Stereotactic radiosurgery for intracranial dural arteriovenous fistulas: a systematic review

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OBJECT The goal of this study was to evaluate the obliteration rate of intracranial dural arteriovenous fistulas (DAVFs) in patients treated with stereotactic radiosurgery (SRS), and to compare obliteration rates between cavernous sinus (CS) and noncavernous sinus (NCS) DAVFs, and between DAVFs with and without cortical venous drainage (CVD).

METHODS A systematic literature review was performed using PubMed. The CS DAVFs and the NCS DAVFs were categorized using the Barrow and Borden classification systems, respectively. The DAVFs were also categorized by location and by the presence of CVD. Statistical analyses of pooled data were conducted to assess complete obliteration rates in CS and NCS DAVFs, and in DAVFs with and without CVD.

RESULTS Nineteen studies were included, comprising 729 patients harboring 743 DAVFs treated with SRS. The mean obliteration rate was 63% (95% CI 52.4%–73.6%). Complete obliteration for CS and NCS DAVFs was achieved in 73% and 58% of patients, respectively. No significant difference in obliteration rates between CS and NCS DAVFs was found (OR 1.72, 95% CI 0.66–4.46; p = 0.27). Complete obliteration in DAVFs with and without CVD was observed in 56% and 75% of patients, respectively. A significantly higher obliteration rate was observed in DAVFs without CVD compared with DAVFs with CVD (OR 2.37, 95% CI 1.07–5.28; p = 0.03).

CONCLUSIONS Treatment with SRS offers favorable rates of DAVF obliteration with low complication rates. Patients harboring DAVFs that are refractory or not amenable to endovascular or surgical therapy may be safely and effectively treated using SRS.

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KEY WORDS arteriovenous fistula; dural arteriovenous fistula; stereotactic radiosurgery; radiosurgery; review

In this systematic review, we evaluate the obliteration rate of DAVFs in patients treated with SRS. We also compare obliteration rates between cavernous sinus (CS) and noncavernous sinus (NCS) DAVFs, and between DAVFs with and without cortical venous drainage (CVD), by using available data in the literature.

Methods

Inclusion Criteria

In our attempt to balance between the largest possible patient population and a relatively homogeneous cohort, the following inclusion criteria for this systematic review were devised: 1) the study must contain at least 5 patients...
who had intracranial DAVFs treated with SRS without concurrent arteriovenous malformations (AVMs) or arterial aneurysms; 2) the study must have included post-SRS outcome data regarding DAVF obliteration rates; and 3) the language of the study must be English. Patients who underwent prior or combined therapies other than SRS for their DAVFs and/or had prior hemorrhages were not excluded.

Literature Search
A systematic literature review was performed on March 3, 2014, using PubMed with the following search term: “dural arteriovenous fistula OR arteriovenous fistula AND radiosurgery.” Following the search, the articles were then screened by title and abstract. The remaining articles underwent further detailed review for relevance and usable data matching the inclusion criteria. Articles with insufficient post-SRS data and overlapping published data from the same institution in a more recent study were excluded. However, those with partially overlapping but supplementary treatment outcomes data from the same institutions were not excluded from the review.

Literature Review and Data Extraction
No registered review protocol was used in this study. This review follows the guidelines set forth by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Statement. Available demographic, radiosurgical, and clinical and radiological outcomes data were extracted from studies that met the inclusion criteria. Demographic data included number of patients, sex, and age. Radiosurgical data included the type of SRS device used (i.e., Gamma Knife, linear accelerator, proton beam) and radiosurgical parameters (mean margin dose, isodose line, and treatment volume). Outcomes data reviewed for each study included duration of follow-ups, complete obliteration rates as determined using modalities specified by the respective studies, hemorrhages following SRS, SRS-related new or worsened neurological deficits, and SRS-related deaths.

