Original Article

Stereotactic radiosurgery for ruptured versus unruptured intracranial arteriovenous malformations

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INTRODUCTION

Cerebral arteriovenous malformations (AVMs) are comprised shunting between abnormal arteries and veins with an intervening nidus.[3] This morphology confers an inherent risk of rupture, with intracranial hemorrhage (ICH) being the most common presentation of brain AVMs.[4] With advances in available techniques, stereotactic radiosurgery (SRS) has become

ABSTRACT

Background: There are a limited data examining the effects of prior hemorrhage on outcomes after stereotactic radiosurgery (SRS). The goal of this study was to identify risk factors for arteriovenous malformation (AVM) rupture and compare outcomes, including post-SRS hemorrhage, between patients presenting with ruptured and unruptured AVMs.

Methods: A retrospective review of consecutive patients undergoing SRS for intracranial AVMs between 2009 and 2019 at our institution was conducted. Chi-square and multivariable logistic regression analyses were utilized to identify patient and AVM factors associated with AVM rupture at presentation and outcomes after SRS including the development of recurrent hemorrhage in both ruptured and unruptured groups.

Results: Of 210 consecutive patients with intracranial AVMs treated with SRS, 73 patients (34.8%) presented with AVM rupture. Factors associated with AVM rupture included smaller AVM diameter, deep venous drainage, cerebellar location, and the presence of intranidal aneurysms (P < 0.05). In 188 patients with adequate follow-up time (mean 42.7 months), the overall post-SRS hemorrhage rate was 8.5% and was not significantly different between ruptured and unruptured groups (10.3 vs. 7.5%, P = 0.51). There were no significant differences in obliteration rate, time to obliteration, or adverse effects requiring surgery or steroids between unruptured and ruptured groups.

Conclusion: Smaller AVM size, deep venous drainage, and associated intranidal aneurysms were associated with rupture at presentation. AVM rupture at presentation was not associated with an increased risk of recurrent hemorrhage or other complication after SRS when compared to unruptured AVM presentation. Obliteration rates were similar between ruptured and unruptured groups.

Keywords: Arteriovenous malformation, Post-radiosurgery hemorrhage, Rupture, Stereotactic radiosurgery
an established alternative to open surgery for patients with surgically inaccessible AVMs or those with high perioperative risk.\textsuperscript{(6)} However, the impact of AVM rupture on the success and complications after SRS has not been rigorously assessed.

Given the increased risk of ICH after initial AVM rupture, SRS has not been traditionally considered a preferred treatment modality in ruptured AVM patients. Although AVM obliteration rates were largely similar between the ruptured and unruptured groups, Ding \textit{et al.} found that prior rupture significantly increased the annual risk of post-SRS hemorrhage in the latency period before nidus obliteration.\textsuperscript{(7)} However, more recent studies have demonstrated a low risk (1.5% within 5 years, 0.2% thereafter) of post-SRS hemorrhage in patients who present with ruptured AVMs.\textsuperscript{(18)}

We contribute a single-center and retrospective study to this growing body of the literature, specifically investigating factors associated with AVM rupture and whether rupture is associated with an increased risk of complications including recurrent hemorrhage after SRS.

**MATERIALS AND METHODS**

The medical records of 210 consecutive patients undergoing SRS for intracranial AVMs between December 2009 and December 2019 were reviewed retrospectively. Institutional review board approval was obtained before review. Patient characteristics including demographics, comorbidities, and presenting symptoms including AVM ruptured versus unruptured presentation were recorded in addition to AVM characteristics including Spetzler-Martin (SM) grade, size, eloquence, deep venous drainage, location, and the presence of intranidal aneurysms. Post-SRS data including AVM obliteration, posttreatment hemorrhage, adverse effect requiring steroids, and adverse effect requiring surgery were also recorded when available. Diagnosis of AVM was made in all cases using computed tomography angiography (CTA), magnetic resonance angiography, or digital subtraction angiography (DSA). The post-SRS scan type demonstrating obliteration, the time to obliteration, and the presence of peri-nidal T2 signal increase/edema on post-SRS MRI were also recorded. The decision to pursue SRS was made on a case basis. SRS is preferentially used for AVMs in deep or critical brain regions, in patients with an unacceptable risk of perioperative complications as well as for those refusing to undergo craniotomy. Open surgeries are more often performed in patients with significant life-threatening hemorrhage resulting in mass effect or in cases where AVMs presented to the surface in noneloquent locations.

