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Original Article

The experience of surgery and endovascular procedure of cerebrovascular disease in the hybrid operating room; Multi-axis robotic C-arm DSA system

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Objective: To report on combined surgical and/or endovascular procedures for cerebrovascular disease in a hybrid operating room (OR).

Methods: Between October 2016 and June 2020, 1832 neurosurgical procedures were performed in a hybrid OR. Our institution's hybrid OR consists of a multi-axis robotic C-arm monoplane digital subtraction angiography (DSA) system with an operating table, 3D-rotational DSA, cone-beam computed tomography (dyna CT), and real-time navigation software. Procedures were categorized into six categories according to purpose: (1) simple diagnosis and follow-up, (2) simple endovascular procedure, (3) combination of surgery and endovascular procedures, (4) rescue surgery after endovascular procedures, (5) frameless stereotactic procedure, and (6) other surgeries requiring C-arm.

Results: Of 1832 neurosurgical procedures in the hybrid OR, 1430 were simple diagnosis and follow-up cases, 330 simple endovascular procedures, 8 combination of surgery and endovascular procedures, 15 rescue after endovascular procedure, 40 frameless stereotactic procedures, and 9 other surgeries. Eight cases of combination of surgery and endovascular procedures, safely performed without wasting time on patient transfer, were performed in seven bypass end endovascular procedures and one case of bow-hunter syndrome in complex cerebrovascular disease. After embolization, craniotomy (or craniectomy) and intracerebral hemorrhage removal were performed in eight patients in-situ. Of the 40 frameless stereotactic procedure, 37 were extraventricular drainage before/after coil embolization in subarachnoid hemorrhage patients. They all mounted conduits in their planned locations.

Conclusions: A hybrid OR for combined endovascular and surgical procedures represents a safe and useful strategy for cerebrovascular disease. In hybrid ORs various neurosurgical procedures can be safely and conveniently performed. Hybrid OR will pioneer a new era in neurosurgical procedures.

Keywords Hybrid operating room, DSA system, Neurosurgical procedure, Endovascular surgery

INTRODUCTION

Expansion of the neuro-intervention area using digital subtraction angiography (DSA) has been applied in patients needing neurosurgical procedures. Hybrid operating rooms (ORs) are pioneering a new era of cerebrovascular disease, which allows immediate confirmation of diagnosis and treatment results without transferring patients.

Over the last three decades, endovascular procedure has been established as an effective and safety treatment for cerebrovascular disease. Most cerebrovascular disease are treated with either surgical procedure or endovascular procedure, but complex and difficult cerebrovascular diseases required a combined of the two treatment methods. Several pioneers have proved and demonstrated the usefulness of the combined approach, however the structural problem has been pointed out regarding patient transfer and multiple anesthesia from the conventional OR to the angioroom.[12)13)] In order to overcome these drawbacks, an integrated OR capable diagnosing and treating for cerebrovascular disease was introduced as a concept of a hybrid operating room.[10)14)]

For example, before the hybrid OR was introduced, patients with subarachnoid hemorrhage had to undergo coil embolization in the angioroom, imaging results such as those from computed tomography (CT) checked, and then moved to the conventional OR for surgeries such as extraventricular drainage (EVD), craniectomy, craniotomy or intracerebral hemorrhage (ICH) removal. In this process, much time was wasted during patient transfer or while waiting for it. However, with the hybrid OR, it is possible to safely perform all processes in one place without wasting time and without the risk associated to patient transfer. In addition, when complex cerebrovascular diseases such as complex aneurysms and arteriovenous malformation are performed in the hybrid OR, more precise diagnosis and treatment plans are possible, while the results after intervention can be immediately checked, resulting in improved outcomes.

We analyzed all neurosurgical procedures performed in a hybrid OR from its opening in October 2016 and report on our clinical experience of combined surgical and endovascular procedures for cerebrovascular disease in the hybrid OR.

