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Review Article

Current status of combined surgical and endovascular methods for intracranial neurovascular diseases in a hybrid operating room

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Abstract: Surgical treatment of intracranial neurovascular diseases primarily comprises two approaches, craniotomy and endovascular intervention. However, one simple approach cannot resolve some complex vascular diseases, and combined operation is necessary. Previously, this type of combined operation was difficult due to an inadequate operating suite. Recently, with the construction of modern hybrid operating rooms and the introduction of advanced software, the hybrid operating room can provide conditions to perform combined treatments. Research on and reports of neurovascular disease treatment in a hybrid operating room are popular. This study searched PubMed for the currently available literature, and a review of the relevant publications revealed that intracranial aneurysms, arteriovenous malformations, dural arteriovenous fistulae, pial arteriovenous fistulae and cerebral sinus thrombosis achieve the best treatment in the hybrid operating room. Intraoperative angiography can help to confirm if aneurysms were clipped completely and if lesions were resected completely. Additionally, three-dimensional reconstruction software can provide precise neuronavigation to access these lesions. For aneurysms and high flow arteriovenous lesions, endovascular manipulation involves occlusion or embolization of the parent artery or feeding artery, which makes surgical treatment convenient. Similar to other manipulations, operations in a hybrid operating room also have some drawbacks, such as operative complications and false-positive and false-negative results. However, the combination of surgical and endovascular methods for intracranial neurovascular diseases in a hybrid operating room is a promising new trend.

Keywords: Intracranial neurovascular diseases, hybrid operating room, treatment

Introduction

A hybrid operating suite, in which craniotomy, DynaCT scanning, and intracranial angiography can be performed during the same session, is becoming popular for neurosurgeons [1]. Currently, digital subtraction angiography (DSA) is still the "gold standard" in assessing intraoperative obliteration of vascular pathology, including aneurysms, arteriovenous malformations (AVMs), and arteriovenous fistulae (AVFs). For these diseases, a hybrid operating room can help with patient diagnosis, identification of complications that may be addressed during treatment, and confirmation of complete resection, obliteration of vascular lesions and parent vessel occlusion at a time when adjustments can be made [2]. Currently, DSA within the hybrid operating room has emerged as a new trend in the field of neurovascular surgery.

Several pioneer works have demonstrated the usefulness of the combined surgical-endovascular approach [3]. In particular, the recent integration of high-resolution three-dimensional biplane angiography in the setting of an endovascular and surgical suite has been a promising step towards improved intraoperative diagnostics and endovascular support during neurovascular surgery. Newly developed virtual navigation software can be used in frameless navigation and in access to deep-seated intracranial lesions [4]. Currently, studies of neurovascular diseases treated in a hybrid operating room are popular. Therefore, this study searched PubMed and reviewed the literature related to intracranial vascular diseases treated in a hybrid operating room.

Intracranial aneurysm

Currently, the treatment of intracranial aneurysm mainly includes surgical treatment and endovascular embolization. Often, a single method can treat these aneurysms. However, some complex aneurysms cannot be completely treated with a single approach, and successful treatment requires a combination of microsurgical and endovascular techniques [5, 6]. Combined treatment is not often performed in the same session in the absence of a hybrid operating room [7]. However, in an advanced hybrid operating room, combined treatment can be performed in a one-stage procedure. Combined operations can be divided into endovascular therapy after surgical treatment and surgical treatment after endovascular manipulation. For some complex aneurysms, intraoperative angiography is valuable both during and after the operation.

Intraoperative angiography

Routine intraoperative angiography performed immediately after treatment with portable equipment or postoperatively in angiography suites is advantageous. Intraoperative angiography allows for the recognition and correction of technical defects before wound closure and, most importantly, is useful in demonstrating incomplete obliteration of intracranial aneurysms and unexpected vessel occlusion. For instance, Katz et al. in 2006 studied a consecutive series of 147 aneurysms and found that routine intraoperative angiography in the surgical treatment of cerebral aneurysms was justified [8]. Furthermore, a recent meta-analysis performed by Stein in 2007 showed that routine intraoperative angiography remains the most cost-effective method to confirm satisfactory surgical aneurysm [9]. Chalouhi et al. in 2012 assessed the surgery for 1093 vascular lesions and found that the use of intraoperative angiography led to either clip repositioning or furthersurgical resection in 8.4% of cases [10]. Therefore, intraoperative angiography was necessary.