**Radiosurgery**

All radiosurgical cases were performed using the Leksell Gamma Knife with Gamma Plan software (Elekta AB) or with the linear accelerator (LINAC). The AVM nidus was defined using magnetic resonance imaging (MRI) and CTA and supplemented with DSA in select cases. The decision to perform SRS was determined based on a combination of patient factors including age and medical comorbidities as well as AVM factors such as larger size and location that may have predisposed a patient to higher risk with open surgery. The margin SRS dose was constructed to include the entire volume of the AVM. A dose of 17.5 Gy (range 17.5–18.5) to the 50% (range 40–70%) isodose line was the most commonly used treatment plan.

**Statistical analysis**

All statistical analysis was carried out in SPSS 27 (IBM Corp. Armonk, NY). A \textit{t}-test was used to compare continuous variables across groups. Pearson’s Chi-square or Fisher’s exact tests were used for comparisons of categorical variables, depending on expected cell count. Binary logistic regression analysis was utilized when examining interval independent variables with associated binary categorical dependent variables. The significance level was set at ≤0.05 and a two-sided probability testing was used.

**RESULTS**

**Study cohort: Patient and AVM factors associated with AVM Rupture**

Of the 210 consecutive patients treated with SRS for intracranial AVMs, the average age was 41 years and 57% of patients were male. The most common AVM presentation was hemorrhage (35%), followed by headache (24%) and seizure (17%). The rate of incidentally discovered AVMs was 22%. Of the 210 patients, 73 presented with a ruptured AVM. [Table 1] demonstrates the differences in patient characteristics between those presenting with ruptured (73) versus unruptured AVMs (137). Obesity was more common in the unruptured AVM patient group ($P = 0.003$). There were otherwise no significant differences in demographics and comorbidities between the groups [Table 1].

On binary logistic regression analysis, smaller AVM size ($P = 0.01$), deep venous drainage ($P = 0.05$), the presence of intranidal aneurysms ($P = 0.02$) as well as midline ($P = 0.001$), and cerebellar location ($P < 0.001$) were associated with AVM rupture at presentation. Prior craniotomy was significantly associated with ruptured AVM presentation (6.9% vs. 0%, $P = 0.005$) [Table 2].

**Post-SRS outcomes: Ruptured versus unruptured presentation**

Overall, 188/210 patients (90%) had complete follow-up information available. Of these, 68 patients (36%) presented with a ruptured AVM and 120 (64%) were unruptured. The
average follow-up time was 43 ± 31 months and was not significantly different between groups (P = 0.16). Overall obliteration rate was 48.4% and while a higher percentage of ruptured AVMs was obliterated (54.4 vs. 45%), this was not statistically significant (P = 0.22). Mean time to obliteration was also not significantly different between ruptured and unruptured groups (28 vs. 33 months, P = 0.17) [Table 3]. Sixteen patients (9%) developed a hemorrhage after SRS and there was no significant difference in post-SRS hemorrhage rate between those presenting with ruptured and unruptured AVMs (10.3 vs. 7.5%, P = 0.51) [Figure 1].

### Post-SRS complications: Ruptured versus unruptured presentation

Overall, there was a 20.2% rate of adverse effect requiring steroids, 9.6% rate of adverse effect requiring surgery, and 51.1% of patients developed increased peri-nidal T2 edema on post-operative MRI. None of these post-SRS complication rates were significantly different between ruptured and unruptured groups [Table 3].

