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Treatment Approaches for Brainstem Arteriovenous Malformations: A Comprehensive Literature Review

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Abstract

Brainstem arteriovenous malformations (BAVMs) represent one of the most formidable challenges in neurosurgery due to their deep location and proximity to vital centers governing autonomic and motor functions. This review synthesizes current evidence across multiple treatment modalities, including microsurgical resection, stereotactic radiosurgery (SRS), and endovascular embolization. Microsurgery offers immediate, definitive obliteration but is associated with high perioperative morbidity, necessitating the use of advanced neurophysiological monitoring and safe entry zones. SRS has become the primary intervention for deep-seated BAVMs, offering a favorable non-invasive profile despite a multi-year latency period and the risk of radiation-induced changes. Endovascular embolization, while rarely curative in isolation, serves as a critical adjunct for reducing nidal volume or stabilizing high-risk features like intranidal aneurysms. The literature increasingly supports a multimodal approach, tailoring treatment to the unique angioarchitecture of each lesion to optimize functional outcomes. However, the absence of randomized controlled trials and the limitations of traditional grading systems like Spetzler-Martin complicate the establishment of standardized protocols. Technological innovations, particularly Diffusion Tensor Imaging (DTI) and precise radiosurgical delivery systems, have significantly enhanced the safety margins of these interventions. Future research must focus on multicenter longitudinal data and the potential for molecular therapies to stabilize the vascular nidus. This review emphasizes that while BAVM management has evolved significantly, the goal remains a delicate balance between achieving complete obliteration and preserving the intricate neurological integrity of the brainstem, requiring a highly individualized and multidisciplinary strategy.

Keywords: Brainstem, arteriovenous malformations, microsurgery, radiosurgery, embolization

Introduction

Arteriovenous malformations (AVMs) are uncommon, vascular abnormalities that have proven difficult to manage due to their location in an area of the body that is both anatomically compact and functionally critical. The brainstem, which connects the Cerebral Hemisphere to the Spinal Cord and Cerebellum, serves as a primary pathway for all motor and sensory systems. The brainstem has three distinct areas from top down: the Midbrain (Mesencephalon), Pons (Metencephalon), and Medulla Oblongata (Myelencephalon). These areas contain very dense tracts and nuclei of the brainstem that regulate motor, sensory, cranial nerves, and autonomic functions. Therefore, minor injuries caused by either the lesion itself or secondary injury during treatment may result in significant loss of function in these areas. Presentations are typically acute and severe. Lawton et al., (1995) reported that in 84% of patients presenting with hemorrhages, there was no prior neurological deficit. They report several vivid examples including patients who were comatose and had been placed in a flexor posturing pattern (due to overlapping thalamic and brainstem involvement); obtundation with hemiplegia and/or hemianopia; or lower cranial deficits/paraparesis (1, 2). Only 31% of the 61-patient cohort reviewed by Lawton et al. (1995) were neurologically intact before treatment. Nonspecific symptoms such as headache/dizziness mask the degree of severity until the AVM ruptures causing devastating neurological deficits. Other presentations may be non-hemorrhagic including progressive hemiparesis; intractable seizures; or incidentally discovered during evaluation for another condition such as Chiari malformation. If untreated, brainstem AVMs become lethal time-bombs. Based on the 61-patient study cited above, it appears that approximately 7.3% of brainstem AVMs will rupture annually; however, after initial rupture, this risk increases significantly to 8.9%. While less than 2% of subsequent ruptures occur, each is unpredictable and potentially disastrous. In addition to the risks associated with subsequent rupture, Lawton et al. (1995) note additional perils associated with residual defects including pulmonary embolism leading to death in one case studied. Hemorrhage is clearly the most common presentation of brainstem AVMs occurring in approximately 80-84% of all patients. Recurrent hemorrhage occurs in up to five instances, resulting in coma; hemiplegia; locked-in state; etc (3, 4, 5).

The purpose of this article is to review current strategies for treating brainstem AVMs, and to combine data from the existing literature regarding the effectiveness of microsurgery, endovascular treatments, and radiosurgery for managing brainstem AVMs. This article reviews anatomy; natural history; clinical manifestations; diagnostic procedures; and compares the advantages/disadvantages of each treatment strategy for brainstem AVMs.

Methodology

This narrative review evaluated and synthesised the existing evidence on the management of brainstem arteriovenous malformations (AVMs).

No formal protocol registration was required given the narrative design of this review. All data were drawn from previously published, peer-reviewed sources; accordingly, no ethical approval or patient consent was necessary.

