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Evolution of treatment and a detailed analysis of occlusion, recurrence, and clinical outcomes in an endovascular library of 260 dural arteriovenous fistulas

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OBJECTIVE Many small series and technical reports chronicle the evolution of endovascular techniques for cranial dural arteriovenous fistulas (dAVFs) over the past 3 decades, but reports of large patient series are lacking. The authors provide a thorough analysis of clinical and angiographic outcomes across a large patient cohort.

METHODS The authors reviewed their endovascular database from January 1996 to September 2015 to identify patients harboring cranial dAVFs who were treated initially with endovascular approaches. They extracted demographic, presentation, angiographic, detailed treatment, and long-term follow-up data, and they evaluated natural history, initial angiographic occlusion, complications, recurrence, and symptomatic resolution rates.

RESULTS Across a cohort of 251 patients with 260 distinct dAVFs, the overall initial angiographic occlusion rate was 70%; recurrence or occult residual lesions were seen on subsequent angiography in 3% of cases. The overall complication rate was 8%, with permanent neurological complications occurring in 3% of cases. Among 102 patients with dAVFs without cortical venous reflux, rates of resolution/improvement of pulsatile tinnitus and ocular symptoms were 79% and 78%, respectively. Following the introduction of Onyx during the latter half of the study period, the number of treated dAVFs doubled; the initial angiographic occlusion rate increased significantly from 60% before the use of Onyx to 76% after (p = 0.01). In addition, during the latter period compared with the pre-Onyx period, the rate of dAVFs obliterated via a transarterial-only approach was significantly greater (43% vs 23%, p = 0.002), as was the number of dAVFs obliterated via a single arterial pedicle (29% vs 11%, p = 0.002).

CONCLUSIONS Overall, in the Onyx era, the rate of initial angiographic occlusion was approximately 80%, as was the rate of meaningful clinical improvement in tinnitus and/or ocular symptoms after initial endovascular treatment of cranial dAVFs.

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KEY WORDS arteriovenous fistula; dAVF; dural arteriovenous fistula; embolization; endovascular; Onyx; NBCA; *N*-butyl cyanoacrylate; interventional neurosurgery; vascular disorders

Dural arteriovenous fistulas (dAVFs) are formidable vascular lesions; patients with these lesions may have a panoply of clinical presentations.[3,7,13,18,23,31,35,38] The complex anatomical pathology of dAVFs catalyzed the evolution of creative endovascular treatment strategies.[11,12,14,16,24,37,39] This evolution was punctuated by the advancement of transvenous approaches in the late 1980s[14] and by the introduction of Onyx (Covidien) in the transarterial (and transvenous) treatment armamentarium approximately a decade ago.[16,24,25,27,29,37,39] Despite the preponderance of technical reports and small case series describing the endovascular treatment of dAVFs,[1,2,25,27,29,34,36,39] there is a paucity of reports describing substantial series of patients.[4,10,26,28] We sought to evaluate the natural history, initial angiographic occlusion rates, recurrence rates, and symptomatic improvement rates across a large series of patients. Armed with a fairly large patient cohort, we also sought to evaluate these parameters across more meaning-

ABBREVIATIONS dAVF = dural arteriovenous fistula; ECA = external carotid artery; MMA = middle meningeal artery; NBCA = *N*-butyl cyanoacrylate; NHND = nonhemorrhagic neurological deficit.

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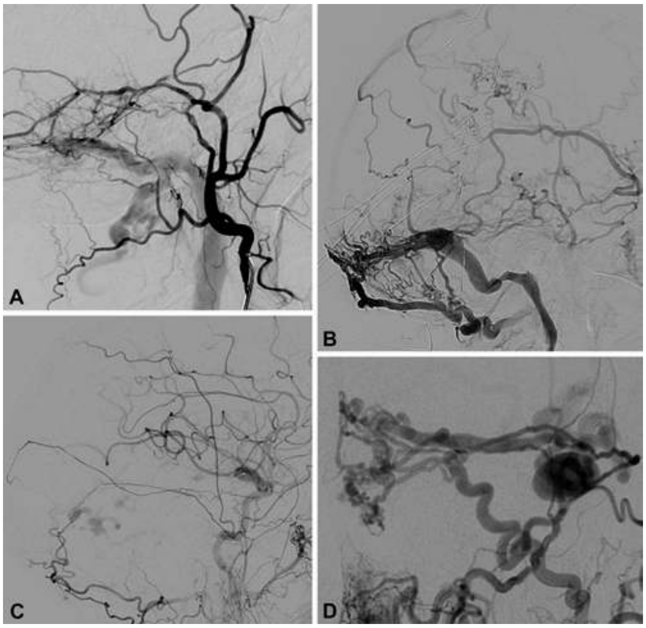

FIG. 1. Sample dAVFs by Djindjian type. A: Lateral projection of an ECA angiogram demonstrating a transverse/sigmoid dAVF supplied by MMA and transosseous occipital artery branches with antegrade sinus drainage (Djindjian Type I, Borden-Shucart Type I, Cognard Type I). B: Lateral projection of an ECA angiogram demonstrating a transverse-sigmoid dAVF supplied by the MMA and transosseous occipital artery branches with retrograde cortical venous reflux (Djindjian Type II, Borden-Shucart Type II, Cognard Type IIb). C: Lateral projection of the late phase of a common carotid artery angiogram demonstrating a tentorial dAVF supplied by the MMA and occipital artery branches with direct cortical venous drainage (Djindjian Type III, Borden-Shucart Type III, Cognard Type III). D: Anteroposterior projection of an ECA angiogram demonstrating a tentorial dAVF supplied by the MMA and occipital artery branches with cortical venous drainage with ectasia (Djindjian Type IV, Borden-Shucart Type III, Cognard Type IV).

ful subgroup analyses—stratification by dAVF drainage pattern and location.