The DAVFs were categorized by location (CS, transverse and sigmoid sinus [TSS], and other locations) whenever possible. The NCS DAVFs included those located at the TSS and other locations. The CS DAVFs were classified using the Barrow classification system, whereas NCS DAVFs were classified using the Borden classification system. For studies that used the Cognard classification system, patients were reclassified using the Borden classification system as follows: Cognard Types I and IIa were categorized as Borden Type I; Cognard Types IIb and IIa + b were categorized as Borden Type II; and Cognard Types III, IV, and V were categorized as Borden Type III. To assess the association between treatment outcomes and CVD, patients were also classified into groups of DAVFs without CVD (Borden Type I or Cognard Types I and IIa) and with CVD (Borden Types II and III or Cognard Types IIb, IIa + b, III, IV, and V). Table 1 outlines the Borden, Cognard, and Barrow classification systems.

Statistical Analysis
Descriptive statistics for this review were determined using SPSS version 20.0.0 (IBM Corp., 2011), whereas statistical analyses of pooled data comparing obliteration rates were performed using Review Manager version 5.2.8 (The Nordic Cochrane Centre; The Cochrane Collaboration, 2012). The DAVF obliteration rates following SRS were extracted for DAVFs with and without CVD, and for CS and NCS DAVFs. Studies with obliteration rates for DAVFs both with and without CVD were included in the meta-analysis comparing their respective obliteration rates. Similarly, studies with obliteration rates for both CS and NCS DAVFs were analyzed in the meta-analysis comparing their respective obliteration rates. Odds ratios for individual studies and the sum of the included studies were computed using the Mantel-Haenszel test.

Under the assumptions of possible clinical diversity and methodological differences among the included studies, the random effects model was implemented in the analyses for this review. Study heterogeneity was detected using the chi-square and I2 test statistics. However, the power of the chi-square test was limited by the inclusion of a small number of studies in the analyses; hence significant heterogeneity was considered to be present when both the chi-square value was within the 10% level of significance (p < 0.10) and the I2 value exceeded 50%. Potential contributions to variations across studies are discussed in the limitations section of this review. Unclear risks of bias

<table>
<thead>
<tr>
<th>Authors &amp; Categories</th>
<th>Description</th>
</tr>
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<tr>
<td>Cognard et al., 1995</td>
<td>Type I: Drainage into dural venous sinus w/ normal antegrade flow</td>
</tr>
<tr>
<td></td>
<td>Type IIa: Drainage into dural venous sinus w/ retrograde flow</td>
</tr>
<tr>
<td></td>
<td>Type IIb: Drainage into dural venous sinus w/ normal antegrade flow &amp; CVD</td>
</tr>
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<td></td>
<td>Type IIa &amp; IIb: Drainage into dural venous sinus w/ retrograde flow &amp; CVD</td>
</tr>
<tr>
<td></td>
<td>Type III: Direct drainage into cortical vein w/o venous ectasia</td>
</tr>
<tr>
<td></td>
<td>Type IV: Direct drainage into cortical vein w/ venous ectasia</td>
</tr>
<tr>
<td></td>
<td>Type V: Direct drainage into perimedullary veins</td>
</tr>
<tr>
<td>Borden et al., 1995</td>
<td>Type I: Drainage into dural venous sinus or meningeal vein</td>
</tr>
<tr>
<td></td>
<td>Type II: Drainage into dural venous sinus &amp; CVD</td>
</tr>
<tr>
<td></td>
<td>Type III: Direct drainage into cortical vein</td>
</tr>
<tr>
<td>Barrow et al., 1985</td>
<td>Type A: Direct high-flow shunts b/w ICA &amp; CS</td>
</tr>
<tr>
<td></td>
<td>Type B: Indirect low-flow shunts b/w meningeal branches of ICA &amp; CS</td>
</tr>
<tr>
<td></td>
<td>Type C: Indirect low-flow shunts b/w meningeal branches of ECA &amp; CS</td>
</tr>
<tr>
<td></td>
<td>Type D: Indirect low-flow shunts b/w meningeal branches of both ICA &amp; ECA &amp; CS</td>
</tr>
</tbody>
</table>

ECA = external carotid artery; ICA = internal carotid artery.
were assumed for retrospective studies. All statistical tests were 2-sided, and \( p < 0.05 \) was considered statistically significant.

