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. The complex anatomical pathology of dAVFs catalyzed the evolution of creative endovascular treatment strategies. This evolution was punctuated by the advancement of transvenous approaches in the late 1980s and by the introduction of Onyx (Covidien) in the transarterial (and transvenous) treatment armamentarium approximately a decade ago. Despite the preponderance of technical reports and small case series describing the endovascular treatment of dAVFs, there is a paucity of reports describing substantial series of patients. 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-
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,21 (Fig. 1, Table 1). This scheme parses out the presence of both cortical venous reflux and venous ectasia,8,12 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.

![Sample dAVFs by Djindjian type](image)

**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).

<table>
<thead>
<tr>
<th>Type</th>
<th>Djindjian-Merland*</th>
<th>Borden-Shucart†</th>
<th>Cognard-Merland‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Drainage into a venous sinus</td>
<td>Drainage into a venous sinus</td>
<td>Antegrade drainage into a venous sinus</td>
</tr>
<tr>
<td>II</td>
<td>Drainage into a venous sinus w/ cortical venous reflux</td>
<td>Drainage into a venous sinus w/ cortical venous reflux</td>
<td>Ila: Drainage into a venous sinus w/ retrograde flow in the sinus&lt;br&gt;IIb: Drainage into a venous sinus w/ cortical venous reflux&lt;br&gt;Ila+b: Combination</td>
</tr>
<tr>
<td>III</td>
<td>Direct cortical venous drainage</td>
<td>Direct cortical venous drainage</td>
<td>Direct cortical venous drainage</td>
</tr>
<tr>
<td>IV</td>
<td>Direct cortical venous drainage w/ venous ectasia</td>
<td>Direct cortical venous drainage w/ venous ectasia</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>Spinal perimedullary drainage</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Djindjian and Merland, 1978.<br>† Borden et al., 1995.<br>‡ 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.

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.

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

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

* Dural AVF types are defined in Table 1.
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 non-target Onyx embolization into the transverse sinus treated with stenting without long-term sequelae, and 1 case of transiently worsened ophthalmoplegia 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 into a cortical vein with ectasia (13% Type IV, Fig. 1D). Of these 158 “high-risk” (Type II–IV) dAVFs, 132 had 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).
Dural AVF embolization
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Dural AVF embolization
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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.13 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.8,11,13,38 Nearly 20 years after Djindjian's classification identified the significance of cortical venous drainage and venous ectasia,12 Borden et al.14 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.
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. 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.

**Evolution of Treatment**

In parallel with early surgical attempts at arterial ligation, the earliest transfemoral endovascular approaches were focused on occlusion of arterial feeders to dAVFs. Kendall and Logue’s 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.

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

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

* Tentorial artery or inferolateral trunk.
point. Kerber and colleagues’ innovative work with acryl


glues paved this avenue, which is still a valuable treatment


approach today via NBCA glue embolization. 20,21 Predomi-


nantly employing NBCA in their reputable experi-


ence with 170 dA VFs, 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 re-


ported 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 re-


mained 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 propor-


tion 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 consid-


erable penetration and casting of the fistula site, often from


a single arterial pedicle’ (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 catheteriza-


tion 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 im-


pact on angiographic occlusion rates despite our attempts


to obliterate far more challenging dAVFs, including ante-


rior fossa and complex torcular lesions. Indeed, consistent


with other series, rates of initial angiographic occlusion


doAVFs with Onyx have roughly approximated 80%. 27,28


Similar to our results, one study of 53 patients demonstrat-


ed statistically significantly greater rates of occlusion after


during 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 be-


tween 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 for-


tuitous circumstances of microcatheter wedging that allow


for excellent NBCA penetration.


Most dAVF series have focused on rates of angi-


ographic occlusion and recurrence. 2,22–24 We chose the term


“initial angiographic occlusion” rather than “cure” to re-


fer to dAVFs occluded after initial treatment. We reserve


the term “cure” to refer specifically to dAVFs with radi-


ographic 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. 5 reported, although short-term recurrence


may occur (6% of cases in their series), long-term digi-


tal 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.


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 treat-


ment. 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 recur-


rent/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 undergo-


ng 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 com-


pare favorably. 26,27,28 Importantly, we demonstrated that


angiographic occlusion was significantly associated with


symptomatic resolution/improvement of the respective


symptoms, particularly ocular symptoms that only im-


proved 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 im-


provement/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 in-
roduction of Onyx on initial angiographic occlusion and the ability to occlude dA VF s 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.

References

dural arteriovenous fistulas presenting as pulsatile tinnitus. *Laryngoscope* 109:54–58, 1999


**Disclosures**

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

**Author Contributions**

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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