Endovascular embolization after surgical treatment

Endovascular parent artery occlusion after microsurgical bypass

For some aneurysms that are difficult to obliterate if the parent artery cannot be safely occluded, combined microsurgical bypass and endovascular parent artery occlusion may be an alternative [11]. This combination is common for aneurysms of posterior circulation due to the narrow operative field because there is very complex anatomy around the aneurysm. For instance, in 2015, Starke et al. reported a ruptured dissecting vertebral aneurysm that incorporates the origin of the posterior inferior cerebellar artery (PICA). Due to the difficulty in obliterating the aneurysm, a PICA-PICA side-to-side bypass to preserve flow was first performed in a hybrid operating room, and an endovascular approach was then utilized to embolize the proximal portion of the aneurysm. The latter approach yielded a satisfactory outcome [12]. A similar patient was treated by Shin et al. in 2013, in which a 17-year-old patient was diagnosed as having a giant fusiform aneurysm at the right P1-P2 junction of the posterior cerebral artery. The aneurysm was treated with a superficial temporal artery-posterior cerebral artery bypass and subsequent coil embolization of the aneurysm with parent artery occlusion, and the patient had an excellent outcome [13]. For posterior aneurysms, endovascular parent artery occlusion after microsurgical bypass was a good choice.

Except for aneurysms of the posterior circulation, middle cerebral artery and other anterior cerebral artery aneurysms should receive a microsurgical bypass followed by an endovascular parent artery occlusion. There are many perforating branches around the aneurysm, so microsurgical bypass followed by endovascular parent artery occlusion can reduce injury to the parent artery and its perforators. For instance, Clarençon et al. in 2014 reported a 29-year-old patient with a giant M1 aneurysm, in which a superficial temporal artery-middle cerebral artery bypass was performed first. Because the perfusion of the bypass was sufficient and the M1 segment was dysplastic, occlusion of both the aneurysm and the M1 segment using coils and Onyx-34 was performed. Accordingly, limited disturbance was obtained, and good recovery was achieved [14]. As another example, Kim et al. in 2005 reported a 51-year-old woman who received treatment for a recurrent A3-A3 junction aneurysm of the anterior cerebral artery. Because the longitudinal fissure was very deep, there was not sufficient space to surgically clip the aneurysm, so the treatment involved two steps: an interhemispheric transcallosal approach for side-to-side anastomosis and endovascular coil embolization of the right A2 branch feeding the aneurysm. Post-procedure angiography demonstrated no ipsilateral aneurysm filling and excellent bilateral distal outflow from the anterior cerebral artery [15]. Therefore, combined procedures including microvascular bypass and endovascular coil embolization in the hybrid operating room are invaluable in the management of complex cerebrovascular lesions.

Endovascular embolization after partial clipping of aneurysm

Some complex or giant aneurysms are difficult to treat by simple clipping. Due to the risk of aneurysm rupture while waiting for the second staged coiling, it is feasible to immediately obliterate the aneurysm remnants under full visual control, making a second staged procedure unnecessary. For instance, Krayenbühl et al. in 2007 reported a complex anterior communicating artery aneurysm to perfect the clipping process of a complex aneurysm and avoid a second staged procedure. The authors used a method of direct intraoperative transaneurysmal coil-assisted clip occlusion of the aneurysm, and a good outcome was achieved [16]. Therefore, simultaneous microsurgical clip application with transaneurysmal coil-assisted obliteration of the aneurysm was feasible.