**Results**

**Study Selection**

The search yielded 1379 articles published between 1972 and 2014. The initial screening process led to the selection of 31 articles. Subsequently, 12 studies were excluded for reasons including insufficient post-SRS outcome data and overlapping published patient data from the same institution in another study. Finally, 19 series comprising 729 patients harboring 743 DAVFs who underwent SRS were identified. \(^3,6,7,12,14,16,39,20,22,23,31–34,37,39,41–42,51\) Figure 1 demonstrates an outline of the systematic review process. Four studies with partially overlapping but supplementary treatment outcomes data from two institutions were included in the systematic review. However, no two studies from the same institution were included in the same part of the analyses. All studies included were retrospective in design, comprising mostly small cohorts. Unclear risks of bias were assigned to all studies.

**Overall Demographic Data, DAVF and Treatment Characteristics, and Outcomes**

There was a slight female predominance among the 19 included studies, with 312 of the 580 patients (53.8%) with available demographic information identified as female. The mean patient age for the 19 studies ranged between 50 years and 69 years. The SRS modalities used were Gamma Knife surgery (GKS) and linear accelerator (LINAC)–based radiosurgery in 15 and 3 studies, respectively; in 1 study the specific SRS modality used was not documented. Prior endovascular embolizations and microsurgeries were performed in 199 of 701 (28.4%) and 34 of 726 (4.7%) of DAVFs, respectively. The mean follow-up period after SRS ranged from 12 months to 50 months (overall mean 28.9 months).

Combining the results of the included studies, in 438 of 642 DAVFs (68.2%) with follow-up data, complete obliteration was achieved following SRS. The mean obliteration rate between individual studies was 63% (95% CI 52.4%–73.6%). Angiography was performed in 292 patients, and complete obliteration was observed in 255 (87.3%). Post-SRS hemorrhage, new or worsened neurological deficit, and death occurred in 9 of 730 DA VFs (1.2%), 9 of 715 patients (1.3%), and 2 of 715 patients (0.3%), respectively. A summary of included SRS series for DAVFs along with the respective radiosurgical parameters is found in Table 2.

**Outcomes for CS DAVFs Versus NCS DAVFs**

Of the 700 DAVFs categorized by location, 323 (46.1%) were located in the region of the CS and 377 (53.9%) were located in NCS regions. Complete obliteration was achieved in 172 of 236 CS DAVFs (72.9%) and in 143 of 247 NCS DAVFs (57.9%). Post-SRS hemorrhages were observed in 0 of 295 patients with CS DAVF and in 3 of 237 patients with NCS DAVF (1.3%). The NCS DAVFs comprised 192 TSS DAVFs (50.9%) and 185 DAVFs at other locations (49.1%). Complete obliteration was observed in 52 of 87 TSS DAVFs (59.8%) and in 38 of 71 DAVFs at other NCS, non-TSS locations (53.5%). Post-SRS hemorrhages were reported in 2 of 142 patients with TSS DAVFs (1.4%) and in 1 of 95 patients with NCS, non-TSS DAVFs (1.1%). A summary of CS and NCS DAVF treatment outcomes following SRS is found in Table 3. Despite the difference in complete obliteration rates between CS and NCS DAVFs, analysis of pooled data based on the random effects model from 5 studies with DAVF obliteration data for both CS and NCS DAVFs, analysis of pooled data based on the random effects model from 5 studies with DAVF obliteration data for both CS and NCS DAVFs demonstrated no significant difference in their complete obliteration rates (OR 1.72, 95% CI 0.66–4.46; \( p = 0.27 \)). No significant heterogeneity among the included studies was found in this analysis (\( \chi^2 = 5.71; p = 0.22; I^2 = 30\% \)). Results of the analysis are summarized in Fig. 2.

