

Clinical Study of Hybrid Surgical Treatment for Low-Grade Brain Arteriovenous Malformations

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Abstract

Background

To investigate the clinical feasibility and preliminary efficacy of hybrid surgery for the treatment of Spetzler–Martin (SM) grade I–II brain arteriovenous malformations (AVMs).

Methods

The clinical data of 12 patients with SM grade I–II brain AVMs who had not undergone any preoperative treatment, such as embolization, and who received surgical treatment in the hybrid operating room of our hospital between June 2019 and June 2023 were retrospectively analyzed. Prognosis was evaluated using the modified Rankin Scale (mRS).

Results

Intraoperative digital subtraction angiography (DSA) showed complete resection in 11 of the 12 patients, while a small residual nidus was detected in one patient. After further management, immediate postoperative DSA confirmed angiographic obliteration in all 12 patients. At 6–24 months of postoperative follow-up, the modified Rankin Scale (mRS) score was 0 in 9 patients, 1 in 1 patient, and 4 in 2 patients. No imaging evidence of lesion recurrence or related complications was observed in any patient.

Conclusion

Hybrid surgery for SM grade I–II brain AVMs may improve the safety and efficiency of surgical procedures by enabling real-time intraoperative assessment of lesion resection and timely additional resection when necessary. This approach demonstrated favorable preliminary angiographic obliteration outcomes and may provide a feasible technical strategy for the surgical treatment of low-grade brain AVMs. However, its long-term efficacy and clinical benefits require further validation in large-scale, prospective controlled studies.

1. Introduction

Brain arteriovenous malformation (AVM) is one of the relatively common cerebrovascular diseases in clinical practice. Epidemiological data indicate that its prevalence is approximately 10–18 per 100,000 population, with an annual incidence of approximately 1.1–1.3 per 100,000 population[1, 2]. As a type of cerebrovascular lesion with complex angioarchitecture, the main treatment modalities for brain arteriovenous malformations (AVMs) include endovascular embolization, microsurgical resection, and stereotactic radiosurgery[3, 4]. However, these conventional treatment modalities have certain limitations in achieving both complete lesion eradication and preservation of neurological function, making it difficult to meet both therapeutic goals simultaneously. With the clinical application of hybrid operating rooms, DSA-guided hybrid surgery has provided a new technical approach for the treatment of

brain AVMs. By integrating the advantages of multiple techniques, this approach effectively balances the dual objectives of lesion management and neurological function preservation[5]. In this study, we retrospectively analyzed the clinical data of 12 patients with Spetzler–Martin (SM)[6] grade I–II brain AVMs who underwent surgical treatment in the hybrid operating room of our institution between June 2019 and June 2023, without prior preoperative embolization or radiosurgery. This study aimed to explore the clinical feasibility and preliminary efficacy of this treatment strategy, thereby providing hypotheses and reference evidence for subsequent clinical research. The results are reported as follows.

2. Materials and Methods

2.1 Participant Selection

This was a single-center retrospective case series. The inclusion criteria were as follows: patients diagnosed with brain AVMs at our institution between June 2019 and June 2023 who underwent surgical treatment in a hybrid operating room; Spetzler–Martin (SM) grade I–II lesions; no prior targeted treatment, such as endovascular embolization or stereotactic radiosurgery; lesion characteristics confirmed by preoperative DSA; and complete clinical data. The exclusion criteria were as follows: severe dysfunction of major organs, including the heart, liver, or kidneys, resulting in inability to tolerate surgery; concomitant intracranial space-occupying lesions; and incomplete follow-up data.

2.2 Surgical Protocol

All 12 patients with brain AVMs underwent a standardized hybrid surgical workflow comprising “angiographic localization–lesion resection–angiographic assessment.” The procedure was performed as follows. After induction of general anesthesia and achievement of adequate sedation, DSA was first performed to accurately determine the size and spatial location of the nidus, as well as the anatomical characteristics of the feeding arteries and draining veins. Intracranial AVM resection was then performed, strictly following the surgical principle of “feeding arteries first, draining veins last.” Aneurysm clips were used intraoperatively to mark key anatomical sites for localization. DSA was performed repeatedly during the operation to assess the extent of nidus resection in real time. If residual lesions were detected, targeted supplementary resection was performed according to the aneurysm clip markers. At the end of the procedure, DSA was performed again immediately to confirm complete removal of the nidus. Postoperative cranial CT scans were routinely obtained to dynamically monitor postoperative complications, such as intracranial hemorrhage and cerebral edema.