Methods

We performed a retrospective analysis of a prospectively maintained endovascular patient database to identify all patients with cranial dAVFs treated endovascularly from January 1996 to September 2015. We excluded patients with spinal dAVFs, children with dural sinus malformations or infantile dural arteriovenous shunts, and patients managed with surgery or radiosurgery as the initial treatment approach. We extracted patient demographic information and symptoms at clinical presentation. For each dAVF, we extracted detailed angiographic information, including specific feeding arteries, venous drainage pattern, and the presence of venous ectasia. Because we do not always inject bilateral vertebral arteries prior to dAVF treatment, we could not accurately estimate the frequency of posterior meningeal artery dAVF supply.

Venous drainage was classified on the basis of the original Djindjian classification scheme[12] (Fig. 1, Table 1). This scheme parses out the presence of both cortical venous reflux and venous ectasia,[12] 2 recognized risk factors for dAVF aggressiveness.[8,13] In our cohort, dAVFs were considered to be multiple lesions only when drainage was into a different venous sinus system or cortical vein; multiple-hole fistulas with a common draining vein/sinus were considered a single entity. We noted the interval occurrence of new nonhemorrhagic neurological deficits (NHNDs) or hemorrhage and the time between initial clinical presentation and initiation of endovascular treatment to help define untreated lesion natural history. In addition to procedural complications, we noted treatment information, including which pedicles were embolized, the embolization agent, and the initial angiographic results. Angiographic and clinical follow-up results were noted along with the rates of radiographic recurrence and specific information on retreatment approaches.

Categorical variable comparisons were performed with the Fisher exact test. Results were considered statistically significant for p values < 0.05.

General Embolization Technique

There has been considerable evolution in treatment technique over the 20-year study period. Our current practice includes placing all patients under general endotracheal anesthesia with neurophysiological monitoring (somatosensory evoked potentials and electroencephalography). Procedures are begun with arterial access via a 6-F sheath and performance of diagnostic angiography,

TABLE 1. Classification of cranial dAVFs

Type	Djindjian-Merland*	Borden-Shucart†	Cognard-Merland‡
I	Drainage into a venous sinus	Drainage into a venous sinus	Antegrade drainage into a venous sinus
II	Drainage into a venous sinus w/ cortical venous reflux	Drainage into a venous sinus w/ cortical venous reflux	IIa: Drainage into a venous sinus w/ retrograde flow in the sinus IIb: Drainage into a venous sinus w/ cortical venous reflux IIa+b: Combination
III	Direct cortical venous drainage	Direct cortical venous drainage	Direct cortical venous drainage
IV	Direct cortical venous drainage w/ venous ectasia		Direct cortical venous drainage w/ venous ectasia
V			Spinal perimedullary drainage

* Djindjian and Merland, 1978.
† Borden et al., 1995.
‡ Cognard et al., 1995.

which is focused on a search for external carotid artery (ECA) pedicles, most commonly the middle meningeal artery (MMA) or occipital artery, or expected internal carotid artery feeding pedicles (as in cases of anterior cranial fossa dAVFs). Patients undergo systemic anticoagulation with heparin. If a reasonable pedicle is disclosed on carotid branch injections, we rarely inject the vertebral arteries prior to embolization as the posterior meningeal artery is rarely a "first choice" arterial pedicle for embolization. For added support, we often attempt to employ triaxial systems with dimethyl sulfoxide and glue-compatible microcatheters. Before embolization, superselective angiography via the microcatheter is performed to evaluate proximity to the fistula point, the presence of potential anastomoses, and the rate of arteriovenous shunting. Our general transarterial embolization agent of choice is Onyx; however, if access to a high-flow fistulous pouch is achieved transarterially, we might employ *N*-butyl cyanoacrylate (NBCA) instead. For most cavernous dAVFs and for cases in which transarterial access within reasonable proximity of the fistula point cannot be achieved or transarterial embolization fails to cast the fistula point, venous access in the common femoral vein with a 6-F sheath is then obtained in an attempt to perform transvenous coil or Onyx embolization. We may also use transvenous access to place a balloon in a venous sinus to mitigate the risk of nontarget embolization of the sinus (Fig. 2). For cavernous dAVFs, we most often perform transvenous coil embolization and supplement with Onyx when coiling does not entirely obliterate the fistula. At the conclusion of the procedure, control angiography is performed to confirm that no further arteriovenous shunting is occurring. Bilateral vertebral artery injections are then performed to ensure that there is no further supply from posterior meningeal/muscular branches when applicable. The patient is extubated and observed in the intensive care unit overnight. Postoperative imaging is performed only when new concerning symptoms develop (severe headache or neurological deficit). Patients are often discharged on the 1st postembolization day. We perform angiographic follow-up at 3–4 months postprocedure for local patients and recommend such follow-up for distant referral patients.

