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ORIGINAL ARTICLE - VASCULAR NEUROSURGERY - OTHER

Treating cerebrovascular diseases in hybrid operating room equipped with a robotic angiographic fluoroscopy system: level of necessity and 5-year experiences

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Abstract

Background A hybrid operating room (OR) equipped with robotic angiographic fluoroscopy system has become prevalent in neurosurgery. The level of necessity of the hybrid OR in treating cerebrovascular diseases (CVD) is rarely discussed.

Objective The authors proposed a scoring and classification system to evaluate the cerebrovascular procedures according to the level of treatment necessity for CVD in a hybrid OR and shared our 5-year experiences.

Methods From December 2009 to January 2016, the registry of cerebrovascular procedures performed in the hybrid OR was retrieved. A scoring system was used to evaluate the importance of the surgical and interventional components of a cerebrovascular procedure performed in the hybrid OR. The score of either component ranged from 1, 1.5, to 2 (1 = no role, 1.5 = supplementary or informative, 2 = important or therapeutic). The total score of a procedure was by multiplying two individual scores. Levels of necessity were classified into level A (important), level B (beneficial), and level C (replaceable).

Results A total of 1027 cerebrovascular procedures were performed during this period: diagnostic angiography in 328, carotid artery stenting in 286, aneurysm coiling in 128, intra-operative DSA in 101, aspiration of ICH under image guidance in 79, intra-arterial thrombolysis/thrombectomy in 51, intracranial angioplasty/stenting in 30, hybrid surgery/serial procedures in 19, and rescue surgery during embolization in 5. According to the scoring system, hybrid surgery and serial procedures scored the highest points (2 × 2). The percentages distributed at each level: levels A (2.3%), B (17.5%), and C (80.2%).

Conclusion This study conveys a concept of what a hybrid OR equipped with robotic angiographic fluoroscopy system is capable of and its potential. For cerebrovascular diseases, hybrid OR exerts its value via hybrid surgery or avoiding patient transportation in serial procedures (level A), via providing real-time high-quality angiography and image guidance (level B), which constituted about 20% of the cases. The subspecialty of the group using the hybrid OR directly reflects on the number of procedures categorized in each level. In a hybrid OR, innovative treatment strategies for difficult-to-treat CVD can be developed.

Keywords Cerebrovascular disease · Cone-beam computed tomography · Digital subtraction angiography · Endovascular · Hybrid operating room · Hybrid surgery · Robotic angiographic fluoroscopy system

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Introduction

With the clinical emergence of C-arm-mounted cone-beam computed tomography (CT) system utilizing high spatial resolution digital flat-panel detector (FPD), which is capable of providing projection radiography, fluoroscopy, digital subtraction angiography (DSA), and volumetric CT in a stationary patient within a single compact suite [18, 28], neurosurgeons have begun to combine the state-of-the-art angiography systems with the operating room (OR) environment [5, 10, 15, 16, 20, 22, 23, 25]. This combination is known as "hybrid OR," in which diagnostic/supplementary angiography can offer surgeons real-time information during a surgery in a single session without the need of patient transportation. However, a hybrid OR exerts its greatest value and holds highest level of necessity in treating a disease that requires a true "hybrid surgery," which means that combined surgical and endovascular procedures are integrated to complete the treatment, or the disease might not be treated easily otherwise. The level of necessity and cost-effectiveness of the hybrid OR in treating cerebrovascular diseases (CVD) has been rarely discussed in the literature [2]. Here, we reported our 5-year experiences in treating CVD with robotic angiographic fluoroscopy system in the hybrid OR and discuss its clinical applications in our institute.

Materials and methods

A robotic C-arm-mounted CBCT system (Artis Zeego; Siemens AG, Forchheim, Germany) designed for the operating room environment was installed in our institute in 2009. This hybrid OR is shared by neurosurgeons and cardiovascular surgeons. From December 2009 to January 2016, the registry of cerebrovascular procedures performed in this hybrid OR was retrieved from the hybrid OR logbook, through which the disease entity, treatment strategy, imaging results, and medical records were reviewed. Cases of brain or spine surgery performed in the hybrid OR were excluded. This study is agreed by the institutional review board. Due to retrospective review of this study, formal consents of each patient were not required.