Endovascular embolization after the treatment of complications from aneurysm

Some aneurysms can cause complications such as mass effect or hydrocephalus. Therefore, sometimes it is necessary to perform the microsurgical operation before the aneurysm embolization to solve these complications. For instance, in 2014, Kizilkilic et al. reported 4 fusiform aneurysms of the basilar artery that were treated with combined endovascular and surgical treatment, and these cases presented with compression of the brain stem and hydrocephalus due to partial thrombosis. First, the surgical procedure, consisting of a ventriculoperitoneal shunt and the posterior fossa decompression, was performed. After surgery, the telescopic stenting of the aneurysmatic vessel segment was performed. The study confirmed that this technique is a safer endovascular approach in treating symptomatic fusiform basilar artery aneurysms by protecting patients from both the hemorrhagic complications of anticoagulant therapy and thrombotic complications due to the interruption of anticoagulant therapy, instead of treating the hydrocephalus and compression by surgical means [17]. Sometimes, coiling of ruptured aneurysms can be performed after emergency craniotomy to evacuate an intracerebral hematoma [2].

Surgical treatment after endovascular manipulation

Surgical clipping after temporary occlusion of parent artery

Appropriate proximal control of parent artery: Appropriate proximal control of a vessel is crucial for microsurgical clipping [18]. Combined endovascular treatment can now be used to provide safe proximal control during the surgical clipping operation [19]. A balloon catheter may be advanced into the ICA or VA prior to aneurysm manipulation and inflated to obtain proximal occlusion [20]. In 2010, Skrap et al. reported a series of 11 paraclinoid and four vertebrobasilar giant aneurysms treated with the temporary balloon occlusion technique, and complete aneurysm occlusion was achieved. This technique improves the safety of the unavoidable exposure of the parent artery in the surgical treatment of such giant aneurysms [21]. When ready to perform the balloon occlusion, anticoagulation therapy with heparin may be introduced as a single bolus of 100 IU/kg during balloon occlusion [4].

Temporary balloon occlusion to aneurysm orifice: Although the proximal control of the aneurysm using a temporary balloon is useful, in some cases it is better if the balloon is placed below the aneurysm neck, especially if the aneurysm ruptured during the operation. It can act as a salvage procedure in the event of an intraoperative rupture. Balloon inflation resulted in adequate hemostasis and provided intraluminal support for optimal clip placement while preserving the parent artery [22]. Therefore, a temporary aneurysm orifice balloon occlusion should be considered instead of the proximal control of the aneurysm if the balloon is allowed in some locations. In 2005, Steiger et al. treated two giant paraclinoid carotid artery aneurysms with this method because the intraluminal space of the parent artery was large and straight enough. The author inserted an occlusion balloon in the internal carotid artery across the aneurysm neck before craniotomy. After craniotomy and dissection of the aneurysm neck, the balloon was inflated under intraoperative angiographic control. Then, the aneurysms were clipped, and good recovery was achieved [23]. This new method is a feasible alternative to retrograde suction decompression [24].

Cerebral hematoma evacuation after endovascular embolization

In patients with aneurysmal subarachnoid hemorrhage (SAH) and hematoma, some authors considered that aneurysm coiling before hematoma evacuation may simplify surgery and can bring good results. Because the brain has a high pressure in the acute setting and because aneurysms are often located in deep hematomas, the exposure and clipping of aneurysmsis difficult. If coiling of the aneurysm dome prevents re-rupture, only hematoma evacuation and decompression will be easy to perform. This approach minimizes the risk of re-rupture and the time of endovascular intervention and reduces the risk of complications without delaying decompression [25]. For intracerebral hematomas caused by aneurysm rupture, coil placement followed by clot evacuation can result in good recovery [26, 27]. Therefore, this approach requires transporting a patient from the angiography suite to the operating room, which takes valuable time and resources [28].

However, in the hybrid operating room, the combination of endovascular embolization and hematoma evacuation can be performed simultaneously. In 2015, Turner et al. reported 3 cases in which a novel technique for minimally invasive evacuation of intracerebral hematomas after endovascular treatment of ruptured intracranial aneurysms was used. A Penumbra Apollo system was used in the angiography suite in conjunction with neuroendovascular techniques to simultaneously address a symptomatic hematoma associated with a ruptured aneurysm, and good outcomes were obtained [29].