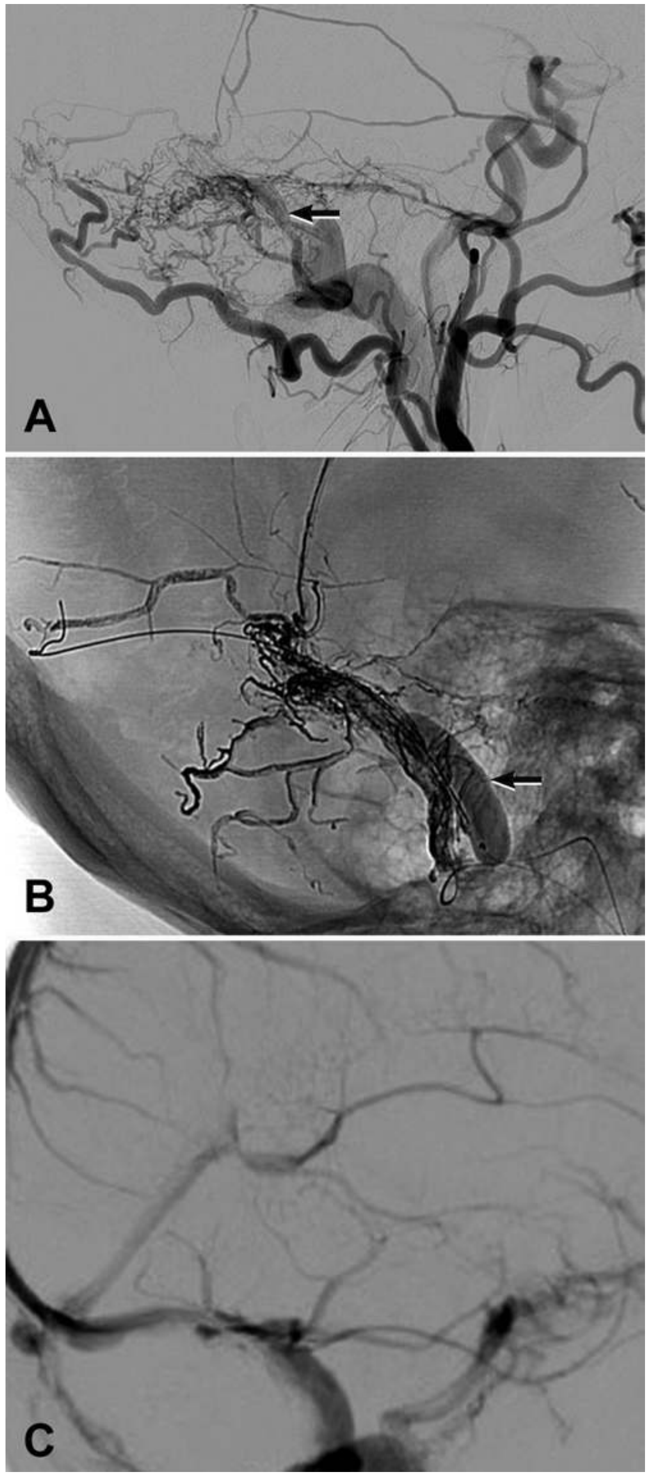

FIG. 2. Lateral view of an ECA injection demonstrating a sigmoid sinus dAVF supplied by MMA and occipital artery branches with a parallel venous pouch (*arrow*, **A**). Supply from the tentorial artery is also seen from reflux into the internal carotid artery. The parent sigmoid sinus is protected by inflation of a balloon in the sinus (*arrow*) during combined single-pedicle MMA simultaneous transarterial and transvenous Onyx embolization (**B:** lateral skull radiograph demonstrating a casted dAVF vein). Sigmoid sinus outflow is preserved (**C:** lateral view of venous phase of internal carotid artery angiogram).

Results

Demographics and Treatment Approaches

Across a cohort of 251 patients with 260 distinct dAVFs, the mean age was 58 ± 16 years (± SD), and there was a male predominance (1.5:1; 60% males) (Table 2). Nineteen dAVFs occurred after a definite history of cranial trauma (7%). Among the 260 dAVFs, presentation was incidental in 11%, and with pulsatile tinnitus in 39%, ocular symptoms in 27%, NHNDs (symptomatic venous hypertension) in 15%, and intracranial hemorrhage in 15%. The most common dAVF location was along the transverse and/or sigmoid sinus (33%). Arterial supply most commonly included the MMA (74%). Occipital artery supply was seen in 56% of dAVFs, tentorial artery supply in 31%, and ascending pharyngeal artery supply in 25%. Transarterial approaches were the most common (55%), with the MMA (56% of cases) and occipital artery (24% of cases) the most commonly embolized pedicles.

TABLE 2. Demographic, presentation, dAVF angiographic, and treatment information for 260 dAVFs among 251 patients: overall and stratified by dAVF venous drainage*

Variable	Overall (n = 260)	Type I (n = 102)	Type II (n = 72)	Type III/IV (n = 86)
Mean patient age (SD), years	58 (16)	56 (15)	60 (16)	58 (15)
Male/female ratio (% male)	1.5:1.0 (60%)	1.0:1.0 (50%)	1.5:1.0 (60%)	3.1:1.0 (76%)
Presentation				
Incidental	28 (11%)	0	4 (6%)	24 (28%)
Tinnitus	101 (39%)	62 (61%)	33 (46%)	6 (7%)
Ocular symptoms	69 (27%)	43 (42%)	23 (32%)	3 (3%)
NHND	38 (15%)	0	15 (21%)	23 (27%)
Hemorrhage	39 (15%)	0	8 (11%)	31 (36%)
dAVF location				
Anterior cranial fossa	6 (2%)	0	0	6 (7%)
Superior sagittal sinus	32 (12%)	2 (2%)	4 (6%)	26 (30%)
Sphenoparietal sinus	5 (2%)	0	0	5 (6%)
Cavernous sinus	59 (23%)	41 (40%)	18 (25%)	0
Transverse &/or sigmoid sinus	85 (33%)	43 (42%)	39 (54%)	3 (3%)
Torcular	15 (6%)	5 (5%)	10 (14%)	0
Tentorial/petrosal	47 (18%)	1 (1%)	0	46 (53%)
Marginal sinus	11 (4%)	10 (10%)	1 (1%)	0
Treatment approach				
Transarterial w/o transvenous	142 (55%)	31 (30%)	35 (49%)	76 (88%)
MMA embolization	145 (56%)	32 (31%)	45 (63%)	68 (79%)
Transvenous w/o transarterial	63 (24%)	42 (41%)	18 (25%)	3 (3%)
Transarterial & transvenous	52 (20%)	26 (25%)	19 (26%)	7 (8%)
Direct puncture in angiography suite (no craniotomy)	14 (5%)	10 (10%)	4 (6%)	0
Occlusion				
Initial angiographic occlusion rate	183 (70%)	71 (70%)	44 (61%)	68 (79%)
Spontaneous thrombosis after partial treatment	6/77 (8%)	4/31 (13%)	1/28 (4%)	1/18 (6%)
Recurrence/occult residual	3/110 (3%)	0/31 (0%)	1/35 (3%)	2/44 (5%)
Complications				
Overall rate	22 (8%)	5 (5%)	7 (10%)	10 (12%)
Permanent neurological complications	8 (3%)	1 (1%)	2 (3%)	5 (6%)
Additional treatment				
Embolization	20 (8%)	10 (10%)	8 (11%)	2 (2%)
Surgery	26 (10%)	3 (3%)	9 (13%)	14 (16%)
Radiosurgery	12 (5%)	6 (6%)	6 (8%)	0