The authors proposed a classification to evaluate the cerebrovascular procedures according to the level of treatment necessity for CVD in a hybrid OR. A scoring system was used to evaluate the importance of the surgical and interventional components of a cerebrovascular procedure performed in the hybrid OR. The score of either component ranged from 1, 1.5, to 2 (1 = no role, 1.5 = supplementary or informative, 2 = important or therapeutic). If we took a hybrid surgery as an example, the surgical component scored 2 because it provided an important access for the subsequent interventional procedure; the interventional component scored 2 because it offered the treatment, in which circumstance each component was therapeutic. The total score of a hybrid surgery was 4 (2 by 2). If we took intra-operative DSA in an aneurysm clipping surgery as an example, the surgical component of the aneurysm clipping scored 2 because it was therapeutic; the interventional component scored 1.5 because it offered supplementary details to assist the surgery. The total score of intra-operative DSA was 3 (2 × 1.5). Aneurysm coiling in the hybrid OR scored 2 (1 × 2) because the surgical component had no role in it and the interventional component was therapeutic. However, if an aneurysm ruptured during coiling and a rescue surgery was needed, the score of the whole procedures changed to 4 (2 × 2) in that both components were therapeutic. Treating CVD in the hybrid OR, a procedure never scored 1 (1 × 1) when both components had no role. A procedure that scored 4 was categorized in level A (Important), that scored 3 in level B (Beneficial), and that scored 2 in level C (Replaceable). The percentages of all the cerebrovascular procedures distributed in each level of necessity of the hybrid OR were calculated.

Results

From December 2009 to January 2016, a total of 1027 cerebrovascular procedures (either emergent or elective) were performed with the robotic angiographic fluoroscopy system. Flow chart of the usual algorithm in patients diagnosed with CVD in our institute was demonstrated in Fig. 1. Among the 1027 cerebraovascular procedures are the following: diagnostic angiography (with or without intra-arterial nimodipine) in 328, carotid artery stenting in 286, aneurysm coiling in 128, intra-operative DSA for aneurysm or arteriovenous malformation (AVM) surgery in 101, stereotactic aspiration of intracerebral hematoma (ICH) in 79, intra-arterial thrombolysis/thrombectomy for ischemic stroke in 51, intracranial angioplasty/stenting in 30, hybrid surgery/serial procedures in 19 [22, 23, 25, 29], and rescue surgery during embolization in 5 [27] (Table 2). No safety issue occurred due to mechanical failure. During this period, there were 1155 brain or spine surgeries (not related to CVD) performed in the hybrid OR as well.

Types of CVD procedures that scored 4 were (1) hybrid surgery, (2) rescue surgery for IPAP, and (3) serial surgical and interventional procedures, in which both surgical and interventional components of the procedure were therapeutic. Types of CVD procedures that scored 3 were (1) intra-operative DSA in aneurysm clipping/AVM excision/bypass surgery and (2) aspiration of ICH under image guidance, in which the surgical component was therapeutic and the interventional component was supplementary or informative. Types of CVD procedures that scored 2 were (1) diagnostic angiography, (2) carotid stenting, (3) aneurysm coiling, (4) thrombolysis/thrombectomy for acute ischemic stroke, and (5) intracranial stenting, in which the surgical component