### AVM factors associated with post-SRS hemorrhage: Ruptured and unruptured presentation

In patients presenting with ruptured AVMs, lower SM grade (P = 0.001) and eloquent AVM location (P = 0.04) were associated with the development of post-SRS hemorrhage [Table 4]. In patients presenting with unruptured AVMs, no AVM characteristics were associated with the development

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**Table 1: Demographic characteristics and comorbidities in 210 patients with intracerebral AVMs: Ruptured versus unruptured at presentation**

| Characteristic | Total (n=210) | Ruptured (n=73) | Unruptured (n=137) | P-value |
|---------------|--------------|----------------|-------------------|---------|
| Age, years (std. dev) | 40.5 (19.0) | 37.7 (20.8) | 42.0 (17.8) | 0.13 |
| Sex | | | | |
| Male | | 45 (61.6) | 74 (54.0) | 0.29 |
| Female | | 28 (38.4) | 63 (46.0) | |
| Race | | | | 0.92 |
| White | 144 (68.6) | 50 (68.5) | 94 (68.6) | |
| Black | 56 (26.7) | 20 (27.4) | 36 (26.3) | |
| Hispanic | 7 (3.3) | 3 (4.1) | 4 (2.9) | |
| Other | 3 (1.4) | 0 (0.0) | 3 (2.2) | |
| Presentation | | | | |
| Hemorrhage | 73 (34.8) | 73 (100.0) | 0 (0.0) | NA |
| Headache | 51 (24.3) | 8 (11.0) | 43 (31.4) | 0.001 |
| Incidental | 46 (21.9) | 0 (0.0) | 46 (33.6) | <0.001 |
| Seizure | 35 (16.7) | 2 (2.7) | 33 (24.1) | <0.001 |
| Other | 22 (10.5) | 0 (0.0) | 22 (16.1) | <0.001 |
| Comorbidities | | | | |
| Smoking | 61 (29.0) | 18 (24.7) | 43 (31.4) | 0.31 |
| HTN | 37 (17.6) | 13 (17.8) | 24 (17.5) | 0.96 |
| Obesity | 25 (11.9) | 2 (2.7) | 23 (16.8) | 0.003 |
| DM | 13 (6.2) | 4 (5.5) | 9 (6.6) | 0.76 |
| CAD | 9 (4.3) | 1 (13.7) | 8 (5.8) | 0.17 |
| MS | 1 (0.5) | 0 (0.0) | 1 (0.7) | 1.00 |

HTN: Hypertension, DM: Diabetes mellitus, CAD: Coronary artery disease, MS: Multiple sclerosis, AVM: Arteriovenous malformation. *Values are number of patients (%) unless otherwise indicated. Mean value is presented with std. dev, Bold values indicate significance of P<0.05.
of post-SRS hemorrhage [Table 5]. The presence of intranidal aneurysms, prior embolization or craniotomy, prior SRS, and AVM obliteration was not associated with the presence or absence of post-SRS hemorrhage in either group.

**DISCUSSION**

ICH is the most common presentation of cerebral AVMs and results in significant morbidity and mortality.\(^{[4,8,11,26]}\) Due to this, numerous studies have examined for risk factors associated with AVM rupture.\(^{[1,20,21,23,35,27]}\) While variability exists in the literature regarding these risk factors, several frequently cited factors include deep locations with deep venous drainage and smaller AVM size;\(^{[5,14,21,32]}\) however, data are conflicting regarding these as well.\(^{[5,10,14,22]}\)

SRS remains an effective treatment option for AVMs with the goal of complete obliteration that typically occurs over a period of 6 months to up to 3 years.\(^{[17,24]}\) Several studies have reported an increased risk of AVM hemorrhage during this latency period that declines after obliteration due to

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**Table 2: AVM characteristics: Rupture versus unruptured at presentation*.