MATERIALS AND METHODS

System and equipment of a hybrid operation room

A floor-mounted multi-axis robotic C-arm monoplane DSA system (Artis zeego, Siemens Healthcare, Forchheim, Germany) equipped with "syngo X workplace" software (Siemens Healthcare, Forchheim, Germany) was employed in all cases. The system and software consist of a 3-dimensional rotational angiograph (3DRA), syngo DynaCT, syngo 3D stenosis measurement, syngo Aneurysm Guidance Neuro and syngo Needle Guidance software (syngo X workplace, Siemens Healthcare, Forchheim, Germany). The hybrid OR was also installed with a radiation-transmitting surgical table (MAGNUS OR Table System, Maquet GmbH, Rastatt, Germany), which allows for head flexion/extension, tilting to the right and left and Trendelenburg positions. We also have a radiolucent skull clamp and horseshoe headrest (Doro Radiolucent Headrest System, Pro Med Instruments, GmbH, Germany). This table and the instrument enable 3DRA and 3D CT in various patient positions. This system allows simultaneous endovascular and surgical treatment without moving the patient to another location or table. During cranial surgery, the multi-axis robotic C-arm is folded and placed so that it does not interfere with the microscope or other movement lines (Fig. 1).

Patient population

Between October 2016 and June 2020, 1832 neurosurgical procedures were performed in our hybrid operation room.

After reviewing all cases, we categorized the procedure into six categories according to purpose: (1) simple diagnosis and follow-up, (2) simple endovascular procedure, (3) combination of surgery and endovascular procedures, (4) rescue surgery after endovascular treatment, (5) frameless stereotactic procedure, and (6) other surgery requiring C-arm (Table 1).