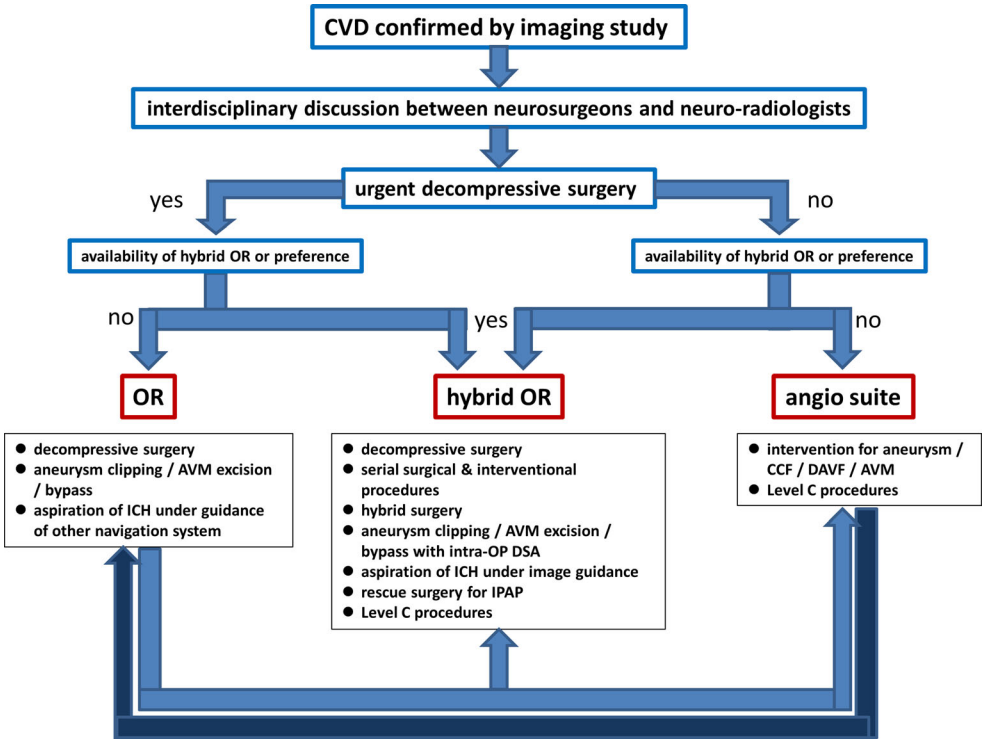

Fig. 1 Flow chart of the usual algorithm in patients diagnosed with CVD in our institute. Take a ruptured cerebral aneurysm with subarachnoid hemorrhage and acute hydrocephalus as an example. The diagnosis is confirmed via CT and subsequent CTA of the brain in the emergent department. Neurosurgeons and neuro-radiologists discussed about the treatment modality. If the hybrid OR and medical staff are available, the patient is sent to the hybrid OR for extraventricular drainage (EVD) tube insertion, then for either clipping or coiling right away. If the hybrid OR is not available, for clipping, the patient is sent to the usual OR for EVD and clipping along with intra-operative ICG angiography; for coiling, the patient is sent to the usual OR for EVD first, then to the neurosurgical intensive care unit, and wait for interventional procedure

had no role in the procedure and the interventional component was therapeutic. However, if intra-procedural arterial perforation (IPAP) occurred during the interventional procedure, a rescue surgery was needed and the surgical component became therapeutic (Table 1).

Necessity of the hybrid OR in treating different kinds of CVD was classified into three levels: level A (Important), level B (Beneficial), and level C (Replaceable). According to the scoring system, a procedure that scored 4 was categorized in level A, that scored 3 in level B, and that scored 2 in level C. The percentages of cerebrovascular procedures distributed in each level were as follows: level A (2.3%), level B (17.5%), and level C (80.2%) (Table 2). The hybrid OR exerted its value in levels A and B, constituting roughly 20% of the cases. The actual utilization of the hybrid OR changes from institutes to institutes, and the specialty of the group using the hybrid OR directly reflects on the number of procedures categorized in each level.

Illustrative cases

Illustrative case 1 was a simple case to demonstrate level A necessity of the hybrid OR when hybrid surgery was required (Fig. 2): A 79-year-old woman suffered blurred visions for 1 month and left limb weakness for 3 days. Imaging studies performed in other hospital showed a dural arteriovenous fistula (DAVF), Cognard type IIb, at the right transverse-sigmoid sinus with severe cortical venous reflux, cerebral edema, and a small ICH at the right occipital lobe. The feeders were occipital and posterior auricular arteries. She had a patent left transverse-sigmoid sinus, but occlusion of the right jugular bulb and a constriction at the right transverse-sigmoid junction were noticed. Conventional treatment route was difficult to access the nidus. Therefore, direct puncture of the right transverse sinus for DAVF embolization via a right occipital burr-hole was performed in the hybrid OR. Other hybrid surgical techniques for cerebrovascular diseases such as direct puncture of the cavernous sinus via endoscopic endonasal route followed by subsequent interventional procedure, which were published by our group elsewhere, also belonged to level A necessity [22, 23, 25, 29].

