Axial T2-weighted MRI obtained approximately 4 months postoperatively demonstrating full resection of the cavernoma with some residual hemosiderin signal change within the thalamus and midbrain. CT, computed tomography.*

right frontal trajectory. There was no macroscopic evidence of residual on intraoperative inspection or postoperative MRI. On routine surveillance MRI 1 month after surgery, there were signs of rehemorrhage in the left thalamus; given there was no radiographically obvious residual cavernoma and the child remained without symptoms, she was followed with close clinical observation. Nine months later, the child developed acute headache and emesis, and MRI demonstrated evidence of a recurrent hemorrhagic cavernoma. She underwent repeat BrainPath® -assisted resection of the left thalamic cavernoma through the same right frontal trajectory. Postoperative MRI demonstrated a focus in the cavity suspicious for residual cavernoma. This case being early in our experience with BrainPath® for nonintracerebral hematoma pathologies, and we learned that there are blind spots on the border zones of the tubes. The child underwent repeat BrainPath® -assisted resection through the same trajectory. However, this time we advanced an endoscope down the tube to inspect the blind spot areas, ensuring gross total resection. Postoperative MRI demonstrated no residual lesion. The child was discharged to her home a few days later with no neurologic deficits.

This report is one of the few large, combined series on the resection of CM and AVMs through the BrainPath® tubular retractor system.[18] Novel to this report is the clip ligation of a ruptured intraventricular anterior choroidal aneurysm through the BrainPath®. Regarding the AVMs, they ranged in Spetzler-Martin grade from I to III; however, they each were compact with a nidus ranging in diameter from 1 to 2 cm. Some had deep venous drainage, and some had intranidal aneurysms. All DSAs at 6 months after resection demonstrated no residual AVM. This demonstrates the effectiveness of the tubular retractor for properly selected deep-seated AVMs. Furthermore, regarding the cavernomas, they ranged in size from 2.5 to 4 cm. Two of the cavernoma resections were performed awake, 1 in a 15-year-old adolescent girl and 1 in a 64-year-old man. Bimanual dexterity and circumferentially toggling the BrainPath® retractor around the circumference of the cavernoma-enabled dissection of the brain-lesion interface and ultimately complete resection in all cases, and, finally, clip ligation of a small intraventricular ruptured aneurysm is a suitable application of the BrainPath® technology, and ultimately yielded complete exclusion of the aneurysm in our case. Further experience with this application to cerebral aneurysms will further delineate its effectiveness and role.

An important consideration in applying the BrainPath® technique is the associated learning curve, which involves using a bimanual technique coaxially along a narrow working channel and finding alternative approaches to enhance resolution and lighting at the depth of the tube. Our experience with BrainPath® began with ICH evacuation, and as our experience matured, we began applying this technique to deep-seated tumors, CMs, and AVMs. Indeed, the need for a second surgery for the patient with the anterior choroidal artery aneurysm was in part due to the fact that this was the first clip ligation our center performed using this technique. Maneuvering the clip, manipulating the aneurysmal neck, assessing the parent vessel, and ensuring that *en passage* and neighboring vessels are not included in the clip are techniques that require experience with bimanually working through a narrow corridor. In addition, the authors believe that the requirement for the third surgery for the child with the left thalamic CM was due to blind spots at the border zones of the tube that the authors had not encountered ago. For this reason, the authors now incorporate endoscopy as an adjunct in deep-seated tumors and CMs resected through BrainPath®.

This study provides clinical support for the use of the BrainPath® technique as an evolving standard of care for certain deep-seated, eloquently located vascular lesions because it tackles previous surgical limitations of safely reaching and visualizing deep-seated problematic lesions. Indeed, our growing experience using the BrainPath® system has resulted in gradual improvements in intraoperative efficiencies and has streamlined our decision-making process regarding patient selection for BrainPath® CM and AVM cases. Additional prospective and comparative studies are needed to examine characteristics of patients most likely to benefit from BrainPath® -assisted resection of vascular lesions.

Limitations

We summarize the operative details and operative and clinical outcomes of a group of patients with a hemorrhagic, deep-seated vascular lesion who were selected to undergo resection through the BrainPath® tubular retractor system. An understanding of safety and efficacy of the BrainPath® tubular retractor for vascular lesions beyond that of our center's experience will require further study.

CONCLUSION

In our selected cohort of pediatric and adult patients with a hemorrhagic deep-seated vascular lesion, the BrainPath® tubular retractor system enabled less-invasive subcortical access and radiographic resolution of hemorrhagic AVMs, CMs, and a cerebral aneurysm, without incurring iatrogenic long-term neurologic deficit. This less-invasive tubular retractor system is a valuable surgical adjunct in the neurosurgeons' armamentarium to surgically manage hemorrhagic deep-seated vascular lesions. Further multicentered and comparative studies will elucidate the surgical indications and long-term surgical and clinical outcomes in ruptured and unruptured vascular lesions.

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