Ventriculostomy of ventricular hemorrhage after endovascular embolization

For those aneurysms with SAH and intraventricular hemorrhage, ventriculostomy should be conducted after successful coil embolization [30]. Currently, the DSA machine has the function of a DynaCT with guidance. In 2012, Tee et al. found that angiographic DynaCT datasets can act as a frameless stereotactic navigation, and pre-operative formal cerebral angiography as an angiographic DynaCT dataset can be used safely and effectively for intra-operative navigation and treatment of cerebrovascular lesions [31]. Therefore, a ventricular drainage tube may be placed in the lateral ventricle without difficulty. Moreover, postoperative DynaCT can confirm if placement of the drainage tube was successful [4].

In 2016, Mori et al. reported that two cases of ruptured aneurysms with packed intraventricular hemorrhage were first treated with endovascular coiling, followed by endoscopic hemorrhage evacuation in a hybrid OR. The hybrid OR enables both treatment approaches to be performed in the same session without the need for patient transfer, thereby shortening the transition time. Additionally, intraoperative cone-beam CT also contributes to the evaluation of residual hematoma [32].

Surgical carotid access for aneurysm embolization

The transfemoral approach is the most common approach for endovascular treatment, but the difficult access routes due to the complicated aortic arch anatomy and tortuous vessels may be circumvented by a direct carotid approach. However, carotid puncture and closure of the carotid puncture site remains an unsolved problem, so surgical carotid access in the hybrid operating room is feasible. In 2015, Ramaswamy et al. reported a 61-year-old patient with significant medical co-morbidities and tortuous vascular anatomy presenting with a large middle cerebral artery aneurysm. To circumvent most of the tortuous vessels, the aneurysm was accessed by direct open exposure of the common carotid artery. Endovascular occlusion of the aneurysm was achieved, and the patient had no post-operative complications [33]. In some special cases, the direct open exposure of the common carotid artery with a puncture is recommended.

Arteriovenous malformation

The role of intraoperative angiography during the microsurgical removal of AVMs has been well established. Advantages include detecting underlying AVMs in patients undergoing emergency evacuation of intracerebral hematomas, localizing deep-seated or small lesions, characterizing feeding and en passage vessels, and documenting complete AVM resection.

Intraoperative angiography

Intraoperative angiography has been used to verify the goals of surgery in the treatment of intracranial AVMs. The procedure can be performed with minimal added time and morbidity. Unlike aneurysms, intracranial AVM can often involve the wide brain. During the surgical resection, the neurosurgeon may have difficulty finding the margin of AVM, so complete removal is not easy. Intraoperative angiography can disclose unexpected residual aneurysms. It is convenient if the AVM resection is performed in the hybrid operating room. In 1999, Munshi et al. reported a series of 25 patients who underwent intraoperative angiography to assess the extent of resection. Intraoperative angiography showed unexpected residual AVM in 2 (8%) of 25 patients. Removal continued, but there was an 18% false-negative rate, suggesting that this procedure has limitations. The late recurrence of AVMs may occur, particularly in children [34]. However, some studies found that intraoperative angiography during microsurgical removal of AVMs in children is feasible. A series of 22 children in Ellis's study in 2010 showed that intraoperative angiography revealed residual AVM in 22.7% of cases, allowing further targeted resection while the patient remained under the same general anesthesia [35].

Intraoperative angiography may be more useful for surgical treatment of cerebral AVM in eloquent brain areas. In 1998, Pietilä et al. studied a series of 21 patients with AVMs in eloquent areas. Angiography-assisted planning of the route of approach to the surgical target further reduces surgical time and trauma. Intraoperative angiography permits a distinction between arteries supplying the AVM and normal vessels and assessing collateral circulation. Therefore, these patients obtained good outcomes [36].

