Neurosurgical Review (2019) 42:783–790
https://doi.org/10.1007/s10143-019-01137-w

TECHNICAL NOTE

One-staged in situ embolization combined with surgical resection for eloquence protection of AVM: technical note

Mingze Wang [1,2,3,4] · Hancheng Qiu [1,2,3,4] · Yong Cao [1,2,3,4] · Shuo Wang [1,2,3,4] · Jizong Zhao [1,2,3,4]

Received: 12 January 2019 / Revised: 8 June 2019 / Accepted: 19 June 2019 / Published online: 30 July 2019

Abstract

Brain arteriovenous malformations (AVMs) near/within eloquent areas are challenging to treat surgically. The insufficient lesion-to-eloquence distance (LED) is related to poor neurological outcomes. This paper reports the use of in situ embolization combined with surgical resection in a one-staged hybrid operation for eloquent area protection. Nine patients who underwent one-staged in situ embolization combined with surgical resection were selected from the database of a prospective clinical trial (NCT03774017). Nidus got partial in situ embolization in the parts located near/within the eloquence. The rest of nidus was removed via a microsurgical procedure in the same operation. The in situ embolization ensured a sufficient LED to prevent eloquent areas and tracts from being damaged in the subsequent resection. All of the patients achieved complete obliteration with no neurological deficits or complications. One-staged hybrid operation initiates closer cooperation between surgical and endovascular treatments and proposes an integrative therapeutic mode for AVMs. The in situ embolization combined with surgical resection is safe and effective for improving the functional outcome of AVMs with eloquence and tracts involved. The clinical trial is registered at ClinicalTrials.gov (NCT03774017, https://clinicaltrials.gov/ct2/show/NCT03774017).

Keywords Brain arteriovenous malformation · One-staged hybrid operation · Surgical resection · Embolization · In situ

Introduction

Brain arteriovenous malformations (AVMs) near/within eloquent areas are challenging to treat surgically. The distance between the AVM and the eloquent cortical areas or tracts affects functional outcomes after surgery [11, 19]. With the assistance of functional magnetic resonance imaging, Jiao et al. [8] proposed a minimum safe lesion-to-eloquence distance (LED) of 5 mm. LED < 5 mm indicates higher risks of neurological deficits due to surgery. Assisting techniques, such as intraoperative electrocorticogram, digital subtraction angiography (DSA), neuronavigation, and awake craniotomy, can help precisely locate the lesion and eloquence and reduce the damage during surgery [11, 12, 17, 19, 25]. Extra electrocoagulation and suction of adjacent parenchyma are common methods of hemostasis that result in damage to adjacent eloquence and tracts when the LED is insufficient.

Preoperative in situ embolization has proven effective at reducing the blood flow and decreasing the difficulty of surgical excision of high-grade AVMs [13, 16, 20, 24]. In situ embolization is proposed and introduced to preoperative embolization for function protection purposes [6, 18]. However, the staged cooperation between surgical and endovascular procedures fails to improve the functional outcome of AVM patients [14]. The multistage multimodality treatment makes each operation stand alone without interacting with one other.

This report describes the technical aspects of in situ embolization combined with surgical resection in a one-staged hybrid operation to treat AVMs near/within eloquent areas. The key point of this technique is to provide sufficient LED by in situ embolization to prevent damage to eloquence in the subsequent surgical resection. A series of cases are described to demonstrate our experience treating AVMs near/within

✉ Jizong Zhao
zhaojz205@163.com

1 Department of Neurosurgery, Beijing Tiantan Hospital, Capital Medical University, No. 119 Southern 4th Ring Road West, Fengtai District, Beijing 100070, China

2 China National Clinical Research Center for Neurological Diseases, Beijing 100070, China

3 Center of Stroke, Beijing Institute for Brain Disorders, Beijing 100050, China

4 Beijing Key Laboratory of Translational Medicine for Cerebrovascular Disease, Beijing 100070, China

eloquent areas and verify the safety and efficiency of this technique. It has been performed successfully over the past 2 years. This report is intended to introduce this technique and the utility of the one-staged hybrid operation to the neurosurgical community.

Methods

This study was approved by the Institutional Review Board at our institution, and written informed consent was obtained from all patients. The cases were retrospectively reviewed from the database of our prospective clinical trial (NCT 03774017) [23] from January 2016 to December 2018. A total of 344 cases of AVMs received one-staged hybrid surgery, including (1) intraoperative DSA + surgical resection, (2) endovascular embolization + surgical resection, and (3) surgical resection + assistant balloon occlusion. An fMRI examination (including blood oxygenation level-dependent (BOLD) and diffusion tensor imaging (DTI) sequences) was recommended for the patients whose AVMs potentially involved eloquences or tracts. The minimum safe LED was quantified as 5 mm via fMRI by Jiao et al.'s work [8]. According to this standard, 70 of 141 patients harbored AVMs with eloquent areas or tracts involved (LED < 5 mm), and 9 of 70 patients received individualized in situ embolization combined with surgical resections. Follow-up angiography of computed tomography, magnetic resonance, or digital subtraction was performed systematically 6 months after the operation. The National Institutes of Health Stroke Scale (NIHSS) and modified Rankin Scale (mRS) were used to evaluate the neurological function of patients 48 h and 7 days after surgery.