A comprehensive literature search was conducted on PubMed, Scopus, and Cochrane Library to identify studies relevant to the management of brainstem AVMs, capturing studies from the modern era of multimodal AVM management. Reference lists of retrieved articles, particularly systematic reviews and key clinical series, were also manually screened to identify additional relevant studies not captured through electronic database searches.

Inclusion criteria were studies reporting patients with brainstem AVMs, at least one active treatment (microsurgery, embolization, radiosurgery, or multimodal), and clinical outcomes (haemorrhage, neurological status, functional independence, or complications).

Exclusio criteria were single-patient studies, lacking brainstem-specific data, non-original articles, conference abstracts without full text, and imaging-only papers without clinical follow-up.

After induplication, title/abstract screening, and text-full text screening, 42 articles met the inclusion criteria and was selected for analysis.

Results

Angioarchitecture and risk stratification

In the general population, the estimated global incidence of brain arteriovenous malformations (AVMs) corresponds to roughly 10 in 100,000. Less than 2.5% of all AVMs constitute brainstem AVMs (BS-AVMs). Given the disease's rarity, its underlying background has typically been studied in broader datasets encompassing other vascular lesions such cavernous malformations or other deeply positioned AVMs like the thalamus, basal ganglia, corpus callosum, or cerebellum. In a retrospective study reviewed by Chen2020, due to their ambiguous borders, diffuse nidus were frequently advocated conservative care, whereas nidus involving the midbrain were favored to be considered for intervention. Partial nidus obliteration had a substantially greater future rupture risk than complete obliteration and conservative care, in line with the same study. Given the brainstem's structural and functional constraints, complete nidus obliteration remains extremely challenging (6, 7, 8). Ten patients (16.4%) had flow-related aneurysms, while twenty-six patients (42.6%) had deep vein drainage. Based on Time of Flight (TOF) images, 16.4% were classified as diffuse nidus. Deep perforating arteries were present in many patients (45 incidents, 73.8%). There were differences in a number of prognostic indicators in the subgroup analysis of long-term outcomes in ruptured and unruptured brainstem AVMs, even though long-term modified Rankin Scale(mRS) were similar between various management modalities in both the rupture group ($p=0.064$) and unruptured group ($p=0.391$). The obliteration rate of various therapeutic techniques differed in the ruptured subgroup ($p<0.001$). AVM size (< 3 cm, 3–6 cm, or > 6 cm), blood flow pattern (deep vs. superficial), and eloquence of the AVM location (eloquent vs. noneloquent) are all specified in the Spetzler-Martin AVM grading system. Patient age (less than 20 years, between 20 and 40 years, or more than 40 years), hemorrhagic appearance (ruptured versus unruptured), and nidus compactness (compact versus diffuse) are all taken into account by the Lawton-Young AVM grading system. The aggregate of the Lawton Young and Spetzler-Martin grades is the supplemented Spetzler-Martin grade. The Spetzler-Martin grading scale is highly proven for supratentorial AVMs, however it does not take into consideration the distinct high-risk characteristics of posterior fossa AVMs. Because all brain stem

AVMs have profound venous drainage, are situated in eloquent parenchyma, and are typically very small, the Spetzler-Martin grading scale does not differentiate between them. While the modified Spetzler-Martin grading system has demonstrated its potential in predicting perioperative outcomes of posterior fossa AVMs, following endovascular therapy no real benefit was noted. As a result, efforts have been made to create schematic classification systems for posterior fossa AVMs (7, 9, 10).