Intraoperative localization of cerebral AVM

Conventional intraoperative angiography can provide information regarding AVM location, according to the relationship between AVM and hematoma [37]. However, modern hybrid operating room senable rotational angiography, and this imaging offers a superior image quality to current options, such as digital subtraction angiography or MRI. Preoperative planning can be greatly aided by the resolution of the angioarchitecture. Furthermore, these images can be used for intraoperative neuronavigation when integrated with widely used frameless stereotactic systems. In 2016, Srinivasan et al. reported a series of 16 patients who were treated with intraoperative localization of cerebral AVMs. During the treatment, DynaCT and 3D DSA were performed, and further and better integration of Dyna CT and 3D-DSA was performed to direct the operation [38]. The technique is more useful in localizing deep-seated or small lesions, characterizing feeding and en passage vessels, and documenting complete AVM resection [1].

Combined endovascular embolization and surgical resection in the same session

AVMs are very difficult to treat completely. If treatment is planned, complete obliteration is the final goal. Some simple AVMs such as Spetzler-Martin grade I and II are easy to treat by simple surgical resection or endovascular embolization [39]. However, for complex AVMs, multimodality treatment is becoming increasingly important. Therefore, the integration of the surgical and imaging suites for combined endovascular and surgical treatment of cerebral AVM may be promising. In 2013, Kotowski et al. reported a series of 25 patients with AVMs who were treated with combined endovascular and surgical interventions. One patient with unruptured AVM underwent endovascular embolization with Onyx first and subsequent surgical resection in the same session, and three patients with ruptured AVM underwent a combined endovascular embolization with Onyx and hematoma and nidus removal in the same session. Other patients were assisted with intraoperative angiography, and good outcomes were achieved [40]. A similar study was performed by Tian et al. in 2014 [41].

In the case of a ruptured AVM, elective embolization followed by surgical resection of the AVM nidus is generally recommended. Emergency embolization and subsequent resection is relatively rare and should be applied only if intracranial pressure is critically high. In 2013, Murayama et al. reported six cases of combined treatment of AVMs. Five presented with severe brain shift, and deep-seated feeding arteries were embolized with NBCA. The immediate resection of the AVM allowed more aggressive postoperative patient management. Good recovery was achieved [42]. Therefore, the hybrid operating room reduces the need for extraoperative angiographic controls and subsequent potential surgical revisions, as small AVM remnants can be detected with high security.

Dural arteriovenous fistulae

Combined surgical and endovascular approaches have been used for complex DAVFs that are not amenable to conventional treatment. If an isolated sinus has cortical venous drainage, endovascular navigation is impossible using a conventional transvenous approach. The combined approaches in the hybrid operating room are helpful and offer several choices.

Endovascular embolization after open surgical direct access

Intracranial DAVFs are difficult to treat, and there are several approaches that can be used to access the fistula, including transarterial and transvenous approaches. However, in some cases, endovascular transarterial treatment can be restricted by tortuous transarterial access [43]. In cases of AVFs accompanied by sinus thrombosis or stenosis or the tortuous vein path, transvenous embolization for femoral vein is sometimes impossible [44]. Currently, the feeding artery and dilated draining vein near the fistula can be punctured or cut down, andopen surgical direct access to the sinus or drainage vein can be used. Direct puncture of fistulas may be adopted. A hybrid technique, combining a microsurgical approach and endovascular embolization, can make the above approaches easier in a modern neurosurgical hybrid operating suite.

The approachof exposing the feeding artery near the fistula

Although the transvenous approach is the first choice for DAVFs, the transarterial approach is still an effective approach. It is still widely used in treating DAVFs. However, endovascular transarterial treatment can be restricted by tortuous transarterial access [45]. Currently, direct access to the feeding artery near the fistula may be attempted. In 2015, Lin et al. treated a middle-aged patient with a Borden III DAVF in a hybrid operating room-angiography suite, and the fistula was fed by multiple external carotid artery branches. Endovascular attempts via conventional transvenous and transarterial routes failed, so the major middle meningeal artery feeder near the fistula was accessed directly after temporal craniotomy was performed under neuronavigation. After Onyx embolization was performed, complete occlusion of the fistula was achieved [46].