Illustrative Case 2 was another case to demonstrate level A necessity of the hybrid OR when serial surgical and interventional procedures were required (Fig. 3). A 63-year-old female, who had headaches, ptosis, and chemosis of the left eye for 3 weeks, presented with

Table 1 This table demonstrated the actual utilization of the hybrid OR equipped with a robotic angiographic fluoroscopy system for cerebrovascular diseases during a 5-year span in our institute. A scoring system was used to evaluate the importance of the surgical and interventional components of a cerebrovascular procedure performed in the hybrid OR. The score of either component ranged from 1, 1.5, to 2 (1 = no role, 1.5 = supplementary or informative, 2 = important or therapeutic). If we took a hybrid surgery as an example, the surgical component scored 2 because it provided an important access for the subsequent interventional procedure; the interventional component scored 2 because it offered the treatment, in which circumstance each component was therapeutic. Therefore, the total score of a hybrid surgery was 4 (2 by 2). More details were described in the manuscript

Type of procedure	Number	Score of importance: surgical × interventional	Total score
Serial surgical and interventional procedures (e.g., decompressive surgery and subsequent embolization for CCF/DAVF with ICH and mass effects)	4	2 × 2	4
Rescue surgery for IPAP	5	2 × 2	4
Hybrid surgery (e.g., interventional procedure via a surgical access)	15	2 × 2	4
Intracranial angioplasty/stenting	30	1 × 2	2
Intra-arterial thrombolysis/thrombectomy for acute ischemic stroke	51	1 × 2	2
Aspiration of ICH under image guidance	79	2 × 1.5	3
Intra-operative DSA in aneurysm clipping/AVM excision/bypass surgery	101	2 × 1.5	3
Aneurysm coiling	128	1 × 2	2
Carotid artery stenting	286	1 × 2	2
Diagnostic angiography	328	1 × 2	2
Total	1027		

AVM arteriovenous malformation, *CCF* carotid-cavernous fistula, *DAVF* dural arteriovenous fistula, *ICH* intracerebral hemorrhage, *IPAP* intra-procedural arterial perforation

slurred speech and gradual onset of loss of consciousness. Initial brain CT revealed multiple left frontal ICHs in unusual locations, and serial brain CT showed mass effects caused by enlarging hemorrhages. Three-dimensional CT angiography revealed a left carotid-cavernous fistula (CCF). Intra-operative DSA confirmed the diagnosis of a type-D CCF with multiple tiny feeders from bilateral internal carotid arteries (ICA) and external carotid arteries (ECA). There were no patient inferior petrosal sinuses to the nidus. Serial surgical and interventional procedures were performed to remove ICH via craniotomy, insert ventricular catheter under image guidance, and embolize the CCF by direct trans-orbital puncture in the hybrid OR.

For level A case of rescue surgery (*Rescue Procedure for Intra-Procedural Arterial Perforation (IPAP) during Coiling*), please see Supplementary Fig. 1; for level B illustrative cases of image guidance (*Dyna-CT guided aspiration of ICH*) and real-time diagnostic angiography (*Intra-Operative DSA for Aneurysm Clipping and AVM excision*), see Supplementary Fig. 2-4.

Table 2 According to the scoring results shown in Table 1, a procedure that scored 4 was categorized in level A, that scored 3 in level B, and that scored 2 in level C. The percentages of the 1027 cerebrovascular procedures distributed in each level of necessity of the hybrid OR are demonstrated below

Level of necessity	Type of procedure	Number	Percentage
A (important)	• Hybrid surgery (difficult-to-access CCF/DAVF in 8; CTO of the ICA in 7)	15	2.3%
	• Rescue surgery for IPAP	5	
	• Serial surgical and interventional procedures (e.g., decompressive surgery and subsequent embolization for CCF/DAVF with ICH and mass effects)	4	
B (beneficial)	• Intra-operative DSA in aneurysm clipping/AVM excision/bypass surgery	101	17.5%
	• Aspiration of ICH under image guidance	79	
C (replaceable)	• Diagnostic angiography	328	80.2%
	• Carotid stenting	286	
	• Aneurysm coiling	128	
	• Thrombolysis/thrombectomy for acute ischemic stroke	51	
	• Intracranial stenting	30	

AVM arteriovenous malformation, *CCF* carotid-cavernous fistula, *DAVF* dural arteriovenous fistula, *ICH* intracerebral hemorrhage, *IPAP* intra-procedural arterial perforation