| AVM characteristic                  | Total (n=210) | Ruptured (n=73) | Unruptured (n=137) | P-value |
|-------------------------------------|--------------|----------------|--------------------|---------|
| Total SM Grade (1–6), mean (std dev) | 2.46 (0.93)  | 2.51 (0.85)    | 2.43 (0.98)        | 0.57    |
| Size (cm)                           |              |                |                    |         |
| <3                                  | 145 (69.0)   | 60 (82.2)      | 85 (62.0)          | 0.01    |
| 3–6                                 | 61 (29.0)    | 12 (16.4)      | 49 (35.8)          |         |
| >6                                  | 4 (1.9)      | 1 (1.4)        | 3 (2.2)            |         |
| Eloquence                           |              |                |                    | 0.46    |
| Yes                                 | 128 (61.0)   | 47 (64.4)      | 81 (59.1)          |         |
| No                                  | 82 (39.0)    | 26 (35.6)      | 36 (40.9)          |         |
| Venous Drainage                     |              |                |                    | 0.05    |
| Deep                                | 110 (52.4)   | 49 (67.1)      | 61 (44.5)          |         |
| Superficial                         | 100 (47.6)   | 24 (32.9)      | 76 (55.5)          |         |
| Side                                |              |                |                    | 0.001   |
| Left                                | 95 (45.2)    | 25 (34.2)      | 70 (51.1)          |         |
| Right                               | 102 (48.6)   | 38 (52.1)      | 64 (46.7)          |         |
| Midline                             | 13 (6.2)     | 10 (13.7)      | 3 (2.2)            |         |
| Location†                           |              |                |                    | <0.001  |
| Frontal                             | 62 (29.5)    | 18 (24.7)      | 44 (32.1)          |         |
| Parietal                            | 45 (21.4)    | 11 (15.1)      | 34 (24.8)          |         |
| Occipital                           | 31 (14.8)    | 7 (9.6)        | 24 (17.5)          | 0.12    |
| Temporal                            | 45 (21.4)    | 13 (17.8)      | 32 (23.4)          | 0.35    |
| Cerebellum                          | 31 (14.8)    | 22 (30.1)      | 9 (6.6)            | <0.001  |
| Midline (Brainstem/Thalamus)        | 26 (12.4)    | 12 (16.4)      | 14 (10.2)          | 0.19    |
| Intranidal Aneurysms                | 30 (14.3)    | 16 (21.9)      | 14 (10.2)          | 0.02    |
| Prior Craniotomy                    | 5 (2.4)      | 5 (6.9)        | 0 (0.0)            | 0.005   |
| Prior SRS                           | 19 (9.0)     | 6 (8.2)        | 13 (9.5)           | 0.76    |
| Prior Embolization                  | 6 (2.9)      | 3 (4.1)        | 3 (2.2)            | 0.42    |

*Values are number of patients (%) unless otherwise indicated. Mean value is presented with std. dev. AVM: Arteriovenous malformation, Bold values indicate significance of P<0.05.

**Table 3: Post-SRS characteristics: Ruptured versus unruptured AVMs*.

| Characteristic                     | Total (n=188) | Ruptured AVM (n=68) | Unruptured AVM (n=120) | P-value |
|------------------------------------|--------------|---------------------|------------------------|---------|
| AVM Obliteration                   | 91 (48.4)    | 37 (54.4)           | 54 (45.0)              | 0.22    |
| Time to Obliteration, months (std dev) | 31.1 (17.0) | 28.2 (16.7)        | 33.2 (17.0)            | 0.17    |
| Peri-nidal increased edema on MRI | 96 (51.1)    | 29 (42.6)           | 67 (55.8)              | 0.08    |
| Posttreatment hemorrhage           | 16 (8.5)     | 7 (10.3)            | 9 (7.5)                | 0.51    |
| Adverse effect requiring steroids  | 38 (20.2)    | 12 (17.7)           | 26 (21.7)              | 0.51    |
| Adverse effect requiring surgery   | 18 (9.6)     | 6 (8.8)             | 12 (10.0)              | 0.79    |
| Follow-up Time, months (std dev)   | 42.7 (30.5)  | 38.6 (27.8)         | 45.1 (31.8)            | 0.16    |

AVM: Arteriovenous malformation, SRS: Stereotactic radiosurgery, MRI: Magnetic resonance imaging. *Values are number of patients (%) unless otherwise indicated. Mean value is presented with std. dev.
progressive vascular injury, proliferation, and thrombosis resulting in endoluminal nidal occlusion.\[12,13,15,24,28-31\]

Without treatment, recurrent AVM hemorrhage is reported to range from 4% to as high as 18% per year.\[9,10,25\]

Few studies have investigated the effects of prior hemorrhage on post-SRS complications including recurrent hemorrhage.