Description of technique

Considerate preoperative plans are needed to determine the target nidus of in situ embolization and the approach following the microsurgical operation. The results of fMRI are an important reference for the operative plan. Digital Imaging and Communications in Medicine (Dicom) files of fMRI are processed at a workstation (Brainlab Cranial 3.0, Brainlab AG, Munich, Germany). The results of the sequences, such as the structural, angiographic, BOLD, and DTI data, are merged in the final result. The nidus with an LED <5 mm and their arterial feeders are labeled as the targets of in situ embolization. The labeled nidus should be embolized as much as possible to increase the safe distance of surgical manipulations. The microsurgical approach is also based on the fMRI results. Its purpose is to protect the eloquent areas and tracts around the approach and determine the plane with sufficient LED.

The operation is performed in a one-staged hybrid operating room (OHOR) consisting of a surgical microscope (Pentero 900, Carl Zeiss Surgical AG, Oberkochen, Germany), a radiolucent operating table (Maquet Holding B.V. & Co. KG, Rastatt, Germany), and a monoplane angiography unit. All three monoplane angiography units mounted in our 3 OHORs are qualified for this work, including the Artis Pheno and Artis Zeego systems (Siemens Healthineers, Erlangen, Germany) and the Allura Xper FD20 system (Philips Healthcare, Best, Netherlands).

The patient is in the surgical position under general endotracheal anesthesia with electrophysiological monitoring. All positions are accepted for the endovascular procedure. However, when the lateral position is used, the head brace might disturb the whole-angle rotation of the C-arm. Femoral access is established using a 6Fr sheath (Avanti Introducer, Cordis Corporation, Miami Lakes, FL, USA) with the Seldinger technique. A 6Fr guide catheter (Envoy, Codman Division of Johnson & Johnson Medical Ltd., Wokingham, Berkshire, UK) is placed at the petrous segment of the internal carotid artery (ICA) or the foraminal segment of the vertebral artery (VA). The candidate feeding arteries that supply the nidus close to the eloquent area or track are primarily inspected via 3-dimensional rotating angiography (3D-RA) through the guide catheter. A flow-dependent microcatheter (Marathon 1.3Fr, eV3, Covidien, Minneapolis, MN, USA; Excelsior SL-10, Stryker Neurovascular, Fremont, CA, USA; or Headway 17, MicroVention, Aliso Viejo, CA, USA) is advanced over a microwire (Synchro 14, Stryker Neurovascular, Fremont, CA, USA, or Traxcess 14, MicroVention, Aliso Viejo, CA, USA) into the target feeding artery under road-mapping. A microcatheter angiography is performed to confirm its feeding area before embolization. Liquid embolic agent (Onyx 18/34, eV3, Covidien, Minneapolis, MN, USA) is injected through the microcatheter under road-mapping. The process of embolization can be repeated in different feeders until the target part of the AVM is excluded from circulation. The guide catheter is withdrawn back to the ipsilateral common carotid artery (CCA) or subclavian artery from ICA or VA, respectively, to reduce the disturbance to intracranial blood flow. The guide catheter is preserved for intraoperative angiography and is slowly flushed by heparin saline to prevent thrombosis. A craniotomy is subsequently performed with the assistance of neuronavigation (Brainlab Cranial 3.0, Brainlab AG, Munich, Germany). The plane adjacent to eloquence should be cautiously and sharply dissected within the occluded region. A properly occluded nidus should be maintained to preserve a sufficient LED. The sensory-evoked potential (SEP) and motion-evoked potential are monitored during the operation (Nicolet Endeavor CR IOM, Natus Medical Incorporated, Pleasanton, CA, USA).

Results

A total of 9 patients (male:female = 6:3) with AVMs near/within the eloquent area or tracts underwent one-staged hybrid in situ embolization combined with surgical resection. The patients' ages ranged from 10 to 52 years (30.4 ± 1 4.8 years on average). The demographic and clinical features are presented in Table 1. Hemorrhage and epilepsy were the most common presentation, occurring in 3 patients (33.3%), respectively. Overall, 44.4% of the AVMs ($n = 9$) were located in the parietal lobe, including one dural AVM with parietal parenchyma. The pyramidal tracts were threatened in 6 cases (66.7%). The other eloquent areas within the minimum safe LED included arcuate fasciculus ($n = 3$), optic radiation ($n = 3$), and motor areas ($n = 2$). The mean maximal size of nidus was 4.3 cm (range 2.1–6.3 cm). The Spetzler-Martin grades ranged from II to V. Satisfactory targeted in situ embolization was performed in all cases. The mean duration of surgical resection was 3.5 h (range 0.6–5.0 h) with a mean intraoperative hemorrhage of 577.8 ml (range 100–1500 ml). Details of the operation are reported in Table 2. There were no postoperative complications. All of the patients' mRS scores decreased at discharge. The NIHSS scores decreased in case 1 (left extremities motor drift) and case 6 (aphasia) and were 0 in the rest of the cases. No residue was reported in follow-up angiography.