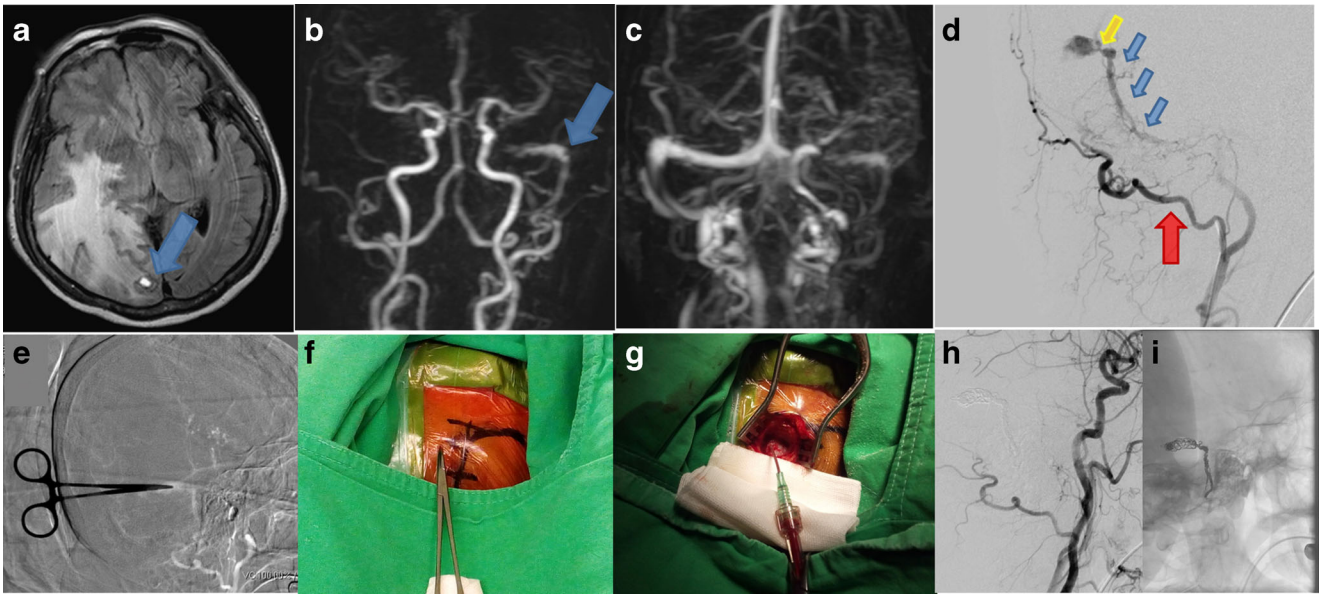

Fig. 2 Direct puncture of the transverse sinus for DAVF embolization via a right occipital burr-hole in the hybrid OR. (Level A) **a** Fluid attenuation inversion recovery sequence of MR imaging revealed cerebral edema at the right occipital region with a small intracerebral hemorrhage (blue arrow) caused by venous hypertension owing to the DAVF. **b** 4D contrast-enhanced MR angiography indicated possible DAVF at the right transverse-sigmoid sinus. **c** In the late phase of the same sequence, cortical venous regurgitation was noted at the right occipital region, and the right internal jugular vein was not patent. **d** In the early arterial phase, DSA image of the right occipital artery (red arrow) showed multiple fistula points at the right sigmoid sinus (blue arrows). Due to occlusion of the right internal jugular vein, the venous blood regurgitated to the cortical veins and drained to the contralateral side (DAVF, Cognard type IIb). The yellow arrow indicated a constriction at the right transverse-sigmoid junction. **e**, **f** Localization of the transverse-sigmoid junction was confirmed in the roadmap view of the fluoroscopy. The actual location was a little higher than expected. **g** After making a burr hole above the right transverse sinus, we punctured and cannulated the sinus with 18-gauge sheathed needle. Detachable coils were then deployed into the nidus through this route. **h**, **i** Complete obliteration of the DAVF was achieved