* Dural AVF types are defined in Table 1.

Overall Treatment Outcomes

The overall initial angiographic occlusion rate was 70%; 8% of partially treated lesions (6/77) went on to spontaneously thrombose. Of 183 patients with initially occluded dAVFs, 110 underwent angiographic follow-up over a total of 111 patient-years (mean follow-up 1 year). Of these 110 patients, 3 (3%) had radiographic recurrence of dAVFs that were initially angiographically occluded. The overall complication rate was 8%, with permanent neurological complications in 3% of cases. Permanent complications included 2 venous infarctions (1 fatal), 3 facial nerve palsies from MMA embolization, 1 middle cerebral artery territory infarction, 1 case of anesthesia dolorosa, and 1 case of worsened ophthalmoparesis after cavernous dAVF embolization.

The Onyx Era

We treated 87 dAVFs over a 10-year period before the introduction of Onyx into our treatment armamentarium (Table 3). Over the subsequent 10-year period, we treated 173 dAVFs, with a specific substantial increase in the number of challenging anterior fossa, tentorial, petrosal, and torcular dAVFs. The overall initial angiographic occlusion rate increased significantly from 60% before the Onyx era to 76% during the Onyx era (p = 0.01), without a significant change in the complication rate (p = 0.64). Among dAVF subgroups, significant improvement in initial angiographic occlusion rates was seen for "high-risk" (Types II–IV) dAVFs (p = 0.02) in the latter period; however, a trending improvement in obliteration rates was seen for all dAVF subtypes.

TABLE 3. Treatment approaches and results before and during the Onyx era

Treatment Approach & Results	No. of Patients (%) Before Onyx (n = 87)	Onyx Era (n = 173)	p Value*
Treatment approach			
Transarterial only	37 (43)	105 (61)	**0.008**
Cure via transarterial-only approach	20 (23)	74 (43)	**0.002**
Cure via single arterial pedicle embolization	10 (11)	50 (29)	**0.002**
Initial angiographic occlusion rate			
Overall	52 (60)	131 (76)	**0.01**
Type I dAVF	27/43 (63)	44/59 (75)	0.28
Type II–IV dAVF	25/44 (57)	87/114 (76)	**0.02**
Superior sagittal sinus dAVF	6/10 (60)	18/22 (82)	0.22
Cavernous sinus dAVF	16/27 (59)	27/32 (84)	0.12
Tentorial/petrosal dAVF	10/13 (77)	31/34 (91)	0.33
Transverse/sigmoid dAVF	14/28 (50)	38/57 (67)	0.16
Torcular dAVF	0/2 (0)	6/13 (54)	0.47
Marginal sinus dAVF	3/4 (75)	7/7 (100)	0.36
Additional treatment			
Embolization	4 (5)	16 (9)	0.22
Surgery	12 (14)	14 (8)	0.19
Radiosurgery	10 (11)	2 (1)	**0.0004**
Complication rates			
All complications	6 (7)	16 (9)	0.64
Permanent complications	2 (2)	6 (3)	0.72

* Boldface type indicates statistical significance.

In the Onyx era, there was a significant increase in the proportion of cases treated via transarterial-only approaches (61% vs 43%, p = 0.008). In addition, when procedures during the Onyx era were compared with those performed before the Onyx era, there was a significantly greater rate of dAVF obliteration via a transarterial-only approach (43% vs 23%, respectively, p = 0.002), as well as significantly more dAVFs obliterated via a single arterial pedicle (29% vs 11%, respectively; p = 0.002). After the introduction of Onyx, re-treatment tended to be via embolization (9% vs 5% of dAVFs prior to the introduction of Onyx, p = 0.22) and less often via surgery (8% vs 14% of all dAVFs, p = 0.19) or radiosurgery (1% vs 11%, p = 0.0004).

"Low-Risk" (Type I) dAVFs

Our treated cohort of dAVFs with venous sinus drainage without cortical venous reflux was composed of 102 dAVFs associated with pulsatile tinnitus (61%) and/or ocular symptoms (42%) (Table 2, Fig. 1A). The most common locations were transverse/sigmoid sinuses (42%) and cavernous sinus (40%). Other locations included marginal sinus (10%), torcular (5%), superior sagittal sinus (2%), and tentorial/petrosal (1%). The treatment approach was most commonly transvenous only (41%). The overall initial angiographic occlusion rate was 70% (75% in the Onyx era).