Illustrative cases

Case 1

A 10-year-old male presented with a sudden burst of headache with numbness in his left leg. Head MRI revealed an AVM located in the right parietal lobe with a hematoma lateral to the lesion. The anterior border of the lesion adjoined to the motor area (left foot) in the cortices and pyramidal tracts in the deep parenchyma with a minimum LED of 3 mm (Fig. 1a, b). The AVM was supplied by arterial feeders from the right precuneal artery, lateral lenticulostriate artery, posterior parietal artery, and parietooccipital artery with both superficial and deep venous drainage (Fig. 1c–f). In the one-staged hybrid operation, an in situ embolization was first performed to occlude the anterior part of the nidus with the embolizing agent (Onyx 18, eV3 Covidien, Minneapolis, MN, USA) through superselected microcatheters to protect the motor area and pyramidal tracts anterior to the lesion (Fig. 1g, h). Then a surgical resection was performed after locating the motor cortical with neuronavigation and electric cortical stimulation to avoid damaging the superficial eloquence. The lesion was completely resected with the anterior occluded nidus retained (Fig. 1i). An intraoperative DSA after resection proved the complete obliteration of the lesion (Fig. 1j, k). The patient's movement and sensation in the left extremities improved. The NIHSS score decreased in the items on left extremities motor drift (5a and 6a) from 1 to 0, and the mRS decreased from 1 to 0 at discharge.

Case 2

A 15-year-old male presented with ventricular hemorrhage 20 months prior. Surgical resection of the AVM was previously performed in a local hospital. Eighteen months after the operation, a follow-up MRI revealed a

Table 1 Demographic and clinical features of 9 patients

Case no.	Age (years), sex	Presentation	AVM location	AVM size (cm)	Adjacent eloquence/tract	LED* (mm)	SM grade	Compact/ diffusive
1	10, M	Ruptured	Right parietal	6.3	Motor area, pyramidal tracts	3.0	5	Compact
2	15, M	Ruptured	Right frontoparietal	3.4	Pyramidal tracts	3.8	4	Diffusive
3	46, M	Incidental	Right occipital	5.0	Optic radiation	0	4	Compact
4	33, F	Epilepsy	Left temporal	3.3	Optic radiation, arcuate fasciculus	0	3	Compact
5	14, F	Hypopsia, limb weakness	Left frontoparietal	3.9	Hand motor area, Pyramidal tracts	1.4	3	Compact
6	52, F	Ruptured	Right frontal	4.8	Pyramidal tracts, arcuate fasciculus	4.2	3	Diffusive
7	28, M	Aphasia	Left temporal	4.8	Optic radiation, arcuate fasciculus	2.1	3	Compact
8	37, M	Epilepsy	Left parietal	2.1	Pyramidal tracts	1.5	2	Compact
9	39, M	Epilepsy	Right frontal	4.9	Pyramidal tracts	4.5	3	Compact

*LED was measured in BrainLAB iPlan 3.0 (Brainlab AG, Munich, Germany) with the results of fMRI

AVM arteriovenous malformation, *LED* lesion-to-eloquence distance, *SM grade* Spetzler-Martin grade

Table 2 Details of operation

Case no.	Arterial feeders from	Superselected arteries	Remained feeders from	Duration of surgical resection (h)	Blood loss (ml)
1	A4, lenticulostriate, M4, P4	M4, lenticulostriate	A4, P4	4.1	500
2	A3	A3	A3	3.7	500
3	P4, meningeal	P4, meningeal	P4	3.1	100
4	P4, occipital	P4, occipital	P4	3.5	800
5	A3, M4	A3	A3, M4	3.3	200
6	A3, M2, M3, lenticulostriate	M2, M3, lenticulostriate	A3, M2, lenticulostriate	4.9	600
7	P2, posterior temporal, meningeal	Posterior temporal	P2	5.0	1500
8	Occipital, superficial temporal	Superficial temporal	Occipital	0.6	200
9	A3, M4, lenticulostriate	A3	M4, lenticulostriate	3.1	800