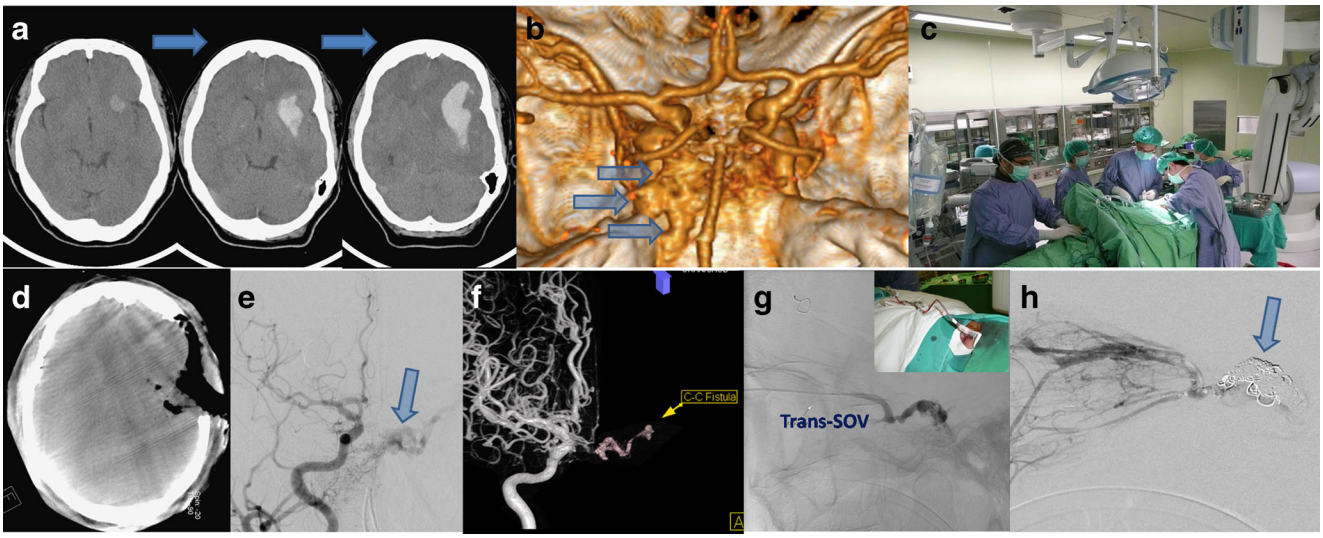

Fig. 3 A type-D CCF with venous hypertension and ICH treated in the hybrid OR. (Level A) **a** Serial brain CT scans showed ICH progression with mass effects. **b** 3D CT angiography showed abnormal and enlarging left cavernous sinus (blue arrows). **c** A craniotomy for ICH removal and decompression was performed. Simultaneously, a femoral approach was prepared for DSA. Of note, we parked the robotic arm (in the upper right corner of this picture) away from the operative field to avoid contamination and offer more space for surgeons. **d** Intra-operative Dyna-CT was used to check the operative result. **e**, **f** DSA confirmed the diagnosis of a type-D CCF (blue arrow in AP view/ pink color indicated by yellow arrow in 3D view). There was no communication of the nidus to other venous sinus/plexus, such as inferior petrosal sinus, for access. **g** Direct trans-orbital puncture to the congested SOV was performed to gain access to the nidus. The inset showed actual operative situation after completion of puncture and cannulation. **f** Tras-SOV embolization of the CCF (coil mass indicated by blue arrow)

Discussion

Types of hybrid OR

Hybrid OR is used to describe an OR installed with advanced imaging system, and the concept of hybrid OR in the field of neurosurgery has been more common in recent years [13, 15]. Modern hybrid OR allows the use of intra-operative CT or magnetic resonance imaging (MRI). There are two types of neurosurgical hybrid OR based on its facility and surgical purpose: (1) digital angiographic fluoroscopy system for neurovascular or spinal surgery [16] and (2) CT or MR imaging for brain tumor surgery [21, 26]. A neurosurgical suite combining all the advanced imaging systems described above (MR imaging, CT, and angiography) seems ideal, but issues on cost-effectiveness may limit its real clinical usage [13]. In our institute, a robotic angiographic fluoroscopy system that consists of a robotic C-arm-mounted cone-beam CT (CBCT) is used. The robotic arm allows flexibility in the working/parking position, and a surgical table can tilt/roll or fit on radiolucent skull clamp for the need of patient positioning. Along with ventilation system and controlled environment, the hybrid OR is different from a standard angiography suite which lacks these features in its inherent design and is always located in a more open space with issues of possible contamination if a neurosurgical procedure is to be performed.