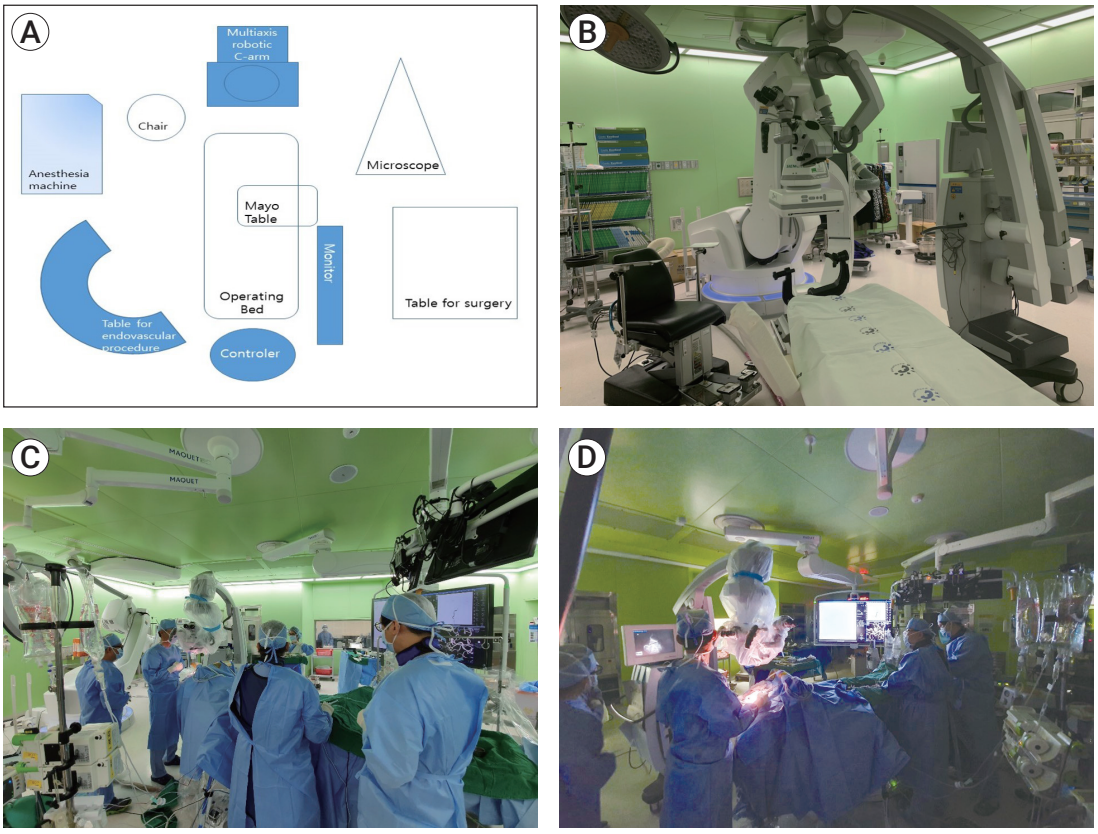

Fig. 1. (A) Schematic image of configuration of the hybrid operating room. (B) Positioning of the microscope and chair during the cranial position. (C) Photo during bypass surgery in case 5. (D) Photo during selective angiography for injection of intra-arterial indocyanine green.

Table 1. Categorized the procedure into six categories according to purpose

	Category	Case No.
1	Simple diagnosis and follow-up	1430
2	Simple endovascular procedures	330
3	Combination of surgery and endovascular procedures	8
4	Rescue surgery endovascular procedures	15
5	Frameless stereotactic procedures	40
6	Other surgery requiring C-arm	9

RESULTS

Between October 2016 and June 2020, a total of 1832 sessions with neurosurgery disease were diagnosed and treated using the hybrid operating system in a neurovascular team without any problems.

(1) Simple diagnosis and follow-up

In the hybrid OR group, 1430 sessions underwent cerebral angiography for the diagnosis and follow-up of cerebrovascular disease.

(2) Simple endovascular procedures

In the hybrid OR, 305 embolization for cerebral aneurysms was performed, carotid artery stenting for carotid artery stenosis in nine cases, chemical angioplasty using nimodipine for vasospasm treatment in another nine, and middle meningeal artery (MMA) embolization to prevent chronic subdural hematoma recurrence in seven cases. Of the 305 embolization cases, 137 occurred in patients with subarachnoid hemorrhage.

(3) Combination of surgery and endovascular procedures

Eight patients were treated with a combination of

surgery and endovascular procedures for five ruptured aneurysms, two unruptured aneurysms and one Bow Hunter syndrome (Table 2).

In three cases, occipital artery (OA)-posterior inferior cerebellar artery (PICA) bypass and trapping was performed in one ruptured PICA involved vertebral artery (VA) dissection and two ruptured PICA aneurysms. One patient had superficial temporal artery (STA)-middle cerebral artery (MCA) double-barrel bypass and trapping for distal internal carotid artery (ICA) giant aneurysms, and selective intra-arterial indocyanine green angiography (ICGA), bypass and trapping for ruptured M1 aneurysm, which is difficult for aneurysm neck clipping.

Actually, before the hybrid OR among the cases in our institution, as a treatment for a ruptured aneurysm, in patient who planned bypass surgery after coil embolization, there was a case of re-bleeding during bypass surgery after an interval of about 3 hours after coil embolization. When the split process was performed as a treatment for PICA aneurysm or PICA involved VA dissecting aneurysm, embolization was performed the next day after bypass, or the embolization was performed after waiting for the anesthesia department to provide anesthesia. After the hybrid OR, surgery and endovascular procedures were continuously performed in hybrid OR without being affected by the wasted time while transferring patient and anesthesiologist schedule. In addition, in hybrid OR, CT images and angiography can be performed immediately, so treatment and surgical result can be immediately confirmed (in bow hunter case), and when a problem occurs, an appropriate response can be taken immediately (in case 8).

In case 4, a 65-year-old male patient visited the hospital with dizziness and syncope, which occurred when he rotated his head to the left. The left VA was compressed by the transverse process and a bony osteophyte identified (Fig. 2). VA decompression, DSA, and dyna CT were simultaneously performed. The bony osteophyte was removed, the transverse process drilled, and the VA confirmed to be sufficiently decompressed. Anterior cervical discectomy and fusion surgery were performed to prevent recurrence of symptoms. This is a case of proper use of DSA in spine surgery in hybrid OR.