In the present study, hemorrhage was the most common presentation of AVMs and was associated with smaller AVM size, deep venous drainage, and the presence of intranidal aneurysms; findings consistent with much of the prior literature. In addition, cerebellar location was found to be significantly associated with ruptured presentation, consistent with prior literature demonstrating that cerebellar AVMs rarely present with seizures, most commonly present with hemorrhage, and have a more aggressive natural history.\[2,19,25,33\]

In an analysis of AVM hemorrhage risk before and after SRS, Ding et al. identified larger AVM size to be positively associated with and deep venous drainage to be negatively associated with hemorrhage before SRS.\[6\] These findings contrast to the present study findings and the majority of the literature. However, these authors attributed their findings to a possible selection bias as unruptured AVMs treated with SRS were more likely to be larger and deeper lesions. These authors did find that patients with post-SRS hemorrhage were more likely to have larger AVMs in deep or eloquent brain regions with associated arterial aneurysms.\[6\]

The present study found an overall post-SRS hemorrhage rate of 8.5% that was not significantly different between those presenting with ruptured and unruptured AVMs over a 43 month mean follow-up time. Development of a new hemorrhage after SRS in patients presenting with a ruptured AVM was associated with an overall lower SM score and eloquent AVM location; however, no factors were associated with new post-SRS hemorrhage in patients presenting with unruptured AVMs. In contrast to prior studies, the presence of intranidal aneurysms was not associated with an increased risk of new AVM hemorrhage after SRS in either group (ruptured vs. unruptured).\[10\] The present study did demonstrate similar rates of AVM obliteration after SRS.

| Characteristic                          | Total (n=68) | No new hemorrhage (n=61) | New hemorrhage (n=7) | P-value |
|----------------------------------------|-------------|--------------------------|---------------------|---------|
| Total SM Grade (1–6), Avg (Std. Dev)   | 2.5 (0.87)  | 3.1 (0.38)               | 2.4 (0.88)          | 0.001   |
| Size (cm)                              |             |                          |                     | 0.13    |
| <3                                     | 56 (82.4)   | 52 (85.2)                | 4 (57.1)            |         |
| 3–6                                    | 11 (16.2)   | 8 (13.1)                 | 3 (42.9)            |         |
| >6                                     | 1 (1.5)     | 1 (1.6)                  | 0 (0.0)             |         |
| Eloquence                              |             |                          |                     | 0.04    |
| Yes                                    | 43 (63.2)   | 36 (59.0)                | 7 (100.0)           |         |
| No                                     | 25 (36.8)   | 25 (40.9)                | 0 (0.0)             |         |
| Venous Drainage                        |             |                          |                     | 1.00    |
| Deep                                   | 46 (67.6)   | 41 (67.2)                | 5 (71.4)            |         |
| Superficial                            | 22 (32.4)   | 20 (32.8)                | 2 (28.6)            |         |
| Side                                   |             |                          |                     | 0.33    |
| Left                                   | 24 (35.3)   | 20 (32.8)                | 4 (57.1)            |         |
| Right                                  | 35 (51.5)   | 32 (52.5)                | 3 (42.9)            |         |
| Midline                                | 9 (13.2)    | 9 (14.8)                 | 0 (0.0)             |         |
| Location†                              |             |                          |                     |         |
| Frontal                                | 16 (23.5)   | 14 (23.0)                | 2 (28.6)            | 0.66    |
| Parietal                               | 11 (16.2)   | 9 (14.8)                 | 2 (28.6)            | 0.32    |
| Occipital                              | 7 (10.3)    | 7 (11.5)                 | 0 (0.0)             | 1.00    |
| Temporal                               | 12 (17.6)   | 12 (19.7)                | 0 (0.0)             | 0.34    |
| Cerebellum                             | 20 (29.4)   | 19 (31.2)                | 1 (14.3)            | 0.66    |
| Midline (Brainstem/Thalamus)           | 12 (17.6)   | 10 (16.4)                | 2 (28.6)            | 0.60    |
| Intranidal Aneurysms                   | 15 (22.1)   | 13 (21.3)                | 2 (28.6)            | 0.65    |
| Prior Embolization                     | 3 (4.4)     | 3 (4.9)                  | 0 (0.0)             | 1.00    |
| Prior Craniotomy                       | 5 (7.4)     | 5 (8.2)                  | 0 (0.0)             | 1.00    |
| Prior SRS                              | 6 (8.8)     | 6 (9.8)                  | 0 (0.0)             | 1.00    |
| AVM Obliterated                        | 37 (54.4)   | 34 (55.7)                | 3 (42.9)            | 0.70    |
| Time to Obliteration, months (std. dev.)| 28.2 (16.7)| 28.9 (17.1)              | 20.3 (10.4)         | 0.40    |
| Follow-up Time, months (std. dev)      | 38.6 (27.8) | 39.3 (29.1)              | 32.9 (11.4)         | 0.28    |