**Outcomes for DAVFs With CVD Versus DAVFs Without CVD**

In studies that reported CS DAVFs using the Barrow classification system, 3 (1.2%), 31 (12.4%), and 19 (7.6%), and
<table>
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<th>Authors &amp; Year</th>
<th>No. of Pts</th>
<th>No. Female Pts</th>
<th>Mean Age (yrs)</th>
<th>No. DA/FS</th>
<th>Mean Radio FU (mos)</th>
<th>Previous Embol, n/N</th>
<th>Previous Microsurgery, n/N</th>
<th>SRS Modality</th>
<th>Mean Margin Dose (Gy)</th>
<th>Isodose Line (%)</th>
<th>Tx Vol (cm³)</th>
<th>Complete Oblit, n/N</th>
<th>Complete Oblit on Angio, n/N</th>
<th>No. w/ Post-SRS Hem</th>
<th>No. w/ Other NeuroDefs</th>
<th>No. Dead</th>
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<td>Pan et al., 2013*</td>
<td>321</td>
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<td>57.8</td>
<td>321</td>
<td>21 for CS, 28 for NCS†</td>
<td>41/321</td>
<td>13/321</td>
<td>GKS</td>
<td>17.2</td>
<td>68.5 for CS, 57.7 for NCS</td>
<td>4.7 for CS, 16.9 for NCS</td>
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<td>NA</td>
<td>NA</td>
<td>17</td>
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<td>0/17</td>
<td>LINAC</td>
<td>18</td>
<td>NA</td>
<td>NA</td>
<td>9/17</td>
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<td>NA</td>
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<td>56.8</td>
<td>9</td>
<td>35†</td>
<td>4/9</td>
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<td>NA</td>
<td>43</td>
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<td>8</td>
<td>57</td>
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<td>2/22</td>
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<td>Yang et al., 2010†</td>
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<td>69</td>
<td>44</td>
<td>19/44</td>
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<td>GKS</td>
<td>20</td>
<td>50 in 42, 60 in 2</td>
<td>2</td>
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<td>Cifarelli et al., 2010</td>
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<td>NA</td>
<td>30/46</td>
<td>30/46</td>
<td>3</td>
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<tr>
<td>Kida, 2009</td>
<td>13</td>
<td>4</td>
<td>54.3</td>
<td>13</td>
<td>24†</td>
<td>7/13</td>
<td>GKS</td>
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<td>NA</td>
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<td>NA</td>
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<td>7/52</td>
<td>3/52</td>
<td>GKS</td>
<td>22</td>
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<td>28/41</td>
<td>28/41</td>
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<td>Koebbe et al., 2005</td>
<td>18</td>
<td>9</td>
<td>65</td>
<td>23</td>
<td>13/23</td>
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<td>GKS</td>
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<td>NA</td>
<td>2.16</td>
<td>15/18</td>
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<td>Pan et al., 2002*</td>
<td>20</td>
<td>9</td>
<td>53</td>
<td>20</td>
<td>19†</td>
<td>NA</td>
<td>NA GKS</td>
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<td>16</td>
<td>10</td>
<td>56</td>
<td>17</td>
<td>24</td>
<td>NA</td>
<td>NA GKS</td>
<td>25, except 1 w/ 20.83</td>
<td>50</td>
<td>NA</td>
<td>10/13</td>
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(continued)
### TABLE 2. Summary of the 19 SRS series for DAVFs included in this systematic review (continued)

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<tr>
<th>Authors &amp; Year</th>
<th>No. of Pts</th>
<th>No. Female Pts</th>
<th>Mean Age (yrs)</th>
<th>No. DAVFs</th>
<th>No. Previous Embo, n/N</th>
<th>Previous Microsurgery, n/N</th>
<th>SRS Modality</th>
<th>Mean Margin Dose (Gy)</th>
<th>Isodose Line (%)</th>
<th>Tx Vol (cm$^3$)</th>
<th>Complete Oblit, n/N</th>
<th>Complete Oblit on Angio, n/N</th>
<th>No. w/ Post-SRS Hem</th>
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<td>Chung et al., 2002</td>
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<td>6</td>
<td>56.3</td>
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<td>17†</td>
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<td>70</td>
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<td>Lewis et al., 1994‡</td>
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<td>61</td>
<td>7</td>
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<td>0</td>
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</tr>
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</table>