A anterior cerebral artery with a total of 5 segments, *M* middle cerebral artery with a total of 4 segments, *P* posterior cerebral artery with a total of 4 segments

residual of AVM located in the right frontoparietal lobe and trunk of the corpus callosum. An in-hospital fMRI identified the pyramidal tracts lying adjacently laterally posterior to the lesion with an LED of 3.8 mm (Fig. 2a, b). The diffusive nidus was supplied by the branches from the right pericallosal artery with both deep and superficial drainage (Fig. 2c, d). In the one-staged hybrid operation, the microcatheter was superselected over a microwire into the distal branches of the arterial feeders. After the identifying angiogram via a microcatheter (Fig. 2e), the embolic agent (Onyx 18, eV3 Covidien, Minneapolis, MN, USA) was injected into the nidus under road-mapping using the balloon-assisted pressure cooker technique (Fig. 2f). The nidus was subtotally occluded with the anterior and inferior edges retained (Fig. 2g, h). The residue was completely resected with a microsurgical procedure under the guidance of neuronavigation (Fig. 2i). The intraoperative DSA revealed complete obliteration of the nidus with the posterior occluded part retained to protect the pyramidal tracts (Fig. 2j, k). No neurological deficit was induced by the procedure. The NIHSS scores 48 h after surgery and at discharge remained zero.

Discussion

In this work, a series of patients with AVMs near/within the eloquent areas and tracts received in situ embolization combined with surgical resections in our hybrid operating theaters. Although the AVMs of the 9 cases differed in location and angioarchitectural features, complete obliterations were acquired in all of the patients without any neurological deficits.

The one-staged hybrid operation is an effective multifunction platform for treating AVMs. Published studies on the one-staged hybrid operation of AVMs have involved a total of 60 cases in 6 studies and demonstrated its efficiency and safety [4, 5, 9, 10, 15, 21]. Among them, the advantages of the one-staged hybrid operation for treating AVMs were proposed [5], including (1) preoperative embolization could help reduce the blood flow of the nidus following surgical resection, (2) additional anesthesia during subsequent operations could be avoided, (3) the intraoperative angiogram after resection could help the rapid quality control, and (4) the extent of AVM obliteration can be observed immediately. However, the majority of current studies reported the effect of intraoperative DSA. Only 25% of patients (15/60) underwent the hybrid operation with endovascular interventions in those studies [9, 10, 15, 21]. In our experience with 344 cases, endovascular intervention combined with surgical resections was performed in 33.1% of patients ($n = 114$), while intraoperative DSA combined with surgical resection was conducted in the rest. The one-staged hybrid operation has proven compatible with not only intraoperative DSA but also varieties of combinations of different endovascular and surgical procedures. The technique demonstrated in this article is one example that focuses on the protection of neurological functions among the methods derived from the one-staged hybrid operation. Another technique was already proposed in our previous work and provides a novel solution to the difficulties of microcatheterization via traditional arterial and venous approaches [22]. More applications of the one-staged hybrid operation remain to be explored.

Our technique provides a safe and effective solution to eloquence protection in surgical treatment of AVMs. Preoperative embolization combined with surgical resection is a primary integration of surgical and endovascular methods and has proven effective for decreasing therapeutic risks and difficulties of high-grade AVMs [2, 3, 6, 7, 16]. It was used to treat brainstem