*Values are number of patients (%) unless otherwise indicated. Mean value is presented with std. dev. \(^1\)AVMs could include more than one location.

AVM: Arteriovenous malformation, SRS: Stereotactic radiosurgery. Bold values indicate significance of P<0.05
between ruptured and unruptured groups in line with Ding et al’s findings. However, Ding et al. identify a lower post-SRS hemorrhage rate after AVM obliteration which the present study was underpowered and not specifically designed to demonstrate.\[6\]

While prior studies have examined outcomes after SRS in adults with hemorrhagic AVMs, few have compared the post-SRS complication rates of ruptured versus unruptured patient populations. Kawashima et al. reported a low post-SRS hemorrhage risk of 1.5% within 5 years and concluded that stand-alone SRS is effective for hemorrhagic AVMs.\[18\] In pediatric patients, Chen et al. compared SRS for unruptured versus ruptured brain AVMs finding similar post-SRS hemorrhage outcomes and obliteration rates; however, they identified a higher rate of symptomatic radiation-induced change (RIC) in those with unruptured AVMs.\[4\] Similarly, Ding et al. reported a higher rate of symptomatic RIC in those with unruptured AVMs, but concluded that radiosurgery does not alter the natural history of the hemorrhage risks of unruptured and ruptured AVMs unless obliteration is achieved.\[7\] In contrast, Maruyama et al. reported that SRS significantly decreases the risk of hemorrhage even before angiographic evidence of obliteration, with the greatest reduction in hemorrhage risk after obliteration.\[24\]

The present study reports a non-statistically significant increased rate of post-SRS hemorrhage in those with ruptured versus unruptured AVMs that are consistent with prior natural history reports. This suggests that SRS did not alter the natural risk of hemorrhage during the follow-up period in either group. This study additionally reports similar rates of obliteration, perinidal increases in T2 edema on MRI and adverse effects requiring steroids or surgery after SRS between those presenting with ruptured and unruptured AVMs suggesting that overall outcomes and complication profiles after SRS are not altered by a ruptured AVM presentation.

**Limitations**

This retrospective study is limited by its retrospective design, small number of patients presenting with hemorrhage and...
developing hemorrhage after SRS along with variability in follow-up. Retrospective studies are subject to unidentified confounders, imbalanced cohorts, incomplete data sets, misinterpretation of data, recall bias, selection bias, and observer bias. Specifically, the selection biases of a purely SRS single-center study limit the generalizability and reproducibility of the analysis and findings as patients undergoing SRS for ruptured AVMs are likely to have smaller AVMs in deeper locations that make them sub-optimal candidates for open surgery. The small number of patients developing a post-SRS hemorrhages in each group also underpowered the ability to detect patient and AVM-related associations with new hemorrhage after SRS. In addition, the time to hemorrhage after SRS was not available, only the presence or absence, limiting the ability to develop conclusions regarding the temporal relationships between obliteration, and post-SRS hemorrhage development.