2.3 Postoperative Follow-up

A standardized postoperative follow-up system was established, including outpatient visits, telephone follow-up, and inpatient reassessment. All patients underwent DSA at 6 months after discharge to comprehensively evaluate vascular morphology and hemodynamic changes in the surgical area and to determine the presence of residual or recurrent lesions.

At 24 months after discharge, patients were followed up in the outpatient clinic, during which neurological status was dynamically recorded and assessed using the modified Rankin Scale (mRS)[7]. By analyzing the trajectories of neurological functional changes, the clinical therapeutic efficacy and long-term prognosis were objectively evaluated. Postoperative complications were defined as new-onset neurological deficits, intracranial hemorrhage, cerebral infarction, seizures, infection, cerebrospinal fluid leakage, and other events occurring within 30 days after surgery. Complication data were collected retrospectively from electronic medical records.

3. Results

3.1 Patient Characteristics

A total of 12 patients with Spetzler–Martin (SM) grade I–II brain AVMs were included in this study. The male-to-female ratio was 7:5, and the patients' ages ranged from 8 to 71 years. Clinical presentations were heterogeneous: 2 patients presented with seizures, 6 were admitted due to intracerebral hemorrhage, and 4 complained of headache. According to the SM grading system, 5 patients had grade I lesions and 7 had grade II lesions. The nidus size ranged from 1.5 to 4.8 cm. Four lesions involved eloquent brain areas, whereas 8 were located in non-eloquent areas. Nine patients had single venous drainage, and 3 had multiple draining veins. Ten lesions were supratentorial, and 2 were infratentorial. All cases were definitively diagnosed by preoperative DSA (Table 1).

Table 1
Basic Clinical Characteristics of the Patients

Patient	Sex	Age (years)	Symptom	Spetzler–Martin Grade	Postoperative mRS Score
1	Female	42	Seizures	II	4
2	Female	29	Intracranial hemorrhage	II	0
3	Male	60	Headache	I	0
4	Male	59	Intracranial hemorrhage	II	0
5	Male	39	Intracranial hemorrhage	II	4
6	Female	71	Headache	I	0
7	Male	59	Headache	II	0
8	Male	53	Intracranial hemorrhage	II	1
9	Male	47	Headache	I	0
10	Male	56	Seizures	II	0
11	Male	8	Intracranial hemorrhage	I	0
12	Female	63	Intracranial hemorrhage	I	0

3.2 Outcome

Intraoperative DSA demonstrated complete disappearance of the nidus in 11 of the 12 patients with brain AVMs, while a small residual lesion was detected in one patient with an SM grade II AVM. For this residual lesion, the surgeon performed immediate additional resection guided by imaging localization. Repeat DSA subsequently confirmed complete resection of the nidus in all 12 patients, yielding an angiographic obliteration rate of 100%. Intraoperative blood loss was controlled within the range of 100–300 mL.

Monitoring of complications within 30 days after surgery showed that none of the patients developed new neurological deficits, intracranial rebleeding, cerebral infarction, seizures, intracranial infection, cerebrospinal fluid leakage, or other related complications.

At 6 months postoperatively, all patients underwent standardized follow-up, including repeat DSA and clinical symptom assessment. No patient showed imaging evidence of lesion recurrence or related clinical symptoms. Among the 6 patients who initially presented with intracranial hemorrhage, no

rebleeding occurred. Patients who presented with seizures experienced no postoperative seizure recurrence. These findings preliminarily indicate stable long-term therapeutic efficacy.

At 24 months postoperatively, neurological function was assessed using the modified Rankin Scale (mRS). The results showed that 9 patients had an mRS score of 0, indicating favorable neurological recovery with complete restoration of activities of daily living and social activities. One patient had an mRS score of 1, indicating slight symptoms without significant disability and the ability to perform routine work. Two patients had an mRS score of 4, indicating a certain degree of disability but the ability to perform self-care with assistance.