Direct surgical access to a major arterial feeder, such as the middle meningeal artery, can be performed safely with neuronavigation guidance in the hybrid operating room. Embolization via direct access to a major feeding artery near the fistula has the advantage of avoiding proximal arterial tortuosity, close placement of the microcatheter to the fistulous point, and injection of a large volume of Onyx without concerns of reflux [47].

A burr hole approach to the draining sinus

If a transvenous approach is the first choice for the DAVF but the routine vein path is not feasible, a burr hole on the sinus may be a good alternative [48]. In 1998, Pierot et al. treated a 68-year-old man with a complex superior sagittal sinus DAVF. A burr hole was drilled in the frontal region in the neurosurgical room. The patient was then transferred to the angiographic room, the superior sagittal sinus was occluded to treat the DAVF, and good recovery was achieved [49]. Additionally in 2007, Kong et al.

reported a multiple-case study including 4 DAVFs with the limitation of endovascular access, in which 3 cases were treated via the transverse-sigmoid sinus junction, and 1 case was treated via the superior sagittal sinus by burr hole opening; good outcomes were achieved [50]. Therefore, the burr hole approach was a good choice. Currently, the burr hole approach can be easily conducted using modern 3D DSA technology in the hybrid operating room. The precise burr hole opening is followed by direct microcatheter placement in the draining sinus [51]. In 2005, Selvarajah et al. treated a posterior fossa DAVF in the angiography suite.Under radiological screening, a retroauricular burr hole was made over the pouch, and a catheter was advanced into the transverse sinus to perform the embolization [44].

The approach of draining a vein near a fistula by craniotomy exposure

Sometimes all of the above approaches fail to access the fistula, including the transvenous approach, and limited venous access requires one to pursue more direct routes to the lesion. A combined craniotomy and puncture of a draining vein may be used as a final option in such circumstances. In 2011, Hurley et al. reported a 75-year-old patient with a dural cavernous fistula with isolated drainage via the dilated superficial middle cerebral vein. No transfemoral or ophthalmic strategy was angiographically apparent, and direct puncture to the cavernous sinus was not feasible. Therefore, in the hybrid operating room, the patient underwent a direct puncture of the superficial middle cerebral vein via an orbitozygomatic craniotomy. The DAVF was catheterized under fluoroscopic guidance and coil-embolized back into the distal superficial middle cerebral vein with complete obliteration of the fistula [52]. A similar treatment was reported by Chaudhary et al. in 2012, in which an 82-year-old woman with cavernous dAVF was treated. First, percutaneous transvenous access failed, and then, a frontotemporal craniotomy was performed to access the superficial middle cerebral vein. Under fluoroscopic guidance, a microcatheter was advanced through this vein into the dAVF, permitting complete coil occlusion [53].

As another example, Shen et al. in 2015 reported a 72-year-old woman with Cognard type IV dural AVF in the cerebellum. No adequate arterial or venous route for endovascular embolization was found by neuroangiography. Therefore, the hybrid technique, combining keyhole pterional craniotomy and embolization with n-butyl cyanoacrylate glue injection via direct cannulation of the periclival venous plexus succeeded in obliterating the dural AVF [54]. The neurosurgical hybrid operating suite is very useful for the treatment of difficult dural AVFs. In some cases, both craniectomy and draining sinus puncture can be performed together. In 2007, Luo et al. reported a case of DAVF of the transverse-sigmoid sinus presenting with intraventricular hemorrhage. Cerebellar infarction developed after transarterial embolization. After the decompressive craniectomy was performed, direct puncture of thetransverse sinus through the bone window and coil occlusion of the fistula were successfully performed [55]. Therefore, decompressive craniectomy may provide an opportunity to occlude DAVFs that cannot be occluded by the transarterial or transvenous approach.