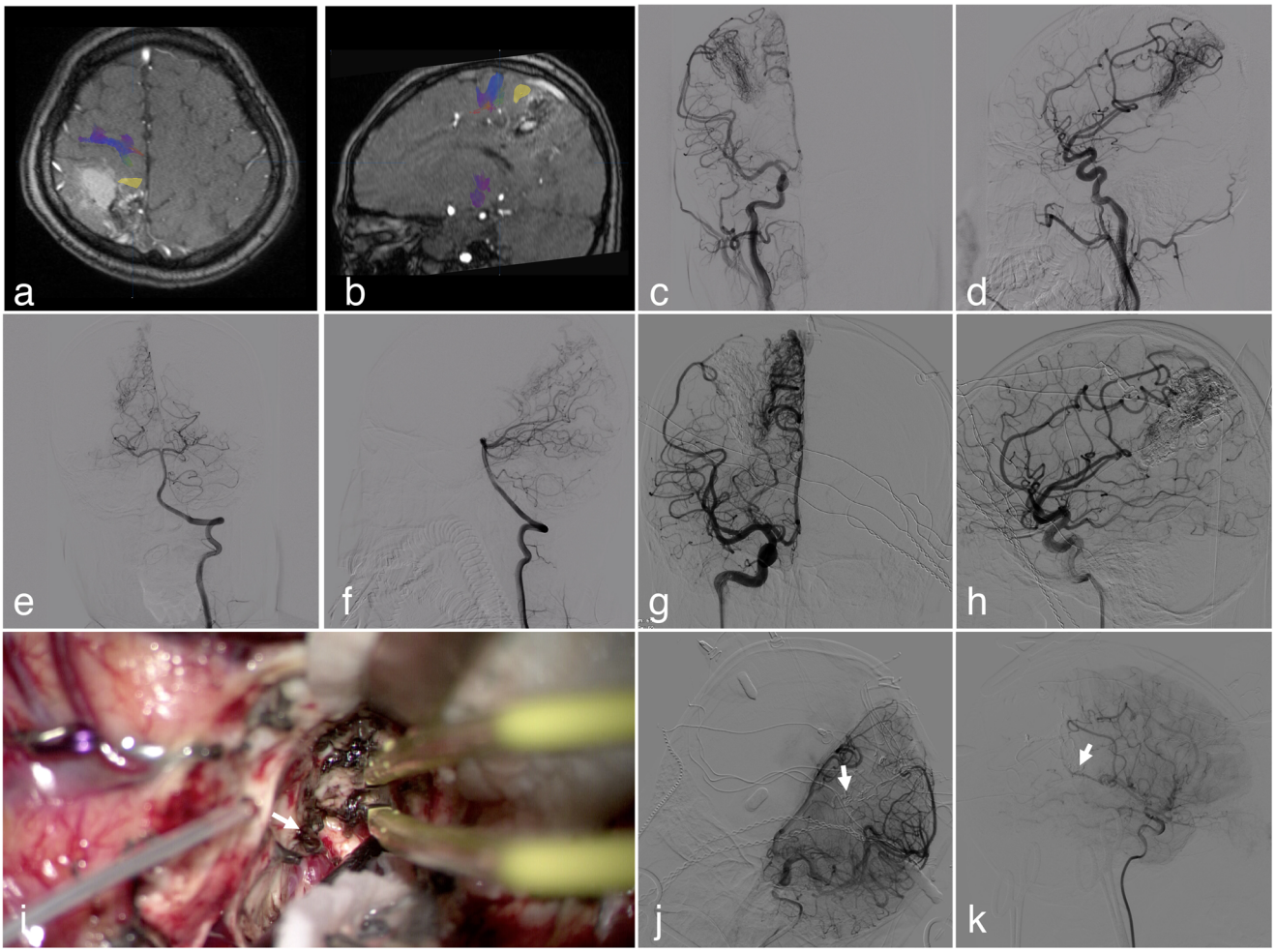

Fig. 1 Case 1. **a**, **b** Preoperative enhanced axial and sagittal T1-weighted MR images infused with reconstructions of the left foot motor area and pyramidal tracts in the workstation. The AVM located in the right parietal lobe with the motor area of the left foot (yellow area) and pyramidal tracts (gradient color area) to the anterior. **c**–**f** Selective right CCA and left VA angiograms. **g**, **h** Right selective ICA angiograms after embolization. The AVM was mostly occluded, especially the anterior part of the nidus, which was adjacent to the motor area. **i** Microscopic view of the surgical field. The nidus was stripped off with the anterior occluded part preserved (white arrow). **j**, **k** Right intraoperative ICA angiograms after resection. The left lateral positioning of the patient limited the rotation of the C-arm. Thus, mirror images were obtained. The nidus was completely obliterated with the anterior occluded part preserved (white arrows). Abbreviations: MR = magnetic resonance; AVM = arteriovenous malformation; CCA = common carotid artery; VA = vertebral artery; PA = posteroanterior; ICA = internal carotid artery

AVMs and developed for in situ embolization combined with surgical resection by Han et al. [6] for its unique capability in eloquence protection. In our work, the in situ embolization combined with surgical resection was introduced to the one-staged hybrid operation for the treatment of eloquent AVMs. Although angioarchitectures are more complicated in supratentorial AVMs, our technique contributed to the complete obliteration in all cases without any neurological deficits. The mechanism of eloquence protection using our technique is not yet clear. According to the experience obtained from our cohort, we postulate it works as follows: First, the targeted in situ embolization could increase the LED to prevent eloquences from being damaged during surgical resection. Second, the embolization provides a bloodless surgical plane for surgical resection and avoids sacrificing the parenchyma for hemostasis manipulations. Finally, embolic agents act as markers of arterial feeders, which prevent negligent damage to nearby arteries.

In this work, we demonstrate our experience using the in situ embolization combined with surgical resection in the one-staged hybrid operation for function protection for treating AVMs near/within eloquence and tracts. A different utilization of the one-staged hybrid operation for treating AVMs is demonstrated, rather than intraoperative DSA only. It provides a new one-staged solution to AVMs, which are difficult to treat using traditional therapeutic methods. However, efficiency and safety need to be further validated with larger-scale studies.