Both patients with an mRS score of 4 had presented with intracranial hemorrhage caused by brain AVMs. Before surgery, they already had severe motor dysfunction due to massive intracranial hemorrhage. After postoperative rehabilitation, their neurological function did not deteriorate compared with the preoperative status and showed slight improvement.

4. Discussion

4.1 Hemorrhagic Brain AVM Localization Challenges

As a typical intracranial vascular structural abnormality, brain arteriovenous malformation (AVM) is pathologically characterized by direct shunting of arterial blood into the venous system without an intervening capillary bed, forming a high-flow, low-resistance arteriovenous shunt. As the disease progresses, the feeding arteries undergo compensatory dilation, and multiple vessels converge into the nidus from different directions. Meanwhile, continuous turbulent flow caused by the abnormal shunt impacts the draining veins, leading to venous tortuosity, dilation, and even varix-like changes (Fig. 1A)[8, 9]. These abnormal hemodynamic alterations not only disrupt the normal balance of intracranial perfusion but also expose the nidus and draining venous walls to abnormal pressure, ultimately making cerebral hemorrhage the most common acute clinical presentation in patients with brain AVMs (Fig. 1B) [10].

In patients with concomitant intracranial hemorrhage, the mass effect of the hematoma may displace the nidus and surrounding normal brain tissue, resulting in marked discrepancies between the intraoperative microscopic anatomy and the preoperative imaging assessment[11]. This may lead to intraoperative localization errors and incomplete lesion resection. Although previous studies have reported that indocyanine green (ICG) videoangiography can assist in intraoperative localization and assessment of treatment efficacy in cerebrovascular surgery[12, 13], its inherent technical limitations make it insufficient to meet the precision requirements of complex brain AVM surgery. On the one hand, ICG videoangiography can clearly visualize only the vascular structures exposed on the surface of the operative field and cannot effectively identify deeply located malformation branches or vessels covered by brain tissue. On the other hand, the tissue penetration of the ICG fluorescence signal is extremely

limited and cannot penetrate layers of normal neural tissue, making it difficult for the surgeon to determine the intraparenchymal extent of the nidus[14–16].

Under such complex localization requirements, excessive traction on normal vessels and brain tissue during blind exploration for the nidus can easily result in iatrogenic injury. In the present study, ICG videoangiography was not used intraoperatively; instead, localization and assessment were performed entirely using DSA. This approach can effectively overcome the technical limitations of ICG and is particularly suitable for the surgical treatment of hemorrhagic brain AVMs.

4.2 Intraoperative DSA Improves AVM Resection

In the hybrid operating room, DSA technology provides an innovative solution to the aforementioned clinical challenges through its advantages of real-time imaging and three-dimensional reconstruction[17]. Previous studies have confirmed its clinical value. Nohra Chalouhi et al.[18] used intraoperative DSA monitoring in 101 surgical patients and successfully identified residual lesions in 9 cases, allowing timely supplementary resection. The present study was a single-center retrospective study with a small sample size and preliminarily verified the feasibility of DSA-guided surgery for brain AVMs in a hybrid operating room. Immediate postoperative angiographic obliteration was achieved in all 12 patients, which is consistent with the above findings and suggests that intraoperative DSA can effectively reduce the rate of residual lesions.

4.3 Hybrid OR Enables Precise Low-Grade AVM Surgery

The American Stroke Association guidelines recommend microsurgical resection as the first-line treatment for brain AVMs with Spetzler–Martin (SM) grades I–II[19]. In the present study, angiographic obliteration was achieved in all 12 patients with SM grade I–II AVMs, with no postoperative complications. These preliminary findings suggest that surgery for low-grade brain AVMs performed in a hybrid operating room may further improve surgical precision and safety. The core value of this approach lies in the integrated DSA-based technical system in the hybrid operating room, which enables a transformation of the surgical workflow through “real-time imaging, precise navigation, and dynamic assessment.” Preoperatively, three-dimensional DSA vascular reconstruction allows the establishment of a detailed anatomical model of the lesion, providing quantitative information for surgical planning. Intraoperatively, real-time DSA navigation guides surgical manipulation and minimizes traction-related injury to normal brain tissue and vessels. Immediate postoperative DSA evaluation can verify the surgical result in real time, effectively avoiding the risk of reoperation caused by residual lesions and reducing the medical burden and surgical stress for patients.