In case 8, PICA trapping was performed after OA-PICA bypass in a patient with ruptured PICA aneurysm. A decrease in bypass flow was observed in the ECA angiogram after trapping. Immediately, the patient was turned over to the prone position, and wound revision performed to check the anastomosis site. After checking and releasing kinked OA by the tightly closed muscle layer, the anastomosis site was checked to confirm that flow was improved, and wound closure performed again.

(4) Rescue surgery after endovascular procedures

We performed one-stage decompressive craniectomy, ICH removal, or subdural hematoma (SDH) removal in eight cases after coil embolization. Burr-hole trephination and SDH removal after MMA embolization were performed in seven patients with recurrent chronic subdural hematoma.

Table 2. Summary of surgery and endovascular procedure combinations

Case No.	Diagnosis	Surgery	Endovascular procedure
1	Ruptured VA dissection	OA-PICA bypass	VA trapping
2	Ruptured VA dissection	OA-PICA bypass	PICA trapping
3	Ruptured giant distal ICA aneurysms	STA-MCA double barrel bypass	ICA trapping
4	Bow hunter syndrome	ACDF	TFCA with head rotation during surgery
5	Unruptured distal MCA aneurysms	STA-MCA double barrel bypass	Selective angiography* and Coiling
6	Mycotic M2 aneurysm	Bypass and clipping	Selective angiography*
7	Ruptured M1 aneurysm	STA-MCA bypass	Selective angiography* and Coiling
8	Ruptured PICA aneurysm	OA-PICA bypass	PICA trapping

VA, vertebral artery; OA, occipital artery; PICA, posterior inferior cerebellar artery; ICA, internal carotid artery; STA, superficial temporal artery; MCA, middle cerebral artery; ACDF, anterior cervical discectomy and fusion; TFCA, transfemoral cerebral angiography
*Technique of injecting diluted indocyanine green into selected artery to identify the target recipient artery