**Total§** | 729 | 312/580 (53.8%) | 743 | 199/701 (28.4%) | 34/726 (4.7%) | 438/642 (66.2%) | 255/292 (87.3%) | 9/730 (1.2%) | 9/715 (1.3%) | 2/715 (0.3%) |

Angio = angiography; embo = embolization; FU = follow-up; hem = hemorrhage; NA = not available; neuro defs = neurological deficits; obl = obliteration; pts = patients; radio = radiological; Tx = treatment.

* Studies with partially overlapping but complementary treatment outcomes data from the same institution.
† Distinction between clinical and radiological follow-up unclear.
‡ Studies with patients treated with combined endovascular embolization and SRS.
§ Excludes earlier studies with partially overlapping but complementary treatment outcomes data from the same institutions.
¶ Based on the number of DAVFs in patients with follow-up.
** Based on the number of patients with follow-up.

Based on the number of DAVFs in patients with follow-up.
198 (78.9%) were categorized as Barrow Types A, B, C, and D DA VFs, respectively. Complete obliteration was observed in 1 of 3 Type A (33.3%), in 11 of 11 Type B (100%), in 3 of 4 Type C (75%), and 6 of 7 Type D (85.7%) CS DA VFs. No post-SRS hemorrhages were reported in any of the CS DA VFs. Among studies that reported NCS DA VFs using the Borden classification system, 105 (47.7%), 60 (27.3%), and 55 (25.0%) were categorized as Borden Types I, II, and III, respectively. Complete obliteration was observed in 52 of 79 Borden Type I (65.8%), 34 of 35 Type II (42.9%), and 12 of 24 Type III (50.0%) NCS DA VFs. Post-SRS hemorrhages were reported in 0 of 85 patients with Borden Type I, in 1 of 38 patients with Type II (2.6%), and in 1 of 27 patients with Type III (3.7%) DA VFs. A summary of SRS outcomes for CS and NCS DA VFs categorized using the Barrow and Borden classification systems is found in Table 3.

Of the 322 DA VFs with known venous drainage patterns, 165 (51.2%) had associated CVD and 157 (48.8%) did not have CVD. Complete obliteration was observed in 69 of 123 DA VFs (56.1%) with CVD and in 76 of 102 DA VFs (74.5%) without CVD. Post-SRS hemorrhage was reported in 0 of 144 DA VFs with CVD (4.2%) and in 0 of 131 DA VFs without CVD (0.0%). A summary of SRS outcomes for DA VFs with and without CVD is found in Table 3. Analysis of pooled data based on the random effects model demonstrated that DA VFs without CVD were associated with a significantly higher rate of complete obliteration following SRS compared with DA VFs with CVD among 9 studies with obliteration data for DA VFs both with and without CVD (OR 2.37, 95% CI 1.07–5.28; p = 0.03). No significant heterogeneity among the included studies was found in this analysis ($\chi^2 = 8.93$; p = 0.35; I$^2 = 10$%). Results of the analysis are summarized in Fig. 3.

Only a few studies investigated the potential factors associated with complete obliteration of DA VFs following SRS. Conflicting factors were found between these studies. Factors found by the included studies to be significantly associated with obliteration are as follows: CS DA VFs, Borden Type I DAVFs, DAVFs without CVD, hemorrhage at presentation, target volume < 1.5 ml, and Cognard Types III or IV DA VFs.7,16,51 Factors found to be nonsignificant are as follows: patient age and sex, prior treatments, DAVF location and size, DAVFs with multiple arteriovenous connections versus DA VFs with single arteriovenous connections, and minimal radiation dose delivered to DA VFs.7,16,42 Table 4 outlines these factors investigated by studies included in this systematic review.