There were 5 procedural complications (5% of cases): 2 cases of venous infarcts (1 causing permanent neurological symptoms), 1 case of sinus thrombosis treated with thrombectomy without long-term sequelae, 1 case of nontarget Onyx embolization into the transverse sinus treated with stenting without long-term sequelae, and 1 case of transiently worsened ophthalmoparesis after embolization of a cavernous dAVF.

Of 62 Type I dAVFs in which the patient presented with pulsatile tinnitus, 51 had at least 1 month of clinical follow-up (82% follow-up rate; mean follow-up 3 years). Among the 62 patients in this cohort, 59% had resolution of tinnitus, 20% had improvement, and 21% had persistent symptoms. Angiographically occluded fistulas were associated with a greater rate of symptomatic resolution/improvement of tinnitus compared with partially treated lesions (90% vs 62%, respectively; p = 0.04). Of 43 Type I dAVFs in which patients presented with ocular symptoms, 40 had at least 1 month of clinical follow-up (93% follow-up rate; mean follow-up 2 years). Among the 43 patients in this group, 48% had resolution of symptoms at follow-up, 30% had improvement, and 22% had persistent symptoms. Angiographically occluded dAVFs were associated with greater rates of symptomatic resolution/improvement of ocular symptoms than were partially treated dAVFs (85% vs 33%, respectively; p = 0.02).

"High-Risk" (Type II–IV) dAVFs

In our group of 260 dAVFs, 72 drained into a venous sinus with cortical venous reflux (28% Type II, Fig. 1B), 53 drained directly into a cortical vein without significant venous ectasia (20% Type III, Fig. 1C), and 33 drained into a cortical vein with ectasia (13% Type IV, Fig. 1D). Of these 158 "high-risk" (Type II–IV) dAVFs, 132 had at least 1 month of untreated follow-up from the time of clinical diagnosis before initiation of any treatment. Over 98.3 patient-years, 3 new NHNDs and 5 hemorrhages occurred, corresponding to annual rates of 3.1% and 5.1%, respectively. The annual clinical event rate was thus 8.1%, increasing to 10.1% for symptomatic dAVFs (NHNDs or hemorrhagic presentation).

There was a male sex predominance among patients with Type II–IV dAVFs, which was stronger among lesions with direct cortical venous drainage (Type III/IV, 76% males) than among lesions with sinus drainage and cortical reflux (Type II, 60% males, p = 0.04 compared with Type III/IV) (Table 2). Type III/IV dAVFs presented more commonly than Type II lesions with NHNDs (27% vs 21%, respectively; p = 0.46) or hemorrhage (36% vs 11%, respectively; p = 0.0004). Type II dAVF locations were similar to Type I dAVFs, including transverse/sigmoid in 54% of cases, cavernous sinus in 25%, torcular in 14%, superior sagittal sinus in 6%, and marginal sinus in 1%. Among Type III/IV dAVFs, the most common lesion location was tentorial/petrosal in 53%. There was no statistically significant difference in male sex predilection, presentation modality, or lesion location between Type III and Type IV dAVFs.

A significantly greater proportion of Type II dAVFs were treated with transarterial-only approaches compared with Type I lesions (49% vs 30%, respectively, p =

0.02), and a significantly greater proportion of Type III/IV dAVFs were treated with transarterial-only approaches compared with Type II lesions (88% vs 49%, respectively, $p < 0.0001$). Similarly, embolization via the MMA was performed significantly more commonly among Type II dAVFs than Type I dAVFs (63% vs 31%, respectively, $p = 0.0001$) and more commonly among Type III/IV dAVFs compared with Type II dAVFs (79% vs 63%, respectively, $p = 0.03$). There was no statistically significant difference in the rate of transarterial-only approaches and MMA embolization between Type III and Type IV dAVFs. The overall initial angiographic occlusion rate for Type II–IV dAVFs was 72%; the rate was significantly higher for Type III/IV compared with Type II dAVFs (79% vs 61%, respectively, $p = 0.01$).

Dural AVF Treatment Stratified by Location

Demographics, treatment approaches, and results are stratified by dAVF location in Table 4. A significant male sex predilection was seen among patients with superior sagittal sinus (75% males), sphenoparietal sinus (80% males), tentorial/petrosal (79% males), torcular (73% males), and marginal sinus (73% males) dAVFs. A slight female sex predilection was seen among patients with cavernous dAVFs (58% females). Pulsatile tinnitus was a common presenting symptom for marginal sinus (82%), transverse/sigmoid (80%), and torcular dAVFs (53%). Ocular symptoms were commonly seen among cavernous sinus (92%) and marginal sinus (45%) dAVFs. NHNDs on presentation were seen in 40% of tentorial/petrosal, 27% of torcular, 16% of superior sagittal sinus, and 12% of transverse/sigmoid dAVFs. Hemorrhagic presentation was seen for 41% of superior sagittal sinus, 40% of sphenoparietal sinus, and 30% of tentorial/petrosal dAVFs.

MMA supply was seen in all sphenoparietal sinus dAVFs (100%) and in the vast majority of superior sagittal sinus (97%), transverse/sigmoid (93%), torcular (93%), and tentorial/petrosal (85%) dAVFs. The occipital artery was the most common supply to transverse/sigmoid dAVFs (96%); it was also commonly seen among torcular (93%) and tentorial/petrosal (64%) dAVFs. As expected, most cavernous sinus dAVFs were supplied via the tentorial artery/inferolateral trunk (88%). Approximately one-half of tentorial/petrosal (55%), transverse/sigmoid (53%), and torcular (47%) dAVFs had supply from the tentorial artery. All marginal sinus dAVFs were supplied via the ascending pharyngeal artery.