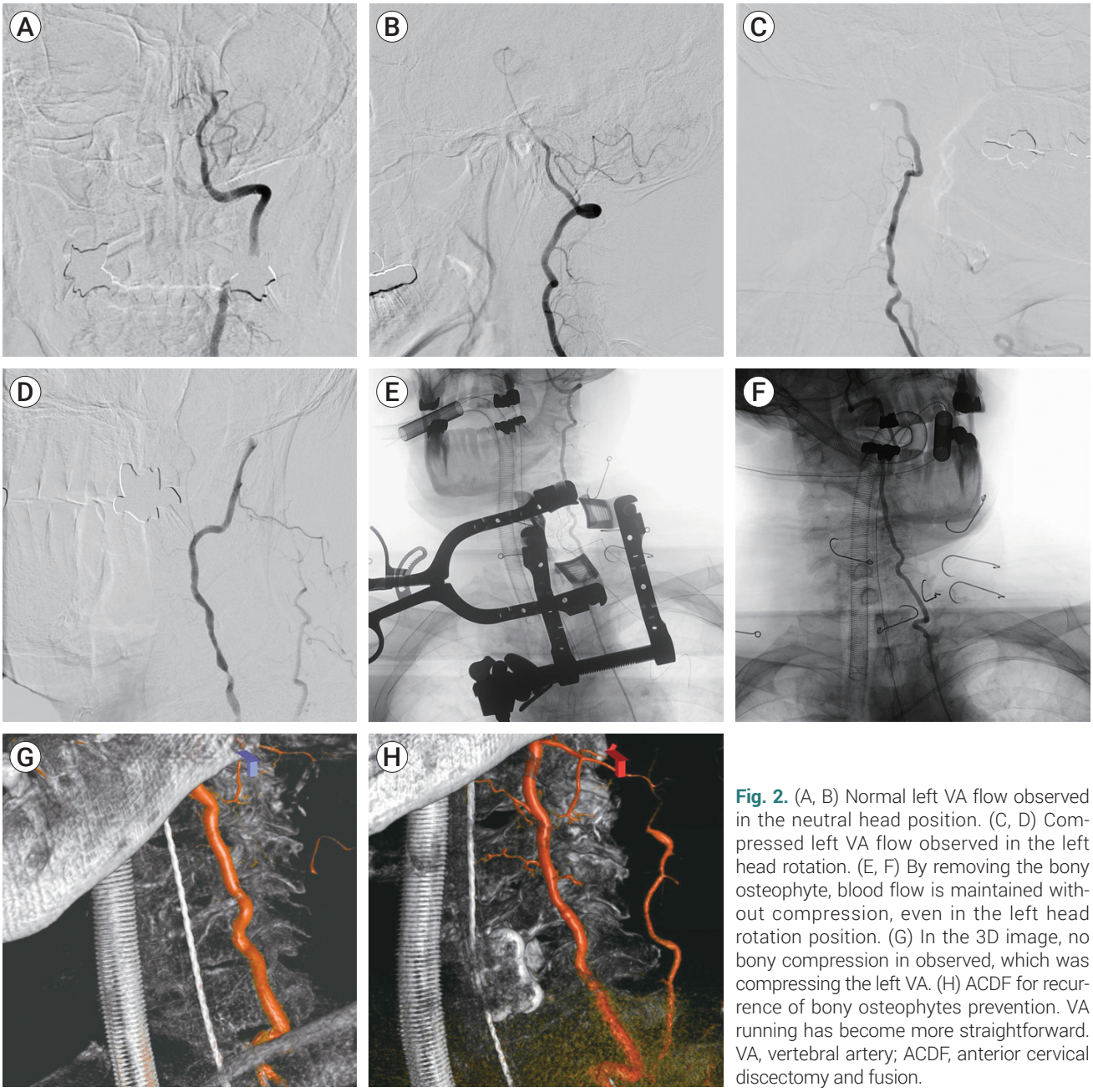

Fig. 2. (A, B) Normal left VA flow observed in the neutral head position. (C, D) Compressed left VA flow observed in the left head rotation. (E, F) By removing the bony osteophyte, blood flow is maintained without compression, even in the left head rotation position. (G) In the 3D image, no bony compression in observed, which was compressing the left VA. (H) ACDF for recurrence of bony osteophytes prevention. VA running has become more straightforward. VA, vertebral artery; ACDF, anterior cervical discectomy and fusion.

For example, a 60-year-old female patient was admitted to the emergency room with altered mental status. Subarachnoid hemorrhage (SAH) and massive ICH were confirmed by plain CT, and a ruptured left MCAB aneurysm confirmed by computed tomography angiogram. Coil embolization was performed, and craniectomy and ICH removal performed immediately after the procedure (Fig. 3).

(5) Frameless stereotactic procedures

A frameless stereotactic procedure was performed in 40 cases. Thirty-seven EVD cases were performed before/after coil embolization in most SAH patients using syngo dynaCT software (Siemens Healthcare) and three ICH aspiration cases were performed (Fig. 4). Prior to hybrid OR, patients with aneurysmal SAH were performed coil embolization in angioroom, transferred to a