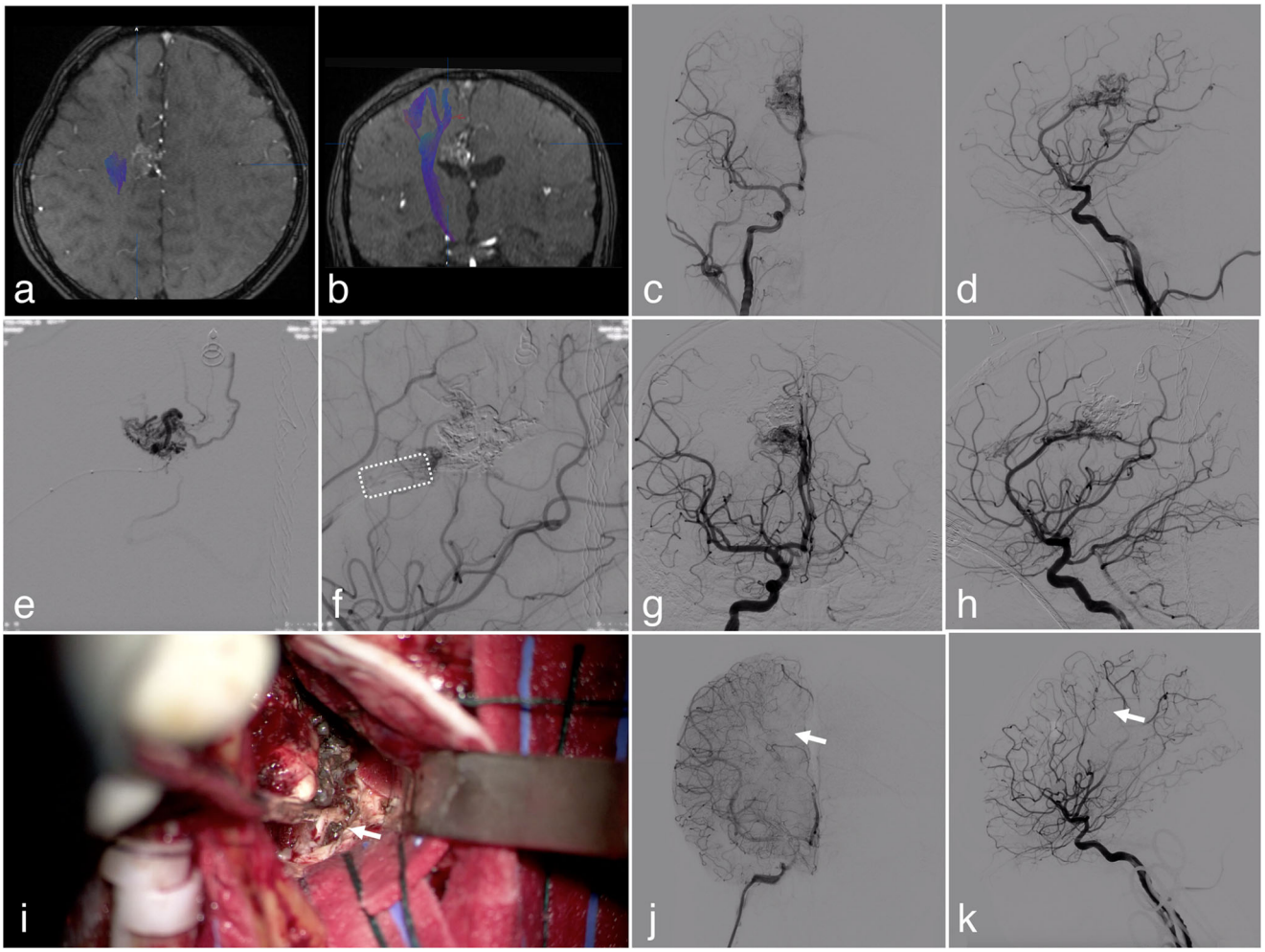

Fig. 2 Case 2. **a**, **b** Preoperative enhanced axial and coronal T1-weighted MR images infused with the reconstructions of the pyramidal tracts in the workstation (gradient color area) revealing the AVM located in the right frontoparietal lobe and trunk of the corpus callosum. The pyramidal tracts lying adjacently laterally posterior to the lesion with an LED of 3.8 mm. **c**, **d** Right selective CCA angiograms. **e** Microcatheter angiogram to verify the target area. **f** The occluded nidus using the pressure cooker technique. A balloon (Scepter C 4 × 20, MicroVention, Aliso Viejo, CA, USA; marked with a white dotted rectangle) was positioned in the proximal trunk of the pericallosal artery and was inflated during embolization to protect the normal upstream arteries. **g**, **h** Right selective ICA angiograms after embolization. The nidus was mostly occluded with the anterior and inferior parts retained. **i** The microscopic view of the surgical field. The posterior occluded nidus (white arrow) was preserved in resection. **j**, **k** Right intraoperative selective ICA angiograms after resection. The AVM was completely obliterated with the posterior occluded part preserved (white arrows)

There are limitations to this work. First, the sample size was small in this study. Only nine patients received this procedure since it was proposed. Further study with a larger sample size will be implemented. Second, a control group, surgically treated without in situ embolization, is necessary to validate the efficiency of this procedure in protecting neurological function. A comparative study is planned that will enroll more participants. Finally, 7 of 9 cases were followed up for 1 year. Case 8 who underwent surgery in June 2018 reached follow-up in 6 months in December 2018. Case 9 underwent the procedure in December 2018 when the data were reviewed. Longer follow-up periods might be required to investigate the recurrence or reappearance of AVMs as reported by Aboukais et al. [1].