CONCLUSION
This study affirms findings from prior studies that smaller AVM size, deep venous drainage pattern, and associated intranidal aneurysms are associated with ruptured presentation. Rates of post-SRS recurrent hemorrhage, increased T2 edema, and adverse effects requiring steroids or surgery were similar between unruptured and ruptured AVM groups indicating a similar post-SRS risk profile in these patient populations. SRS did not appear to alter the natural history of recurrent AVM hemorrhage in this population.

Declaration of patient consent
Institutional Review Board (IRB) permission obtained for the study.

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Conflicts of interest
There are no conflicts of interest.

REFERENCES
1. Al-Shahi R, Warlow C. A systematic review of the frequency and prognosis of arteriovenous malformations of the brain in adults. Brain 2001;124:1900-26.
2. Arnaout OM, Gross BA, Eddleman CS, Bendok BR, Getch CC, Batjer HH. Posterior fossa arteriovenous malformations. Neurosurg Focus 2009;26:E12.
3. Chen CJ, Ding D, Derdeyn CP, Lanzino G, Friedlander RM, Southerland AM, et al. Brain arteriovenous malformations: A review of natural history, pathobiology, and interventions. Neurology 2020;95:917-27.
4. Chen CJ, Lee CC, Ding D, Tseng SW, Kearns KN, Kano H, et al. Stereotactic radiosurgery for unruptured versus ruptured pediatric brain arteriovenous malformations. Stroke 2019;50:2745-51.
5. Crawford PM, West CR, Chadwick DW, Shaw MD. Arteriovenous malformations of the brain: natural history in unoperated patients. J Neurol Neurosurg Psychiatry 1986;49:1-10.
6. Ding D, Chen CJ, Starke RM, Kano H, Lee JY, Mathieu D, et al. Risk of brain arteriovenous malformation hemorrhage before and after stereotactic radiosurgery. Stroke 2019;50:1384-91.
7. Ding D, Yen CP, Starke RM, Xu Z, Sheehan JP. Effect of prior hemorrhage on intracranial arteriovenous malformation radiosurgery outcomes. Cerebrovasc Dis 2015;39:53-62.
8. Drake CG. Cerebral arteriovenous malformations: Considerations for and experience with surgical treatment in 166 cases. Clin Neurosurg 1979;26:145-208.
9. Fults D, Kelly DL Jr. Natural history of arteriovenous malformations of the brain: A clinical study. Neurosurgery 1984;15:658-62.
10. Graf CJ, Perret GE, Torner JC. Bleeding from cerebral arteriovenous malformations as part of their natural history. J Neurosurg 1983;58:331-7.
11. Hartmann A, Mast H, Mohr JP, Koennecke HG, Osipov A, Pile-Spellman J, et al. Morbidity of intracranial hemorrhage in patients with cerebral arteriovenous malformation. Stroke 1998;29:931-4.
12. Ilyas A, Chen CJ, Ding D, Buell TJ, Raper DM, Lee CC, et al. Radiation-induced changes after stereotactic radiosurgery for brain arteriovenous malformations: A systematic review and meta-analysis. Neurosurgery 2018;83:365-76.
13. Ilyas A, Chen CJ, Ding D, Mastorakos P, Taylor DG, Pomeraniec IJ, et al. Cyst formation after stereotactic radiosurgery for brain arteriovenous malformations: A systematic review. J Neurosurg 2018;128:1354-63.
14. Jayaraman MV, Marcellus ML, Do HM, Chang SD, Rosenberg JK, Steinberg GK, et al. Hemorrhage rate in patients with Spetzler-Martin grades IV and V arteriovenous malformations: Is treatment justified? Stroke 2007;38:325-9.
15. Kano H, Flckinger JC, Tonetti D, Hsu A, Yang HC, Flannery TJ, et al. Estimating the risks of adverse radiation effects after gamma knife radiosurgery for arteriovenous malformations. Stroke 2017;48:84-90.
16. Kano H, Kondziolkda D, Flckinger JC, Yang HC, Park KJ, Flannery TJ, et al. Aneurysms increase the risk of rebleeding after stereotactic radiosurgery for hemorrhagic arteriovenous malformations. Stroke 2012;43:2586-91.
17. Karlsson B, Lax I, Söderman M. Risk for hemorrhage during the 2-year latency period following gamma knife radiosurgery for arteriovenous malformations. Int J Radiat Oncol Biol Phys 2001;49:1045-51.
18. Kawashima M, Hasegawa H, Shin M, Shinya Y, Ishikawa O, Koizumi S, et al. Outcomes of stereotactic radiosurgery for hemorrhagic arteriovenous malformations with or without prior resection or embolization. J Neurosurg 2020.
19. Khaw AV, Mohr JP, Sciacca RR, Schumacher HC, Hartmann A, Pile-Spellman J, et al. Association of infratentorial brain arteriovenous malformations with hemorrhage at initial presentation. Stroke 2004;35:660-3.
20. Kim H, Al-Shahi Salman R, McCulloch CE, Stapf C, Young WL. Untreated brain arteriovenous malformation:
Patient-level meta-analysis of hemorrhage predictors. Neurology 2014;83:590-7.