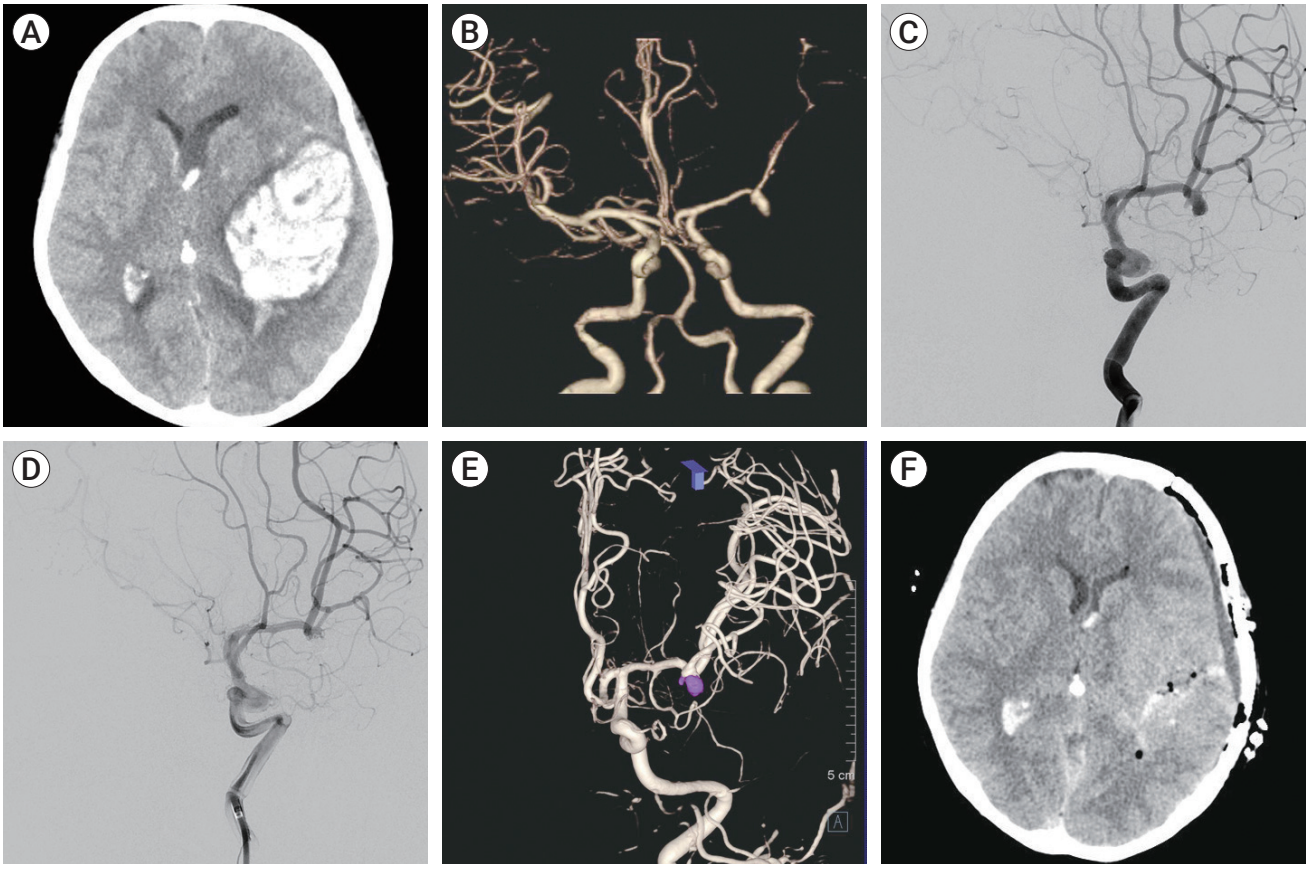

Fig. 3. (A) On CT, massive intracranial hemorrhage in the left temporal lobe. (B) CT angiography showing an aneurysm at left MCA. (C) A ruptured aneurysm in TFCA. (D, E) After embolization, the aneurysm was well occluded. (F) Postoperative image after craniotomy and ICH removal. CT, computed tomography; MCA, middle cerebral artery; TFCA, transfemoral cerebral angiography; ICH, intracerebral hemorrhage.

CT room for CT scans, and transferred to an emergency room or intensive care unit. After that, if EVD was determined to be necessary, the patient was transferred to the OR in coordination with the anesthesiology department, and EVD was performed, which resulted in a lot of wasted time. However, after hybrid OR, all of this process was omitted. After coil embolization, we immediately determined whether EVD was needed through dyna CT and performed EVD using this image as a frameless stereotactic image.