In additional to single-armed CBCT system, intra-operative biplane rotational angiography system has been developed and applied in neurovascular surgery [1, 3]. However, due to the cumbersomeness of the biplane angiography system, the patient's position in surgery is rotated 90° away from the angiographic position [3]. Special modifications of the OR settings are required to allow basic patient positioning for open surgery [1]. Otherwise, hybrid surgery and image-guided neurosurgical procedures cannot be performed simultaneously. In the authors' opinion, a single robotic C-arm digital angiographic fluoroscopy system is more versatile in the OR and has acceptable compromise of the image quality that balances the efficacy of endovascular use and the convenience of open neurosurgery.

Level of necessity of hybrid OR for cerebrovascular diseases

According to the scoring system and classification the authors proposed, there were levels of necessity in treating cerebrovascular diseases (CVD) in the hybrid OR equipped with a robotic digital angiographic fluoroscopy system: level A (Important), level B (Beneficial), and level C (Replaceable). In level A, the hybrid OR was important and exerted its most value. It provided effective and minimally invasive approaches for cases that were considered difficult-to-treat by either open micro-neurosurgery or endovascular intervention alone. In our institute, CVD requiring a hybrid surgery were difficult-to-access CCF/DAVF and CTO of the ICA. Part of the hybrid surgery experiences have been published in the literature by our group [22, 23, 25]. The hybrid OR was also important for serial surgical and interventional procedures. In clinical scenarios that demanded decompressive procedure and endovascular treatment be done, such as ruptured CCF/DAVF with ICH and mass effects, treating these patients in the hybrid OR could avoid patient transportation and time for preparation, as in Illustrative Case 2 (Fig. 3). As to the treatment of cerebral aneurysms, we do not perform intentional reconstruction of the aneurysmal neck by clipping and subsequent obliteration of the aneurysm by endovascular coiling. Therefore, treating cerebral aneurysms in the hybrid OR was categorized in level B (clipping surgery with intra-OP DSA) or level C (coiling) in this series.

In level B (Beneficial) necessity, neurosurgeons could perform operations with accuracy and shorten operation time by using image-guidance system. The robotic digital angiographic fluoroscopy system can provide real-time CT-like images during surgery, and these image data can be used in combination with neurosurgical navigation system [11], which facilitates aspiration of ICH or insertion of ventricular catheter in difficult cases (Supplementary Fig. 2). In the hybrid OR, real-time intraoperative imaging assisted neurosurgeons to visualize three-dimensional relationships between the vascular lesion and normal structures. It is an intra-operative armamentarium to check whether residual lesions exist and confirm normal vessel patency/flow velocity, which avoids delayed revision surgery and patient transportation [2, 6, 8, 24]. Although indocyanine green (ICG)-based video angiography is a simple and safe way to evaluate blood flow intra-operatively under surgical microscope, it is used to supplement rather than to replace DSA [9, 12]. The limitation of ICG angiography includes constricted surgical field of interest and restricted visibility only to those exposed vessels under microscope. Aneurysm clipping can be treated in a usual OR with a mobile C-arm X-ray system that can replace partial function of the hybrid OR. However, a mobile C-arm X-ray system does not harbor 3D reconstruction ability [19]. In our institute, it took about 15 to 20 min to get the intra-operative DSA with 3D reconstruction done. We simplified the draping process by using a disposable C-arm cover to wrap around the surgical site to the patient's upper torso, which ensured the rotating robotic arm unobstructed. In our opinion, intra-operative DSA in aneurysm clipping, AVM excision, and bypass surgery is really beneficial.

In level C (Replaceable) necessity, the use of the robotic C-arm-mounted CBCT system depended on the subspecialty of the group using the hybrid OR, which directly reflected on the number of procedures categorized in each level. The actual utilization of the hybrid OR changes from institute to institute.

In this study, about 80% of the cerebrovascular procedures for treating CVD in the hybrid OR were categorized into this level, which could be performed in a standard angiographic suite as well. In our institute, the hybrid OR is located adjacent to the neurosurgical intensive care unit, so the level C procedures were much easily arranged in our hybrid OR than in the standard angiographic suite. The authors can comfortably perform aneurysm coiling in the hybrid OR and handle IPAP via an immediate rescue surgery [27]. In writing this manuscript, the authors had thought about that if all the 128 cases of aneurysm coiling were categorized in to level B, the percentages wound have been changed to level A (2.3%), level B (30.0%), and level C (67.7%), but we could not do these changes abiding by the scoring system.