Conservative management

Each treatment strategy may have a unique set of indications. Following embolization, patients with partial obliteration of the nidus would be advised for stereotactic radiosurgery (SRS), but there was inconsistent adherence among patients. Due to the ambiguous boundaries, diffuse nidus was frequently recommended conservative therapy in a study by Chen2020. When embolization was carried out close to vital perforating arteries or deep brainstem nuclei, persistent deficits were infrequently seen, but the majority of neurologic deficits were brief and resolved during follow-up (11, 12, 13, 15). In a case series by Thines2011, the yearly incidence of bleeding was 10.8% prior to intervention and 1.8% following intervention. At the last follow-up visit, rebleeding was not substantially linked to neurological decline(Thines2011). Sorenson2019 reported that feeding arterial or intranidal aneurysm was present in 80% of individuals who suffered another rupture. These results support the notion that therapeutic approaches aimed at these AVM-associated characteristics—that are angiographic weak areas inside AVM itself—may also be beneficial in lowering the risk of bleeding. The stereotactic radiosurgery group had an overall incidence of follow-up hemorrhage of 18.8%, while the conservative group had a risk of 16.7% (6, 14, 15, 16). The conservative group had an annual risk of recurrent bleeding of 4.8%, while the radiosurgery cohort had a risk of 3.7%. According to Ai&Xu2021, two patients (8%) experienced a post-SRS hemorrhage with an average follow-up of more than five years, and the yearly incidence of post-SRS bleeding ranged from 1.9% to 7%. One of the important consequences post-treatment was neurological impairments. While some of them had severe deficits including hemiplegia, ataxia, and oculomotor paralysis, others had modest, temporary abnormalities like diplopia and sensorineural hearing loss. In a series, three patients experienced increasing deficits right after surgery, but all recuperated close to their preoperative position within a year. In 74% of instances, therapeutic complications were the cause of worldwide neurological impairment according to Thines2011. As reported, hemorrhagic presentation suggested a more aggressive natural course, and in order to prevent hemorrhage, prompt therapy for neurological recovery or rehabilitation was undertaken. Furthermore, in 19 (83%) of these 23 individuals, bleeding was linked to substantial presenting neurological dysfunction (mRS score of ≥ 2) (4, 17, 18). A left hemiparesis, total right seventh cranial nerve palsy, impaired hearing of the right ear, diminished sensation in the spread of the first division of the fifth cranial nerve on the right, lack of the corneal reflex, moderate right-sided cerebellar ataxia, right sixth cranial nerve palsy, lack of the right-sided gag reflex, impaired right vocal cord, and left hemisensory impairment of pain as well as temperature were the most commonly observed neurological deficits post-hemorrhage. In brainstem AVMs treated using Gamma Knife Surgery(GKS), there was an elevated frequency of neurologic impairments linked to radiation-induced alterations. This series had a 10.6% complication percentage (5.9% permanent issues and 4.7% reversible issues). Patients with past bleeding, deep AVM placement, predominantly deep venous drainage, and related aneurysms had an unfavorable natural history.

Microsurgical Resection

Microsurgical resection of brainstem AVMs is often regarded as the most definitive treatment for achieving immediate obliteration, yet it remains one of the most technically demanding procedures in neurosurgery due to the exquisite density of nuclei and white matter tracts within the brainstem (19, 20). The literature emphasizes that success is predicated on the "two-pial" approach or the use of safe entry zones to minimize damage to healthy parenchyma. Unlike supratentorial AVMs, brainstem lesions offer virtually zero margin for error; even minor traction on the brainstem can result in devastating cranial nerve palsies or autonomic instability. Recent series suggest that resection is most appropriate for small, superficial, or pial-based AVMs, particularly those that have previously bled and created a surrounding hematoma cavity that provides a surgical corridor (21). The integration of neurophysiological monitoring—including motor evoked potentials (MEPs), somatosensory evoked potentials (SSEPs), and brainstem auditory evoked responses (BAERs)—is now considered mandatory to navigate these high-stakes environments. While microsurgery offers the highest cure rate in selected cases, the high risk of immediate postoperative morbidity often shifts the preference toward less invasive modalities for deep-seated lesions (23).

Endovascular Embolization

Endovascular embolization has transitioned from a primary curative intent to a predominantly adjunctive role in the management of brainstem AVMs. The complex angioarchitecture of the brainstem, often involving fragile perforating arteries from the basilar or vertebral arteries, presents significant risks for ischemic complications during the delivery of liquid embolic agents like Onyx or N-butyl cyanoacrylate (NBCA) (25, 26). Current literature highlights that curative embolization is rare for BAVMs, typically reserved for small, single-pedicle lesions. Instead, its primary utility lies in "targeted" embolization to eliminate high-risk features such as intranidal or flow-related aneurysms prior to surgery or radiosurgery. Embolization can also be used to reduce the high-flow volume of a malformation to make subsequent Stereotactic Radiosurgery (SRS) more effective (27, 28). However, the risk of "normal perfusion pressure breakthrough" or venous outflow obstruction leading to brainstem edema remains a critical concern, necessitating a cautious, often staged, approach to prevent acute neurological deterioration (30, 31).

Stereotactic Radiosurgery (SRS)

Stereotactic Radiosurgery (SRS) has emerged as the preferred primary treatment for small to medium-sized brainstem AVMs that are deep-seated or lack a safe surgical corridor. The mechanism relies on radiation-induced endothelial proliferation and progressive luminal occlusion, which typically takes two to three years to achieve complete obliteration (32). Literature consistently demonstrates that BAVMs are more sensitive to radiation-induced changes than their supratentorial counterparts, often requiring lower doses to avoid symptomatic radiation injury. The primary limitation of SRS is the "latency period," during which the patient remains at risk for recurrent hemorrhage (10, 34). Furthermore, the brainstem’s low tolerance for radiation means that larger volumes are often treated with marginal doses, leading to lower obliteration rates compared to smaller lesions. Despite these drawbacks, the non-invasive nature of SRS and its favorable long-term morbidity profile make it the mainstay for patients who cannot tolerate the acute risks of microsurgery (35, 36).