Surgical resection after endovascular embolization

Surgical resection after endovascular embolization has been rarely performed, but it is effective. In 2013, Murayama et al. reported three patients who underwent transarterial embolization followed by surgical resection of dAVFs. First, endovascular transarterial feeder occlusion was performed using embolic coils or N-butyl-cyanoacrylate. Subsequently, a small craniotomy was made under intraoperative angiography guidance, and the draining vein was obliterated with minimal bleeding [42].

Direct puncture of the DAVFs

Direct puncture of the AVFs is effective, but it is difficult to complete due to the lack of precise navigation [56]. In the hybrid operating room, the DSA machine can provide precise navigation. For example, the use of XperGuide software allows the operator to obtain an intraprocedural computed tomography and to identify the optimum needle entry point and trajectory to avoid at-risk structures, such as the optic nerve. In 2014, Puffer et al. reported a 66-year-old woman with cavernous DAVF. By using XperGuide planning software to safely guide catheter access to the cavernous sinus via transorbital puncture, the fistula was obliterated completely [57]. Therefore, the XperGuide software guidance system is helpful during direct transorbital puncture of the cavernous sinus because it allows better monitoring of real-time needle location along a safe trajectory selected by the operator to avoid damaging local soft tissue structures.

Additionally, direct puncture of DAVF can be treated by using the foramen ovale approach [58]. In 2013, Urdaneta-Moncada et al. reported a clival DAVF. In a hybrid operating room, a three-dimensional rotational angiogram of left ICA injections was obtained and reconstructed to the CT format. This procedure was conducted to select the angle to align the anteroposterior projection with the trajectory from the left foramen ovale to the DAVF. The patient then underwent successful occlusion of the clival DAVF [59]. Therefore, in a hybrid operating room, percutaneous embolization via the foramen ovale is safe and feasible in treating DAVF. Sometimes, more aggressive methods can be adopted. In 2015, Dye et al. reported a patient with DAVF of the paracavernous venous plexus, integrated stereotactically guided open surgical and intraoperative direct embolization was performed, and the complete resolution of the fistula was achieved [60].

Other cerebral vessel disease

In addition to intracranial aneurysm, AVM, and DAVF, some other intracranial vascular diseases can be treated in a hybrid operating room, such as cerebral venous sinus thrombosis and pial AVF.

Cerebral venous sinus thrombosis

Cerebral venous sinus thrombosis is often difficult to manage, and prompt mechanical recanalization with thrombectomy is promising; this procedure provides rapid recanalization with no increased risk of hemorrhage from use of thrombolytic agents. However, the rheolytic catheter may not be able to navigate tortuous intracranial vein and sinus anatomy. Therefore, a transcranial approach for direct mechanical thrombectomy of dural sinus thrombosis is promising. In 2004, Chahlavi et al. reported two patients with dural sinus thrombosis, in which mechanical thrombectomy was subsequently performed through a burr hole over the dural sinus using the thrombectomy catheter in a hybrid operating room. Sinus patency was restored following treatment, and both patients demonstrated neurological recovery [61]. A similar treatment was performed by Lee et al. in 2014. In a hybrid operating room, a burr hole over the anterior superior sagittal sinus was performed for daily endovascular anterograde procedures using the AngioJet rheolytic catheter device and chemical thrombolysis. Near-complete recanalization was achieved [62].

In the future, the advanced hybrid operating room may provide more information about the occluded sinus by DynaCT or three-dimensional reconstruction, which can make the treatment of cerebral venous sinus thrombosis in a hybrid operating room promising.