The majority of marginal sinus (91%), cavernous sinus (69%), and transverse/sigmoid sinus (51%) dAVFs drained into a venous sinus without cortical venous reflux (Type I). All 5 treated sphenoparietal sinus dAVFs were Type III. All 6 treated anterior cranial fossa dAVFs were Type III/IV, as were 98% of tentorial/petrosal and 81% of superior sagittal sinus dAVFs. Notably, 5 of the 6 anterior cranial fossa dAVFs were Type IV (83%). Cortical venous reflux was seen in 67% of torcular dAVFs.

Transvenous approaches were used for the majority of marginal sinus (82%) and cavernous sinus (71%) dAVFs. Transarterial-only approaches were used in all sphenoparietal sinus (100%, all via the MMA) and in most superior sagittal sinus (97%; 94% via MMA), anterior cranial fossa (83%, all via ethmoidal branches), tentorial/petrosal (81%; 77% via MMA), and torcular (80%) dAVFs. Embolization was commonly via occipital artery (87%) and MMA branches (80%) in the treatment of torcular dAVFs.

Excellent initial angiographic occlusion rates were achieved in all sphenoparietal sinus (100%) and in most marginal sinus (91%), tentorial/petrosal (87%), and superior sagittal sinus (75%) dAVFs. Lower initial angiographic occlusion rates were seen for torcular dAVFs (40%, $p = 0.02$ compared with all other locations) and anterior cranial fossa dAVFs (33%, $p = 0.06$ compared with all other locations). Excluding torcular and anterior cranial fossa dAVFs, the overall initial angiographic occlusion rate in the Onyx era was 80%.

Of 85 patients with transverse/sigmoid dAVFs, 68 presented with pulsatile tinnitus; 49 of these 68 had at least 1 month of clinical follow-up (mean 2.3 years). Resolution was seen in 61% of cases, improvement in 20%, and persistent/worsening symptoms in 18%. Of 59 cavernous dAVF cases, 48 of 54 patients who initially presented with ocular symptoms had at least 1 month of clinical follow-up (mean follow-up 1.9 years). Thirty-five percent had resolution of symptoms at follow-up, 46% had improvement, and 19% had persistent/worsening symptoms.

Discussion

The evolution of our understanding of the natural history and endovascular treatment armamentarium for cranial dAVFs has evolved considerably since the earliest classification scheme and the early endovascular work of Djindjian et al.[11,12] Beyond drainage into leptomeningeal veins, initially identified by Houser et al.[15] as a risk factor for an aggressive course, symptomatic presentation and venous ectasia are both recognized as independent risk factors for a more aggressive clinical course.[8,13,38] Nearly 20 years after Djindjian's classification identified the significance of cortical venous drainage and venous ectasia,[12] Borden et al.[6] attempted to extrapolate their scheme to spinal dAVFs. Although few employ the Borden-Shucart classification for spinal dAVFs, most refer to the so-called "Borden" classification of cranial dAVFs (Djindjian Type I–III dAVFs). Merland, Djindjian's pupil, coauthored a paper with Cognard to update the Djindjian classification scheme to stratify Type II lesions and Type V lesions with spinal drainage (Table 1).[10]

The dAVFs without cortical venous drainage (low risk/Djindjian Type I) may cause debilitating headaches, pulsatile tinnitus, or ocular symptoms.[13,31,32] Interestingly, we found that although there was no association of age with fistula type, there was a male sex predilection among patients with high-risk dAVFs, particularly Type III/IV lesions (76% male). On the other hand, in contrast to all other locations, there was a female sex predilection among patients with cavernous dAVFs (58% females). Given that many patients were referred from other centers, we were able to perform a post hoc analysis of event rates in the interval between initial clinical presentation and our initiation of treatment. Over this period, we found an annualized NHND rate of 3.1% and a hemorrhage rate of 5.1% for dAVFs with cortical venous drainage (high risk/Djindjian Types II–IV). These results are similar to those published

TABLE 4. Demographic, presentation, dAVF angiographic, and treatment information stratified by location for 260 dAVFs