### Discussion

Stereotactic radiosurgery was initially used in the treatment of AVMs in 1970 and was subsequently used to treat DA VFs in the late 1970s. Barcia-Salorio and colleagues first reported the use of SRS for treating DA VFs in 1982, followed by an SRS case series for DA VFs composed of 25 cases of CS DA VFs in 1994.23 Since then, a...
number of other studies have investigated the use of SRS for treating DAVFs in other locations, with variable rates of success. This systematic review of the literature, comprising 19 studies, found a reasonable rate of complete DAVF obliteration (63%), with relatively low complication rates. Although the complete obliteration rate determined using angiography is higher (87.3%), this may be biased because invasive modalities such as angiography are often performed to confirm complete obliteration following obliteration observed using noninvasive imaging modalities. The associated rates of post-SRS hemorrhage, neurological deficit, and mortality were 1.2%, 1.3%, and 0.3%, respectively. However, variations in obliteration and complication rates, such as risks of hemorrhage, may be dependent on factors such as the location and angioarchitecture of DAVFs. Therefore, we also categorized SRS treatment outcomes for DAVFs by location and venous drainage pattern.

**Comparison of CS DAVFs and NCS DAVFs**

Cavernous sinus DAVFs represent a subset of lesions that are distinct from NCS DAVFs. In contrast to other intracranial dural venous sinuses, the CS is located extradurally, not between the periosteal and meningeal layers.\(^1\)\(^2\) Due to its many routes of venous drainage, the presenting symptoms and signs of a CS DAVF are often benign.\(^4\)\(^6\) These symptoms include blurred vision, bruit, diplopia, exophthalmos, chemosis, and glaucoma. Given the benign features of low-flow CS DAVFs and possibility of spontaneous occlusion, some authors have advocated conservative treatments, including cervical carotid artery and jugular vein compressions, as first-line therapies for these lesions.\(^1\)\(^5\)\(^6\) However, some cases present with intractable intraocular hypertension or reduced ocular perfusion pressure, thereby warranting more rapid interventions to prevent progressive vision loss.\(^3\)\(^6\)\(^4\)\(^9\)

Due to their unique anatomy and symptomatology, CS DAVFs are often categorized using the Barrow classification system.\(^4\) Type A fistulas represent direct high-flow shunts between the internal carotid artery and the CS, comprising mostly traumatic fistulas formed as a result of a tear in the cavernous segment of the internal carotid artery. These fistulas do not typically resolve spontaneously, and therefore require rapid intervention for cases of progressive visual loss. Barrow Type A CS DAVFs are often adequately treated via endovascular approaches, which provide immediate results. Thus, the number of Type A CS DAVFs treated using SRS is low (1.2% of reported CS

**TABLE 4. Factors associated with DAVF obliteration via SRS among included studies**

<table>
<thead>
<tr>
<th>Authors &amp; Year</th>
<th>Associated w/ DAVF Oblit</th>
<th>Not Associated w/ DAVF Oblit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yang et al., 2013</td>
<td>CS DAVFs</td>
<td></td>
</tr>
<tr>
<td>Cifarelli et al., 2010</td>
<td>Borden Type I DAVFs No CVD</td>
<td>Sex Prior endovascular therapy for DAVF Prior craniotomy for DAVF Location of DAVF Size of DAVF Multi-hole vs single-hole DAVF</td>
</tr>
<tr>
<td>Hanakita et al., 2012</td>
<td>No CVD Hem at presentation Target vol &lt;1.5 ml Cognard Types III or IV DAVF</td>
<td>Age Sex Location of DAVF Prior therapy</td>
</tr>
<tr>
<td>Söderman et al., 2006</td>
<td>Minimal radiation dose to DAVF</td>
<td></td>
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</table>
DAVFs).21 Because complete obliteration of DAVFs following SRS is delayed, with a typical latency period of 1–3 years, SRS may represent a more suitable treatment modality for indirect, low-flow CS DAVFs classified as Barrow Types B, C, and D. In the largest SRS series for CS DAVFs to date, Pan et al. observed a complete obliteration rate of 70% with no reported cases of post-SRS hemorrhage or neurological morbidty in 156 indirect low-flow CS DAVFs.24 Based on the compiled data from studies included in this review, a complete obliteration rate of 73% was achieved in CS DAVFs treated with SRS. Therefore, the decision between conservative management and intervention should be individualized for each patient; consideration should be given to the severity of symptoms, DAVF angioarchitecture, and the efficacy and safety of treatments.