Conclusion

The one-staged hybrid operation initiates closer cooperation between surgical and endovascular methods and is an integrative therapeutic mode for AVMs. Using this platform, in situ embolization combined with surgical resection is safe and effective for improving the functional outcome of AVMs near/within eloquences and tracts.

Acknowledgments H. Li and M. Zhao provided critical advice on our work. This report relied on the careful perioperative management of neurosurgeons and nurses at our institute.

Author contributions Conception and design: Zhao, S. Wang, and Y. Cao. Analysis and interpretation of the data: M. Wang. Drafted the article: M. Wang. Critically revised the article: Qiu and Y. Cao. Reviewed the submitted version of the manuscript: H. Qiu, Y. Cao, S. Wang, and J. Zhao. Approved the final version of the manuscript on behalf of all of the authors: M. Wang, H. Qiu, Y. Cao, S. Wang, and J. Zhao.

Funding This study was supported by Beijing Science and Planning Project (No. D161100003816005) and Key Technologies Research and Development Program (No. 2016YFC1301800).

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflicts of interest.

Ethical approval The study was approved by the Institutional Review Board of Beijing Tiantan Hospital (approval number KY2016-034-02).

Informed consent Written informed consent was obtained from the participants before recruitment, including their permission for the anonymous publication of their information and images in this study and other academic uses. For the participant under the age of 18 years or with limited capacity for civil conduct, written consent was obtained from at least one of their legal guardians.