Variable	Anterior Fossa (n = 6)	Superior Sagittal Sinus (n = 32)	Sphenoparietal Sinus (n = 5)	Cavernous Sinus (n = 59)	Tentorial/ Petrosal (n = 47)	Transverse/ Sigmoid Sinus (n = 85)	Torcular (n = 15)	Marginal Sinus (n = 11)
Mean age (SD), yrs	62 (12)	57 (16)	66 (10)	57 (17)	57 (17)	57 (13)	57 (22)	66 (8)
Male/female (% male)	1:1 (50%)	3:1 (75%)	4:1 (80%)	0.7:1.0 (42%)	3.7:1.0 (79%)	1.2:1.0 (55%)	2.8:1.0 (73%)	2.7:1.0 (73%)
Presentation								
Incidental	5 (83%)	5 (16%)	3 (60%)	3 (5%)	11 (23%)	3 (4%)	2 (13%)	0
Tinnitus	0	4 (13%)	0	9 (15%)	3 (6%)	68 (80%)	8 (53%)	9 (82%)
Ocular symptoms	0	3 (9%)	0	54 (92%)	1 (2%)	4 (5%)	2 (13%)	5 (45%)
NHND	0	5 (16%)	0	0	19 (40%)	10 (12%)	4 (27%)	0
Hemorrhage	1 (17%)	13 (41%)	2 (40%)	2 (3%)	14 (30%)	6 (7%)	1 (7%)	0
Arterial supply								
MMA	0	31 (97%)	5 (100%)	22 (37%)	40 (85%)	79 (93%)	14 (93%)	1 (9%)
Occipital artery	0	14 (44%)	0	0	30 (64%)	82 (96%)	14 (93%)	5 (45%)
Tentorial artery	0	3 (9%)	0	52 (88%)*	26 (55%)	45 (53%)	7 (47%)	0
Ascending pharyngeal artery	0	1 (3%)	0	3 (5%)	12 (26%)	37 (44%)	3 (20%)	11 (100%)
Drainage pattern								
Venous sinus only	0	2 (6%)	0	41 (69%)	1 (2%)	43 (51%)	5 (33%)	10 (91%)
Venous sinus w/ cortical venous reflux	0	4 (13%)	0	18 (31%)	0	39 (46%)	10 (67%)	1 (9%)
Direct cortical venous drainage	1 (17%)	16 (50%)	5 (100%)	0	28 (60%)	3 (4%)	0	0
Direct cortical venous drainage + ectasia	5 (83%)	10 (31%)	0	0	18 (38%)	0	0	0
Treatment approach								
Transarterial w/o transvenous	5 (83%)	31 (97%)	5 (100%)	10 (17%)	38 (81%)	39 (46%)	12 (80%)	2 (18%)
Transvenous w/o transarterial	1 (17%)	1 (3%)	0	42 (71%)	2 (4%)	8 (9%)	0	9 (82%)
Transarterial & transvenous	0	0	0	4 (7%)	7 (15%)	38 (45%)	3 (20%)	0
Direct puncture in angiography suite	0	0	0	14 (24%)	0	0	0	0
Embolized arterial pedicles								
MMA	0	30 (94%)	5 (100%)	8 (14%)	36 (77%)	54 (64%)	12 (80%)	0
Occipital artery	0	1 (3%)	0	0	14 (30%)	35 (41%)	13 (87%)	0
Ascending pharyngeal artery	0	0	0	0	2 (4%)	3 (4%)	0	2 (18%)
Posterior meningeal artery	0	0	0	0	2 (4%)	2 (2%)	3 (20%)	0
Other	5 (83%)	0	0	5 (8%)	1 (2%)	1 (1%)	0	0
Initial angiographic occlusion rate	2 (33%)	24 (75%)	5 (100%)	43 (73%)	41 (87%)	52 (61%)	6 (40%)	10 (91%)
Overall complication rate	1 (17%)	5 (16%)	0	4 (7%)	6 (13%)	5 (6%)	1 (7%)	0
Permanent neurological complications	0	0	0	2 (3%)	6 (13%)	0	0	0
Additional treatment								
Embolization	0	1 (3%)	0	5 (8%)	1 (2%)	9 (11%)	4 (27%)	0
Surgery	3 (50%)	7 (22%)	0	5 (8%)	4 (9%)	4 (5%)	3 (20%)	0
Radiosurgery	0	0	0	3 (5%)	0	6 (7%)	3 (20%)	0

* Tentorial artery or inferolateral trunk.

in a recent pooled analysis of 395 dAVFs that included 254 lesions with cortical venous drainage, and annual NHND and hemorrhage rates of 4% and 6%, respectively.[13] This natural history study also found venous ectasia to be a significant risk factor for hemorrhage, with an annual hemorrhage rate of 21% for these lesions (Type IV). Minimally symptomatic or asymptomatic dAVF with cortical venous drainage had an annual hemorrhage rate of 2%; this rate increased to 10% for those associated with NHNDs and to 46% for hemorrhagic lesions.[13]

Evolution of Treatment

In parallel with early surgical attempts at arterial ligation,[15,17,22] the earliest transfemoral endovascular approaches were focused on occlusion of arterial feeders to dAVFs.[11] Kendall and Logue's[19] elegant depiction of venous hypertension and the mere need to "disconnect" the fistula in cases of spinal dAVFs helped revolutionize our understanding of this lesion class and is the mainstay of treatment approaches today. Endovascular approaches thus needed to present a way to permanently occlude the fistula point. Kerber and colleagues' innovative work with acryl glues paved this avenue, which is still a valuable treatment approach today via NBCA glue embolization.[5,20,21] Predominantly employing NBCA in their reputable experience with 170 dAVFs, Baltsavias and Valavanis[4] reported an initial anatomical cure rate of 60.5% for low-risk and 69% for high-risk lesions. Permanent morbidity was reported for 2.3% of cases over a 16-year period.

Glue embolization, in combination with transvenous approaches for coil occlusion of fistulas, served as the mainstay of treatment approaches during the first half of our evaluated period in this study. Notwithstanding the introduction of Onyx, transvenous coil embolization remained the overall predominant treatment approach for cavernous and marginal sinus dAVFs (71% and 82% of cases, respectively). However, following the introduction of Onyx, there was a significant increase in the proportion of cases treated via transarterial-only approaches (43% to 61%, $p = 0.008$) and effective angiographic occlusion via transarterial-only approaches (23% to 43%, $p = 0.002$), in the pre- versus post-Onyx eras, respectively. This reflects the exceptional "pushability" of Onyx that allows considerable penetration and casting of the fistula site, often from a single arterial pedicle[1] (Figs. 2 and 3).

Considering our transarterial cases, the most commonly embolized pedicle was the MMA (56% of cases), which reflects its relative proclivity toward easy distal catheterization and preponderant involvement in dAVF supply (74% of cases had MMA supply). Although it had no significant effect on complications, the introduction of Onyx into the treatment armamentarium had a significantly positive impact on angiographic occlusion rates despite our attempts to obliterate far more challenging dAVFs, including anterior fossa and complex torcular lesions. Indeed, consistent with other series, rates of initial angiographic occlusion of dAVFs with Onyx have roughly approximated 80%.[27,28] Similar to our results, one study of 53 patients demonstrated statistically significantly greater rates of occlusion after treatment with Onyx as compared with NBCA.[27] We intentionally did not compare results between dAVFs treated with Onyx versus those treated with NBCA, but rather between the time Onyx was introduced into the treatment armamentarium and prior to that period. We continue to use NBCA in circumstances of high-flow shunts and fortuitous circumstances of microcatheter wedging that allow for excellent NBCA penetration.