21. Kondziolka D, McLaughlin MR, Kestle JR. Simple risk predictions for arteriovenous malformation hemorrhage. Neurosurgery 1995;37:851-5.

22. Laakso A, Dashti R, Juvela S, Isarakul P, Niemelä M, Hernesniemi J. Risk of hemorrhage in patients with untreated Spetzler-Martin grade IV and V arteriovenous malformations: A long-term follow-up study in 63 patients. Neurosurgery 2011;68:372-7; discussion 378.

23. Laakso A, Dashti R, Seppänen J, Juvela S, Väärt K, Niemelä M, et al. Long-term excess mortality in 623 patients with brain arteriovenous malformations. Neurosurgery 2008;63:244-53; discussion 253-45.

24. Maruyama K, Kawahara N, Shin M, Tago M, Kishimoto J, Kurita H, et al. The risk of hemorrhage after radiosurgery for cerebral arteriovenous malformations. N Engl J Med 2005;352:146-53.

25. Ondra SL, Troupp H, George ED, Schwab K. The natural history of symptomatic arteriovenous malformations of the brain: A 24-year follow-up assessment. J Neurosurg 1990;73:387-91.

26. Perret G, Nishioka H. Report on the cooperative study of intracranial aneurysms and subarachnoid hemorrhage. Section VI. Arteriovenous malformations. An analysis of 545 cases of cranio-cerebral arteriovenous malformations and fistulae reported to the cooperative study. J Neurosurg 1966;25:467-90.

27. Pollock BE, Flickinger JC, Lunsford LD, Bissonette DJ, Kondziolka D. Factors that predict the bleeding risk of cerebral arteriovenous malformations. Stroke 1996;27:1-6.

28. Pollock BE, Flickinger JC, Lunsford LD, Maitz A, Kondziolka D. Factors associated with successful arteriovenous malformation radiosurgery. Neurosurg 1998;42:1239-44; discussion 1244-37.

29. Pomeraniec IJ, Ding D, Starke RM, Liu KC, Mrachek EK, Lopes MB, et al. Delayed cyst formation after stereotactic radiosurgery for brain arteriovenous malformations. J Neurosurg 2018;129:937-46.

30. Schneider BF, Eberhard DA, Steiner LE. Histopathology of arteriovenous malformations after gamma knife radiosurgery. J Neurosurg 1997;87:352-7.

31. Shuto T, Ohtake M, Matsunaga S. Proposed mechanism for cyst formation and enlargement following gamma knife surgery for arteriovenous malformations. J Neurosurg 2012;117:135-43.

32. Spetzler RF, Hargraves RW, McCormick PW, Zabramski JM, Flom RA, Zimmerman RS. Relationship of perfusion pressure and size to risk of hemorrhage from arteriovenous malformations. J Neurosurg 1992;76:198-213.

33. Wilkins RH. Natural history of intracranial vascular malformations: A review. Neurosurgery 1985;16:421-30.

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