Multimodal Therapy

The contemporary paradigm for treating brainstem AVMs increasingly favors a multimodal approach, recognizing that no single modality is a panacea for complex lesions. This strategy typically involves a combination of partial embolization followed by SRS, or SRS followed by microsurgical resection of the residual nidus if obliteration is not achieved. The literature suggests that multimodal therapy aims to balance the "obliteration-to-morbidity" ratio. For instance, embolization can be used to treat associated aneurysms or high-flow shunts, thereby reducing the immediate hemorrhage risk, while SRS addresses the residual nidus over time (24). In some cases, the "pax radiologica" approach is taken, where the goal is not necessarily complete obliteration but the stabilization of high-risk angioarchitectural features. However, critics of multimodal therapy point out that each additional intervention carries an additive risk of complication, and the cumulative morbidity can sometimes exceed that of a single, well-executed primary treatment (33).

Comparative Summary of Outcomes Across Modalities

Comparing outcomes across modalities for BAVMs is notoriously difficult due to selection bias: microsurgery is usually reserved for the most favorable superficial lesions, while SRS is used for the most difficult deep-seated ones. Microsurgery generally provides the highest immediate obliteration rates (ranging from 80% to 100% in carefully selected series) but carries a higher risk of immediate neurological deficit. SRS offers obliteration rates between 60% and 80% for small lesions with a delayed effect, but with a significantly lower incidence of acute complications. Embolization alone rarely achieves cure, with obliteration rates often below 20%, but it serves as a crucial stabilizer. A cross-study analysis indicates that the highest rates of "good" functional outcomes (Modified Rankin Scale 0–2) are found in multimodal cohorts where the treatment plan is tailored to the specific angioarchitecture, rather than adhering to a rigid single-modality protocol.

Discussion

Role of Grading Systems and Their Limitations

The Spetzler-Martin (SM) grading system, while the gold standard for supratentorial AVMs, is widely regarded as insufficient for the brainstem. Because all BAVMs are located in "eloquent" tissue and usually have deep venous drainage, they automatically start at a higher grade, which limits the system’s granularity (34). Specialized scales like the Lawton-Young supplementary grade or the modified Spetzler-Ponce classes are often utilized to better predict surgical risk. However, even these struggle to account for the specific location within the brainstem (e.g., ventral midbrain vs. dorsal medulla), which dictates the surgical approach and potential cranial nerve involvement. The literature suggests a need for a dedicated BAVM grading system that incorporates nidal volume, presence of deep perforator supply, and the specific brainstem segment to better guide clinical decision-making (35).

Technological Advances Improving Outcomes

Significant strides in neuro-imaging and intraoperative technology have redefined the safety limits of BAVM treatment. Advanced MRI sequences, such as Diffusion Tensor Imaging (DTI) with tractography, allow surgeons to visualize the displacement of vital white matter tracts (like the corticospinal tract) around the nidus, facilitating a safer surgical trajectory (29, 41). In the radiation suite, the advent of Gamma Knife Icon and CyberKnife has allowed for more precise fractionated dosing, reducing the risk of radiation-induced edema in the brainstem. Furthermore, the use of intraoperative indocyanine green (ICG) video-angiography and micro-Doppler ultrasound has enhanced the real-time assessment of nidal obliteration and the preservation of "en passage" vessels. These technologies have collectively shifted the focus from mere survival to the preservation of high-level neurological function (22).

Complications: Mechanisms and Prevention

Complications in BAVM treatment are often catastrophic and arise from the unique anatomy of the region. Ischemic complications usually stem from the occlusion of critical perforating arteries that supply the brainstem nuclei. Hemorrhagic complications may occur due to incomplete resection, venous outflow obstruction during embolization, or "staged" treatment imbalances (42). Prevention strategies highlighted in the literature include the "hypotensive challenge" during anesthesia to test for vascular autoregulation and the use of ultra-selective micro-catheterization during embolization. For SRS, the use of rigorous dose-volume histograms (DVH) to keep the brainstem surface dose within safe limits is the primary preventative measure against late-onset radiation necrosis. Postoperative management also plays a role, with aggressive blood pressure control being paramount to prevent reperfusion injury (36).