Most dAVF series have focused on rates of angiographic occlusion and recurrence.[2,25–28] We chose the term "initial angiographic occlusion" rather than "cure" to refer to dAVFs occluded after initial treatment. We reserve the term "cure" to refer specifically to dAVFs with radiographic evidence of persistent vein/fistula casting and persistent angiographic occlusion at least 4 months after treatment on formal complete angiographic evaluation. As Chandra et al.[9] reported, although short-term recurrence may occur (6% of cases in their series), long-term digital subtraction angiography following short-term digital subtraction angiography revealing occlusion consistently demonstrated durable obliteration (median follow-up 28 months). In contrast to some series,[25,26] we specifically evaluated the initial angiographic occlusion rate. Providing a total final angiographic occlusion rate after potential multimodality therapy is of little clinical value to both the clinician and the patient when initially evaluating a lesion and when counseling on the risks and benefits of a single planned intervention.

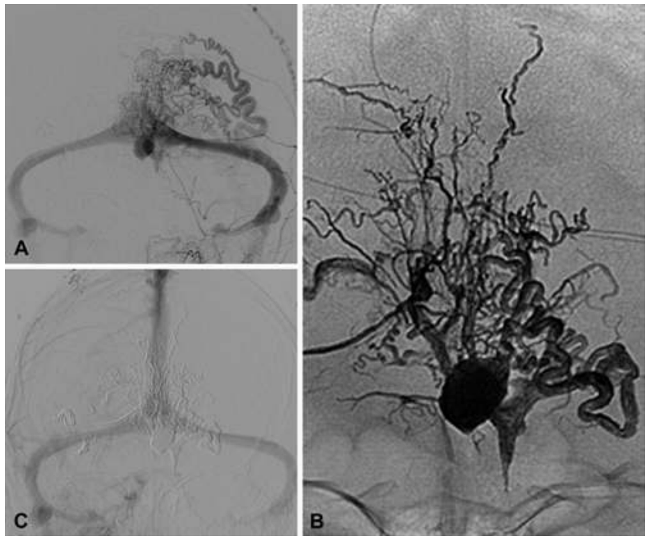

FIG. 3. A complex torcular dAVF (**A:** anteroposterior view, venous phase of ECA injection) was treated via transarterial Onyx embolization. The Onyx cast demonstrates excellent penetration of the fistula with reflux into the other arterial pedicle (**B:** anteroposterior view, Onyx cast. **C:** anteroposterior view, angiographic result).

We also do not consider dAVFs to be occluded unless the draining vein was casted with an embolizing agent. High-risk cranial (and spinal) dAVFs that are "occluded"/occult after transarterial treatment without penetration of the draining vein are evaluated for potential further treatment. This approach likely contributes to our relatively low recurrence rate in comparison with some series.[2] Of 110 initially occluded dAVFs undergoing angiographic follow-up at our institution, we observed 3 cases of recurrent/occult residual dAVFs (3%). Similar to our results, recurrence was demonstrated in only 1 of 33 cases with angiographic follow-up in a study of 53 patients undergoing NBCA or Onyx embolization of dAVFs.[27]

Of greater clinical value to patients with low-risk dAVFs, we additionally evaluated clinical outcomes with respect to pulsatile tinnitus and/or ocular symptoms after initial endovascular treatment. Although outcomes have been evaluated in only a few reports, our outcomes compare favorably.[30,32,33] Importantly, we demonstrated that angiographic occlusion was significantly associated with symptomatic resolution/improvement of the respective symptoms, particularly ocular symptoms that only improved in 33% of partially treated cases. Overall, 59% of patients had resolution of tinnitus and 48% had resolution of ocular symptoms. Of clinical significance, tolerable improvement/resolution of tinnitus and ocular symptoms was seen in 79% and 78% of cases, respectively; these patients did not undergo further treatment.

Conclusions

This study demonstrates a significant impact of the introduction of Onyx on initial angiographic occlusion and the ability to occlude dAVFs via transarterial-only approaches or even a single pedicle. Limitations of our study include its retrospective nature, its single institutional analysis without independent outcome adjudication, and its relatively limited follow-up. Nonetheless, we demonstrate fairly consistent, simple findings that may prove of clinical value when counseling patients: an overall rate of approximately 80% for initial angiographic occlusion in the Onyx era, and an approximately 80% rate of meaningful clinical improvement in tinnitus and/or ocular symptoms after treatment. Initial angiographic results should be evaluated with careful scrutiny for effective casting of the draining vein, and delayed follow-up complete angiography must be performed to confirm a true durable angiographic "cure" for high-risk lesions. With more stringent criteria for the declaration of initial angiographic occlusion and subsequent angiographic cure, recurrence after dAVF treatment is rare.

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Disclosures

Dr. McDougall reports that he is a consultant for ev3 and MicroVention.

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Conception and design: Albuquerque, Gross, McDougall. Acquisition of data: Gross, Moon. Analysis and interpretation of data: Albuquerque, Gross, McDougall. Drafting the article: Gross. Critically revising the article: all authors. Reviewed submitted version of manuscript: Albuquerque. Statistical analysis: Gross. Administrative/technical/material support: Albuquerque, McDougall. Study supervision: Albuquerque, McDougall.

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