Pial AVF

If a patient has a complex high-flow AV fistula, a scheduled transarterial feeder occlusion followed by surgical occlusion of the draining vein may be the best treatment option in a hybrid operating room. In 2011, Murayama et al. reported a complex pial AVF, and surgical clipping and AVF removal were performed in a hybrid operating room. Before the operation, 3-dimensional angiography was performed. After clipping the feeding arteries, intraoperative angiography demonstrated residual fistula supplied by small branches. A final intraoperative angiogram demonstrated complete obliteration of the fistula. During the operation, the flexible C arm enabled the best working position to be obtained without moving the patient [4]. In 2013, Murayama et al. continued to summarize and again reported two cases with pial AVF, and subsequent surgical obliteration of the fistula was conducted without difficulty because of the immediate occlusion of feeders in a hybrid operating room. Simultaneous treatment can minimize the risk of recruitment of new feeding arteries to the fistulas and reduce patient stress [42].

Drawbacks

The use of combined surgical and endovascular methods for intracranial neurovascular diseases in a hybrid operating room has drawbacks. Potential drawbacks of angiography include the associated incidence of complications [63, 64]. A review of 1003 cerebrovascular cases showed that the overall complication

Table 1. An outline of neurovascular diseases treated in hybrid operating rooms and literature cited

Intracranial aneurysm
1 Intraoperative Angiography [8-10]
2 Endovascular embolization after surgical treatment
(1) Endovascular parent artery occlusion after microsurgical bypass [11-15]
(2) Endovascular embolization after partial clipping of aneurysm[16]
(3) Endovascular embolization after the treatment of complications from aneurysm [2, 17]
3 Surgical treatment after endovascular manipulation
(1) Surgical clipping after balloon temporary occlusion of parent artery
①*Appropriate proximal control of parent artery* [18-21]
②*Temporary balloon occlusion to aneurysm orifice* [22-24]
(2) Cerebral hematoma evacuation after endovascular embolization [25-29]
(3) Ventriculostomy of ventricular hemorrhage after Endovascular Embolization [4, 31, 32]
4 Surgical carotid access for aneurysm embolization [33]
Arteriovenous malformation
(1) Intraoperative Angiography of AVM [34-36]
(2) Intraoperative localization of cerebral AVM [37, 38]
(3) Combined endovascular embolization and surgical resection in the same session [39-42]
Dural arteriovenous fistulas
1 Endovascular embolization after open surgical direct access
(1) The approach of exposing feeding artery near the fistula [45-47]
(2) A burr hole approach to the draining sinus [44, 48-51]
(3) The approach of draining a vein near fistula by craniotomy exposure [52-55]
2 Surgical resection after endovascular embolization [42]
3 Direct puncture of the DAVFs [56-60]
Other cerebral vessel disease
1 Cerebral venous sinus thrombosis [61, 62]
2 Pial AVF [42]

rate was 0.99% with only 1 neurologic complication (0.09%), which resulted in transient visual ischemia. Additionally, morbidity was attributable to 5 retroperitoneal hematomas, 3 minor groin hematomas, and 1 acute limb ischemia. Other centers have reported complication rates of 3%, but this value may be attributable to a small number of patients and variable patient selection. Moreover, false-positive and false-negative results are a potential drawback of intraoperative angiography but are uncommon [65].

Conclusion

Intraoperative angiography performed in an integrated biplane angiography/surgery hybrid operating room is a safe and useful adjunct to surgery and may enable combining endovascular and surgical procedures for the treatment of complex vascular lesions. Currently, in the operating room, intracranial aneurysms, arteriovenous malformations, dural arteriovenous fistula, pial arteriovenous fistula and cerebral sinus thrombosis can receive reasonable treatment. Intraoperative angiography can help to confirm if the aneurysms were clipped completely and if the lesions had been resected completely. Additionally, three-dimensional reconstruction software can provide precise neuronavigation to access these lesions. For aneurysms and high flow arteriovenous lesions, endovascular manipulation can occlude or embolize the parent artery or feeding artery, which makes the subsequent surgical treatment more convenient. However, operations in hybrid operating rooms also have some drawbacks, such as operative complications and false-positive and false-negative results. However, the combination of surgical and endovascular methods for intracranial neurovascular diseases in hybrid operating roomsis a new and promising trend. An outline of neurovascular diseases treated in hybrid operating rooms and the cited literature are shown in **Table 1**.

Disclosure of conflict of interest

None.

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