Limitations of Current Literature

The primary limitation of the current literature on BAVMs is the lack of high-level evidence, such as randomized controlled trials (RCTs). Due to the rarity and heterogeneity of these lesions, most studies are retrospective institutional series or case reports, which are prone to selection and publication bias (37). Furthermore, there is a lack of standardized reporting for outcomes and complications; some studies use the Glasgow Outcome Scale, while others use the Modified Rankin Scale, making meta-analysis difficult. The definition of "obliteration" also varies between studies—some requiring digital subtraction angiography (DSA) and others accepting MRA—which can lead to overestimations of cure rates. There is also a dearth of long-term follow-up data (beyond 10 years), which is critical for understanding the true "cure" rate of SRS (38).

Future Directions

The future of BAVM management likely lies in the integration of molecular biology and precision engineering. Research into the genetic markers of AVM growth and rupture may eventually allow for pharmacological stabilization of the nidus, reducing the risk of hemorrhage without the need for invasive intervention. In the realm of gene therapy, there is interest in using viral vectors to induce targeted vascular regression. From a technical standpoint, the development of robotic-assisted endovascular systems may provide the precision needed to navigate the fine perforators of the brainstem with higher safety (39, 40). Finally, large-scale multicenter registries (like the Brain Vascular Malformation Consortium) will be essential to aggregate enough data to formulate truly evidence-based guidelines and develop a dedicated BAVM-specific grading scale.

Conclusion

The literature clearly suggests that the management of arteriovenous malformations (AVMs) located in the brainstem, which can include AVMs at the level of cranial nerves III-VI and VII, remains among the most challenging cerebrovascular treatments available due to the conflicting objectives of total elimination, avoidance of future bleeding and preservation of neurological function. While microsurgical resection may be an effective method of treating certain AVMs with favorable location or surface characteristics, and/or accessible via a surgical corridor, endovascular embolization is commonly utilized as a supporting therapy to reduce the size of the nidus and subsequently decrease shunting through the AVM. However, based on the results of the referenced studies, endovascular embolization alone is insufficient as a definitive treatment in complex AVMs in the brainstem. Microsurgical resection is generally recommended for select patients who have AVMs with favorable anatomy and whose brainstem lesion(s) provide a safe access route. Conversely, endovascular therapy should be considered as an adjunctive procedure in most cases where blood flow into the AVM needs to be reduced prior to a definitive procedure being performed, or as part of the overall management plan for reducing the volume of the AVM. Radiosurgery has emerged as an additional viable therapeutic alternative for brainstem AVMs that are either too deeply situated within the brainstem to be safely removed via surgery, or are so compact that they cannot be adequately resected. Although radiosurgery provides an opportunity to cure these lesions with fewer risks compared to surgical intervention, there are several disadvantages associated with this modality including prolonged time required for complete obliteration of the AVM and continued need for post-treatment surveillance.

During the preparation of this work, the author(s) used Grammarly AI and Google Gemini. The application of these tools was strictly limited to improving grammar, spelling, style, and formatting. All intellectual content is the original work of the authors.

Ethics statement: Given that this review utilized previously published data from studies that had already obtained ethics approval and consent to participate, no additional ethics approval or consent was required for this research.

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Abbreviations

Arteriovenous malformations (AVMs)

Brainstem arteriovenous malformations (BAVMs)

Stereotactic radiosurgery (SRS)

Digital subtraction angiography (DSA)

N-butyl cyanoacrylate (NBCA)

Magnetic resonance imaging (MRI)

Computed tomography (CT)

Modified Rankin Scale (mRS)

Blood-brain barrier (BBB)

Central nervous system (CNS)

Motor evoked potentials (MEPs)

Somatosensory evoked potentials (SSEPs)

Brainstem auditory evoked responses (BAERs)

Indocyanine green (ICG)

Radiation-induced complications (RIC)

Normal perfusion pressure breakthrough (NPPB)

Linear accelerator (LINAC)

Diffusion tensor imaging (DTI)

Intranidal aneurysm (INA)

Transvenous embolization (TVE)

Spetzler-Martin (SM)

Dose-volume histogram (DVH)

Glasgow Outcome Scale (GOS)

Transammoniacal embolization (TAE)

Flow-related aneurysm (FRA)

Computed tomography angiography (CTA)

Magnetic resonance angiography (MRA)

Radiation-induced changes (RICs)

A randomized trial of unruptured brain arteriovenous malformations (ARUBA)

Intraoperative neurophysiological monitoring (IONM)