Noncavernous sinus DAVFs also comprise a heterogeneous cohort of lesions with variable presenting symptoms. Patients with DAVFs involving the TSS often present with pulsatile tinnitus and bruit, and those with superior sagittal sinus DAVFs can suffer from progressive dementia.22 Intracranial hemorrhage, the most devastating presentation of DAVFs, is more commonly seen in DAVFs involving the tentorium or anterior fossa.1,2  To better characterize DAVF hemorrhagic risk, the Borden and Cognard classification systems are used.5,8,9 Borden Types II and III and Cognard Types Iib–V DAVFs confer significantly higher risks of hemorrhage than Borden Type I and Cognard Types I and Iia DAVFs. Thus, these high-risk DAVFs usually warrant more immediate treatments in which modalities such as endovascular embolization and microsurgical ligation are used.9 As reflected in our results, fewer Borden Types II and III DAVFs were treated using SRS than Type I lesions. In the largest series of NCS DAVFs treated using SRS, Pan et al. observed a similar trend.34 Compared with the post-SRS obliteration rate for CS DAVFs (73%), the rate for NCS DAVFs appears to be lower (60%). However, this difference was not statistically significant in the pooled data analysis (p = 0.27). Post-SRS hemorrhage was observed more frequently in NCS DAVFs (1.3%) than in CS DAVFs (0%). Further categorization of NCS DAVFs demonstrated comparable obliteration rates for TSS DAVFs (60%) and DAVFs in other non-TSS locations (54%). Therefore, the efficacy of SRS does not seem to be restricted by DAVF location. More emphasis should be placed on understanding the angioarchitecture of DAVFs when selecting patients for SRS treatment.

Comparison of DAVFs With CVD and DAVFs Without CVD

It is well recognized that DAVFs with CVD have a significantly greater risk of hemorrhage compared with those without CVD. Söderman et al. reported a 1.5% annual risk of hemorrhage in 53 patients with unruptured DAVFs with CVD.41 In the same study, this risk increased to 7.4% per year for those with ruptured DAVFs. Strom et al. reported a similar annual hemorrhage rate of 1.4% in 17 patients harboring DAVFs with CVD without prior hemorrhage.45 The risk increased to 7.6% in those with DAVFs with CVD who presented with hemorrhage or nonhemorrhagic neurological deficit. Detailed analyses by Gross and Du of published studies found 6% and 10% annual hemorrhage rates for Borden Types II and III DAVFs, respectively, in contrast to an annual hemorrhage rate of 0% for Borden Type I DAVFs.13 Although an annual hemorrhage rate of 3% for unruptured DAVFs with CVD was found in their study, the rate increased to 46% per year for ruptured DAVFs with CVD. The recurrence of bleeding can occur within the first few weeks following the initial hemorrhage. Duffau et al. observed a rebleeding rate of 35% within the first 2 weeks after the initial hemorrhage.11 Significant mortality rates of up to 10.4% annually have been associated with the persistence of CVD.47 Given the high morbidity and mortality rates observed in untreated or partially treated DAVFs with CVD, urgent treatment using modalities that offer immediate obliteration should be recommended for these lesions. Due to the risk of hemorrhage during the latency period between treatment and obliteration, SRS should not be recommended as the sole and/or first-line treatment for DAVFs with CVD. In this systematic review, we observed a higher risk of post-SRS hemorrhage for DAVFs with CVD compared with those without CVD (4.2% vs 0%). In addition, we found a significantly lower obliteration rate for SRS-treated DAVFs with CVD compared with those without CVD (p = 0.03). Therefore, patients harboring DAVFs with CVD should undergo endovascular embolization, microsurgical resection, or a combination of the two as initial therapy to rapidly reduce or eliminate the risk of hemorrhage. Stereotactic radiosurgery can be offered as an adjuvant or salvage therapy in cases refractory to embolization or surgery.29 For patients harboring DAVFs without CVD, the decision to treat should be based on the severity of symptoms. Close observation should be recommended to patients with nondisabling symptoms, whereas SRS and/or endovascular embolization should be reserved for those with intractable symptoms.