This treatment paradigm transforms the traditional linear workflow of “preoperative assessment–intraoperative manipulation–postoperative verification” into a closed-loop system of “dynamic assessment–real-time adjustment–immediate verification,” thereby providing an optimized technical pathway for the surgical treatment of brain AVMs. Nevertheless, the clinical benefits of this approach require further validation in large-scale controlled studies.

4.4 Clinical Outcomes and Limitations of Hybrid OR–Guided AVM Resection

In the present study, 12 patients with Spetzler–Martin (SM) grade I–II brain AVMs were treated in a hybrid operating room. Immediate postoperative DSA assessment demonstrated a 100% angiographic obliteration rate, and the intraoperative blood loss ranged from 100 to 300 mL. Compared with the 8.9% residual lesion rate after microsurgical resection reported in the literature[18], the preliminary findings of this small-sample study suggest that the combination of a hybrid operating room and DSA technology may have potential advantages in reducing postoperative residual lesions in low-grade brain AVMs.

Notably, intraoperative DSA in one patient revealed a small residual lesion. Retrospective analysis indicated that this was mainly attributable to intraoperative bleeding, which compromised exposure of the operative field and thereby affected complete identification and resection of the lesion. After the residual lesion was detected, additional resection was performed immediately, ultimately achieving complete obliteration. This case further highlights the value of real-time intraoperative DSA assessment, which can effectively compensate for the limitations of the surgical field.

No procedure-related complications occurred in any patient postoperatively. Two patients had a postoperative modified Rankin Scale (mRS) score of 4; both were patients with SM grade II AVMs who had presented preoperatively with massive intracranial hemorrhage involving the motor cortex, and both already had a preoperative mRS score of 4. After systematic postoperative rehabilitation, their limb motor function improved compared with the preoperative status. These findings suggest that surgery performed in the hybrid operating room did not aggravate pre-existing neurological deficits and demonstrated a favorable safety profile.

This study has several limitations that should be clearly acknowledged and quantitatively interpreted. First, the sample size was small, comprising only 12 retrospectively reviewed cases from a single center; therefore, selection bias was inevitable, and the generalizability of the findings is limited. Second, the study lacked a control cohort and did not include a direct comparison with conventional microsurgical resection; consequently, the absolute clinical benefit of treatment in a hybrid operating room could not be confirmed.

5. Conclusion

In conclusion, DSA-guided surgical treatment of Spetzler–Martin grade I–II brain AVMs in a hybrid operating room enables precise preoperative localization of the nidus, thereby effectively reducing iatrogenic tissue injury. Repeated intraoperative DSA allows real-time assessment of lesion resection, facilitating timely detection and additional resection of residual nidus. In this small cohort of 12 patients, this approach achieved a 100% immediate postoperative angiographic obliteration rate, with no complications occurring within 30 days after surgery, preliminarily demonstrating favorable clinical

feasibility and safety. This treatment strategy provides a feasible technical pathway for the surgical management of low-grade brain AVMs and may improve the precision of operative manipulation.

This study was a single-center, small-sample, retrospective study. Its long-term efficacy, clinical benefits, and cost-effectiveness remain to be further validated in large-sample, multicenter, prospective controlled studies. In addition, hybrid procedures require alternating between craniotomy-based microsurgical manipulation and endovascular intervention, which may increase the complexity of anesthetic management and the risk of surgical site infection. Future efforts should focus on optimizing the surgical workflow and establishing standardized protocols to further reduce potential risks.

Declarations

This study was conducted in strict accordance with the principles outlined in the World Medical Association Declaration of Helsinki (latest revision) for medical research involving human subjects. All participants provided written informed consent prior to their involvement, with full disclosure of the purpose, procedures, potential risks, and benefits of the study. Personal identifiers were anonymized and protected throughout data collection, analysis, and reporting to ensure confidentiality.

7. Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

8. Author contributions

Haitong Liu prepared the first draft of the manuscript. Jinfang Liu optimized the experimental protocol, validated key data, and prepared the figures and tables. Juncheng Wang provided technical support and processed the samples. Benlei Li conducted the literature review and prepared the experimental materials. Xin Dai and Dixiong Rao validated the supplementary data and compiled the raw materials. Bin Zhang designed and coordinated the study, reviewed the manuscript, and finalized the manuscript. All authors read and approved the final manuscript.

9. Clinical trial number

Not applicable.

10. Data Availability

The datasets used during the current study are available from the corresponding author on reasonable request.

11. Funding information

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12.Ethical approval

The study protocol was reviewed and approved by the Medical Research Ethics Committee of the General Hospital of Ningxia Medical University, with the approval number: KYLL-2025-2648.

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Figures

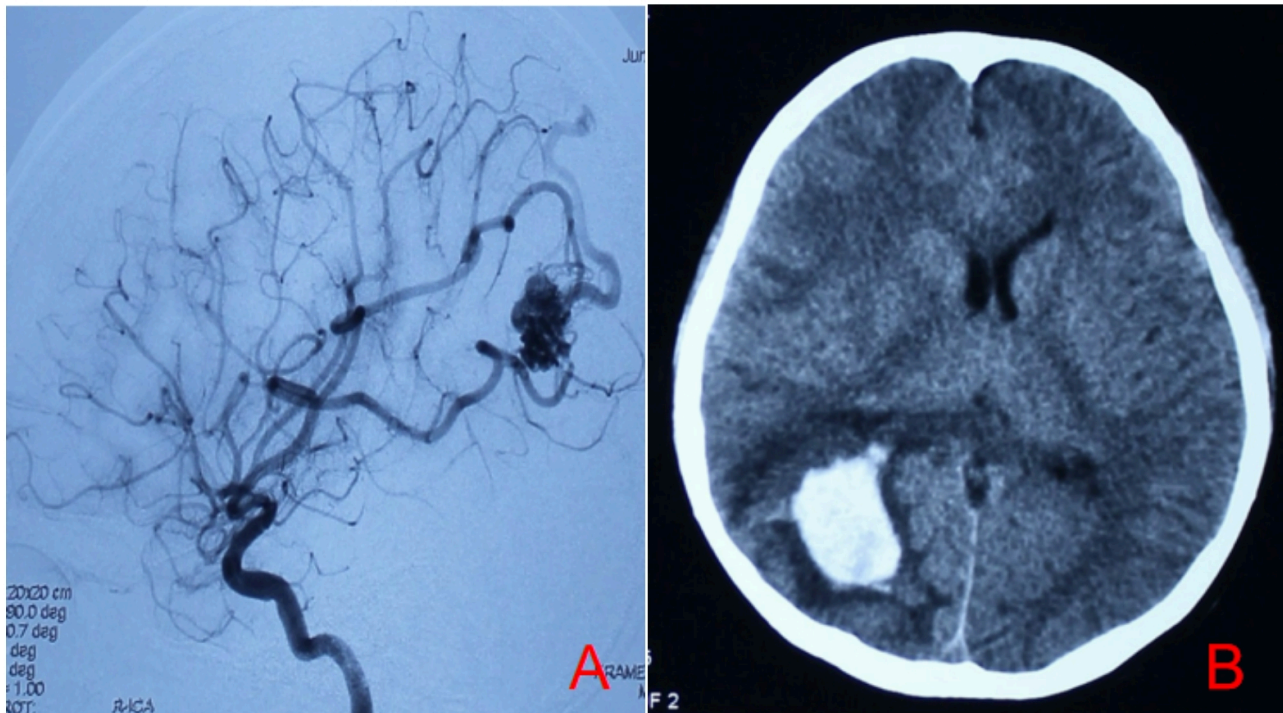


Figure 1

Preoperative imaging data of the patient

(A) DSA demonstrates a brain AVM nidus with tortuous, dilated draining veins. (B) Right occipital lobe intracerebral hemorrhage.