Cost-effectiveness of hybrid OR

The levels A and B procedures constituted 19.8% in this series, which appeared to be small in percentages. However, the cost of setup and maintenance of the hybrid OR equipped with a robotic digital angiographic fluoroscopy system is affordable in a medium-to-small-sized hospital, compared with that of the hybrid OR equipped with MRI system. It was difficult to calculate the actual cost-effectiveness of a hybrid OR because this was not a randomized control study, and some invisible costs could not be calculated, such as time and risks saved by avoiding patient transportation from place to place. The value and cost-effectiveness of a hybrid OR equipped with a robotic digital angiographic fluoroscopy system could be apparently appreciated when a hybrid surgery is the only possible solution to treat the disease or when intra-procedural endovascular complications occur, such as intra-procedural arterial perforation (IAPR). According to the Cerebral Aneurysm Rerupture After Treatment (CARAT) study, IPAR was 5% with coiling, and 63% of the patients with IPAR had periprocedural death or disability [4]. In the hybrid OR, neurosurgeons can perform immediate ventricular catheter insertion or direct conversion to decompressive surgery for the patients with IPAR. Of the 128 aneurysm coiling cases in our series, five suffering from IPAR received immediate ventricular catheter insertion, and the coiling procedures could be continued thereafter (Supplementary Fig. 1). There was no mortality among these five patients, and they recovered to pre-treatment status or better at the 3-month follow-up [27].

Limitations

This single-institute study was retrospective in nature, and there was no control group. The actual utilization of the hybrid OR changes from institute to institute. The use of the robotic C-arm-mounted CBCT system depended on the subspecialty of the group using the hybrid OR, which directly reflected on the number of procedures categorized in each level. In this series, the largest case numbers came from diagnostic angiography and carotid artery stenting, which reflected on the subspecialty of the group using the hybrid OR in our institute. It was difficult to systemically compare the effectiveness among various neurosurgical hybrid OR settings at present time.

In treating cerebral AVM, CCF, and DAVF via the interventional procedure, biplane angiography system is still the gold standard, as two simultaneous projections are necessary to assess the precise location of the nidus. Hence, for the best interest of the patient, we routinely treat AVM, CCF, and DAVF in a standard angiography suite if the treatment does not require a surgical component. From our experiences, less than 5% of the CCF/DAVF cases required either hybrid surgery or serial neurosurgical/endovascular approaches in the hybrid OR. Annual volume of the aneurysm treatment in our institute is around 80 cases for clipping (one fourth clipped in the hybrid OR and the rest in usual OR) and 30 cases for coiling. Because the hybrid OR was not always available, clipping cases were largely performed in the usual OR in our institute, which could undermine the real number of patients who would benefit from the treatment performed in the hybrid OR. For coiling of a simple aneurysm, it could be done in the hybrid OR; for cases requiring biplanar angiography system, i.e., flow diverter placement, the hybrid OR was not preferred. Because the standard of practice changes along with the advancement of technology, the proportion in microsurgical and endovascular perspectives will differ with time. However, outcome comparison of different treatment modality is beyond the scope of the current study.

To date, some preliminary series of treating CVD in the hybrid OR have been published in the literature [1–3, 5–7, 10, 13–17]. In this study, we presented our 5-year experiences of the clinical applications of the hybrid OR in treating various CVD. The authors recognize that microsurgical and endovascular techniques are complementary in managing complex cerebrovascular diseases. It is important to utilize either or combined techniques in suitable clinical scenarios and at the same time to understand limitations of each. Hybrid cerebrovascular neurosurgery is a good alternative for cases that were considered difficult to treat in the past. Its application will likely become more widespread and versatile in the future.

Conclusion

This study conveys a concept of what a hybrid OR equipped with robotic angiographic fluoroscopy system is capable of and its potential. For cerebrovascular diseases, hybrid OR exerts its value via hybrid surgery or avoiding patient transportation in serial procedures (level A), via providing real-time high-quality angiography and image guidance (level B), which constituted about 20% of the cases. The

subspecialty of the group using the hybrid OR directly reflects on the number of procedures categorized in each level. In a hybrid OR, innovative treatment strategies for difficult-to-treat CVD can be developed.

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Compliance with ethical standards

Conflict of interest All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee (IRB TCVGH No. CE17084A) and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. For this retrospective study, formal consents were not required.

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