In patients selected to undergo endovascular embolization, SRS may represent an effective complementary therapy.7,12,22,23,35,39,51 Although endovascular embolization may provide immediate symptomatic relief and reduction of hemorrhage risk, the treatment may not afford long-term cure in cases of subtotal obliteration or delayed recanalization.24 Therefore, SRS serves as a complementary treatment by potentially increasing the likelihood of permanent DAVF occlusion.24,51 However, the timing of embolization and SRS remains controversial. Some authors argue that embolization prior to SRS can reduce target volume and blood flow, thus facilitating obliteration by SRS. In contrast, others contend that the target margin may be obscured when embolization is performed prior to SRS, resulting in inadequate target delineation and ineffective treatment.

Study Limitations

This systematic review is limited by the pooled data available from largely retrospective, single-center studies, with all of the limitations and weaknesses inherent to retrospective designs. In an attempt to reduce the nuances separating detailed classification systems, best efforts were made to classify DAVFs into broader categories. Not all studies were included in this systematic analysis; insufficient DAVF obliteration outcomes data led to the ex-
clusion of certain studies from analyses. Insufficient outcomes data from some studies also limit certain comparative statistical analyses. Despite no significant findings in the tests of heterogeneity, the variability in the methods of clinical evaluation and determination of complete DAVF obliteration among studies remains difficult to overcome.

Verification of complete obliteration varied depending on the study institution; MRI or MR angiography, digital subtraction angiography, or a combination of these imaging modalities may have been used in different studies. Ideally, obliteration would be confirmed with cerebral angiography. However, when this is not advisable or the patient refuses, MRI and MR angiography or CT and CT angiography have been shown to be reasonable surrogates for cerebral AVMs, and this approach has been extended to DAVFs in contemporary practice.30,38 In addition, baseline characteristics of patients may vary significantly. Stereotactic radiosurgery was not the primary or sole treatment for all patients in this review; some patients underwent prior microsurgical ligation and/or embolization of their DAVFs. Patients in this review may also have been selected for SRS due to poor candidacy for microsurgery and/or embolization. However, data from these studies were insufficient to make such a distinction. Also, we did not differentiate results based on the type of SRS device used (e.g., LINAC, GKS, and so on) and cannot be certain if the results here are generalizable to all SRS platforms. Thus, results of this review should be interpreted with caution, and they may not be generalizable to all patients.

Conclusions

Stereotactic radiosurgery affords favorable rates of complete DAVF obliteration with acceptably low complication rates. Obliteration rates do not differ significantly between CS DAVFs and NCS DAVFs. However, DAVFs without CVD are associated with significantly higher obliteration rates than DAVFs with CVD. Therefore, careful patient selection for SRS based on DAVF angioarchitecture and hemorrhage risk is recommended. For DAVFs with CVD, SRS should be used as an adjuvant or salvage therapy. However, for DAVFs without CVD, SRS may be considered as a first-line therapy for patients who are unable or unwilling to undergo endovascular or surgical intervention, or it may be used in combination with embolization.

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Author Contributions
Conception and design: Chen, Lee. Acquisition of data: Chen. Analysis and interpretation of data: Chen, Lee. Drafting the article: Chen, Lee, Ding. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Sheehan. Statistical analysis: Chen.

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