References

1. Aboukais R, Vinchon M, Quidet M, Bourgeois P, Leclerc X, Lejeune JP (2017) Reappearance of arteriovenous malformations after complete resection of ruptured arteriovenous malformations: true recurrence or false-negative early postoperative imaging result? J Neurosurg 126:1088–1093. https://doi.org/10.3171/2016.3.JNS152846
2. Chiluwal A, Dehdashti AR (2017) Surgical treatment of a complex grade III Spetzler-Martin posterior temporal arteriovenous malformation. Neurosurg Focus 43:V9. https://doi.org/10.3171/2017.7.FocusVid.1786
3. Del Maestro M, Luzzi S, Gallieni M, Trovarelli D, Giordano AV, Gallucci M, Ricci A, Galzio R (2018) Surgical treatment of arteriovenous malformations: role of preoperative staged embolization. Acta Neurochir Suppl 129:109–113. https://doi.org/10.1007/978-3-319-73739-3_16
4. Fandino J, Taussky P, Marbacher S, Muroi C, Diepers M, Fathi AR, Remonda L (2013) The concept of a hybrid operating room: applications in cerebrovascular surgery. Acta Neurochir Suppl 115:113–117. https://doi.org/10.1007/978-3-7091-1192-5_24
5. Gruter BE, Mendelowitsch I, Diepers M, Remonda L, Fandino J, Marbacher S (2018) Combined endovascular and microsurgical treatment of arteriovenous malformations in the hybrid operating room. World Neurosurg 117:e204–e214. https://doi.org/10.1016/j.wneu.2018.05.241
6. Han SJ, Englot DJ, Kim H, Lawton MT (2015) Brainstem arteriovenous malformations: anatomical subtypes, assessment of "occlusion in situ" technique, and microsurgical results. J Neurosurg 122:107–117. https://doi.org/10.3171/2014.8.JNS1483
7. Hartmann A, Mast H, Mohr JP, Pile-Spellman J, Connolly ES, Sciacca RR, Khaw A, Stapf C (2005) Determinants of staged endovascular and surgical treatment outcome of brain arteriovenous malformations. Stroke 36:2431–2435. https://doi.org/10.1161/01.STR.0000185723.98111.75
8. Jiao Y, Lin F, Wu J, Li H, Wang L, Jin Z, Wang S, Cao Y (2018) A supplementary grading scale combining lesion-to-eloquence distance for predicting surgical outcomes of patients with brain arteriovenous malformations. J Neurosurg 128:530–540. https://doi.org/10.3171/2016.10.JNS161415
9. Kotowski M, Sarrafzadeh A, Schatlo B, Boex C, Narata AP, Pereira VM, Bijlenga P, Schaller K (2013) Intraoperative angiography reloaded: a new hybrid operating theater for combined endovascular and surgical treatment of cerebral arteriovenous malformations: a pilot study on 25 patients. Acta Neurochir 155:2071–2078. https://doi.org/10.1007/s00701-013-1873-z
10. Li K, Guo Y, Qu L, Xu B, Xu K, Yu J (2018) Hybrid surgery for an arteriovenous malformation fed by an accessory middle cerebral artery and drained by a developmental venous anomaly: a case report and literature review. Exp Ther Med 16:1994–2000. https://doi.org/10.3892/etm.2018.6372
11. Lin F, Zhao B, Wu J, Wang L, Jin Z, Cao Y, Wang S (2016) Risk factors for worsened muscle strength after the surgical treatment of arteriovenous malformations of the eloquent motor area. J Neurosurg 125:289–298. https://doi.org/10.3171/2015.6.JNS15969
12. Lin F, Jiao Y, Wu J, Zhao B, Tong X, Jin Z, Cao Y, Wang S (2017) Effect of functional MRI-guided navigation on surgical outcomes: a prospective controlled trial in patients with arteriovenous malformations. J Neurosurg 126:1863–1872. https://doi.org/10.3171/2016.4.JNS1616
13. Link TW, Winston G, Schwarz JT, Lin N, Patsalides A, Gobin P, Pannullo S, Stieg PE, Knopman J (2018) Treatment of unruptured brain arteriovenous malformations: a single-center experience of 86 patients and a critique of the a randomized trial of unruptured brain arteriovenous malformations (ARUBA) trial. World Neurosurg 120:e1156–e1162. https://doi.org/10.1016/j.wneu.2018.09.025
14. Morgan MK, Heller GZ (2018) The role of embolization before surgery for Spetzler-Ponce class B and C brain AVMs: a prospective cohort series. J Neurosurg Sci 62:429–436. https://doi.org/10.23736/S0390-5616.18.04371-0
15. Murayama Y, Arakawa H, Ishibashi T, Kawamura D, Ebara M, Irie K, Takao H, Ikeuchi S, Ogawa T, Kato M, Kajiwara I, Nishimura S, Abe T (2013) Combined surgical and endovascular treatment of complex cerebrovascular diseases in the hybrid operating room. J Neurointerv Surg 5:489–493. https://doi.org/10.1136/neurintsurg-2012-010382
16. Pasqualin A, Scienza R, Cioffi F, Barone G, Benati A, Beltramello A, Da Pian R (1991) Treatment of cerebral arteriovenous malformations with a combination of preoperative embolization and surgery. Neurosurgery 29:358–368
17. Pietila TA, Stendel R, Jansons J, Schilling A, Koch HC, Brock M (1998) The value of intraoperative angiography for surgical treatment of cerebral arteriovenous malformations in eloquent brain areas. Acta Neurochir 140:1161–1165
18. Rubio RR, Vigo V, Bonaventura RD, Abla AA (2018) Right retrosigmoid approach for in situ occlusion of brainstem arteriovenous malformation surrounding the trigeminal nerve: 3-dimensional operative video. Oper Neurosurg (Hagerstown) 16:E42. https://doi.org/10.1093/ons/opy171
19. Sano H, Kato Y, Iritani K, Akashi K, Kanno T (1998) Minimally invasive surgery for cerebral AVM in the eloquent cortex. J Clin Neurosci 5(Suppl):98–105
20. Sun L, Zhang H, Ren J (2017) Microsurgical resection of a high-grade occipital arteriovenous malformation after staged embolization. Neurosurg Focus 43:V11. https://doi.org/10.3171/2017.7.FocusVid.1769

21. Tian J, Lin Z, Zhang J, Yang Q, Huang J, Zhang H, Li M, Huang J, Zong X (2014) Combined surgical and endovascular treatments of complex cerebral arteriovenous malformation in hybrid operating room. Zhonghua Yi Xue Za Zhi 94:3763–3766
22. Wang MZ, Qiu HC, Wang S, Cao Y, Zhao M, Zhao JZ (2018) A new technique for transvenous embolization of brain arteriovenous malformations in hybrid operation. Chin Med J 131:2993–2996. https://doi.org/10.4103/0366-6999.247199
23. Wang M, Jiao Y, Cao Y, Wang S, Zhao J (2019) Surgical management of complex brain arteriovenous malformations with hybrid operating technique: study protocol of a prospective registry and a pragmatic clinical trial. BMC Neurol 19:75. https://doi.org/10.1186/s12883-019-1289-3
24. Wong J, Slomovic A, Ibrahim G, Radovanovic I, Tymianski M (2017) Microsurgery for ARUBA trial (a randomized trial of unruptured brain arteriovenous malformation)-eligible unruptured brain arteriovenous malformations. Stroke 48:136–144. https://doi.org/10.1161/STROKEAHA.116.014660
25. Yonekawa Y, Imhof HG, Bjeljac M, Curcic M, Khan N (2005) Three cases of AVM at eloquent areas finally treated with conventional microsurgical method. Acta Neurochir Suppl 94:105–110