(6) Other surgeries requiring C-arm

In our institution, four cases of lumbo-peritoneal shunt and five cases of ventriculo-atrial shunt were performed in this hybrid OR. In lumbo-peritoneal shunt surgery, the thecal sac was punctured at the L3-4 or L4-5 level using a multi-axis robotic C-arm, and the tip of the lumbar catheter was confirmed to be located at the L1-2 level. In the ventriculo-atrial shunt, the distal catheter was accurately placed in the lower third of the superior vena caver using the C-arm and peel-away sheath.

DISCUSSION

Advantages of hybrid OR

We tested the feasibility, safety, and utility of the hybrid OR in the diagnosis and treatment of various neurosurgical diseases. Combined surgery and endovascular procedures have become popular and essential processes for the treatment of complex cerebrovascular diseases. However, in general, these combined treatment processes are performed in the conventional OR and angioroom separately and patients have to be transferred between pro-

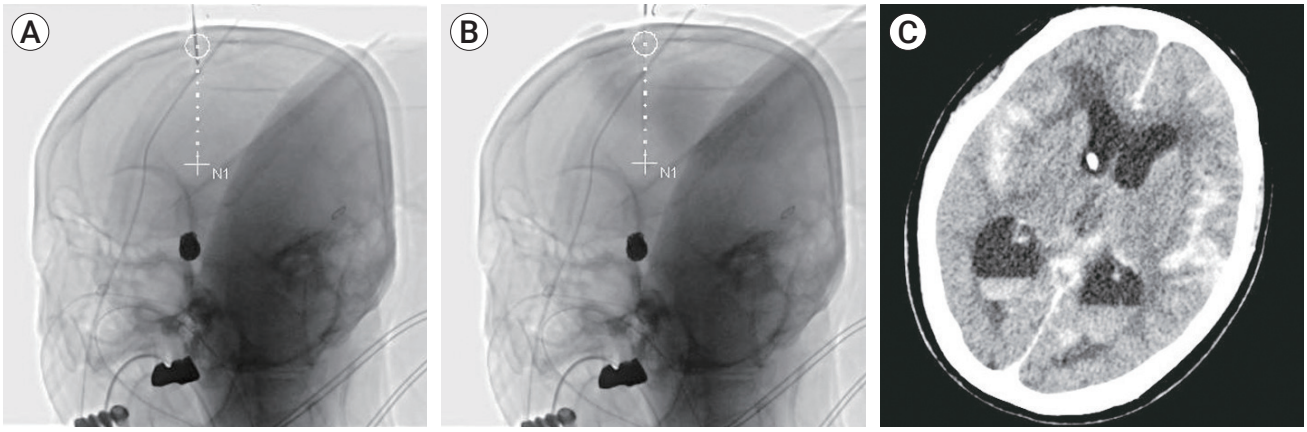

Fig. 4. (A, B) EVD catheter insertion along an imaginary auxiliary line. (C) Confirmation of EVD catheter location in the target point. EVD, extraventricular drainage.

cedures. In this separation process, a lot of time is wasted on transport and the patient can be exposed to danger. Split processes imply a big inconvenience for complex cerebrovascular disease, while hybrid OR greatly reduces morbidity and mortality in complex cerebrovascular disease.[3)21)] In a hybrid OR, bleeding causes can be conveniently identified, and the location of an aneurysm or arteriovenous malformation verified to avoid any blinding hemorrhage that can lead to life-threatening events during surgery.[1)13)] In addition, the DSA in the OR is no longer subject to any other endovascular procedures, which ensures that the procedure can be performed without inconvenience.[14)] One-stage combined surgery and endovascular procedures for multiple cerebral aneurysms difficult to clip or coil alone can be achieved in the hybrid OR.

Combined bypass and endovascular procedures for complex cerebrovascular disease

In the treatment of complex aneurysms, a combination of bypass or clipping and endovascular procedures is now a widely known, safe, and essential treatment modality. In particular, combined treatments for giant aneurysms or aneurysms requiring the sacrifice of the parent artery (e. g., ruptured PICA involving VA dissection) ensure better results.[9)12)16)] This combination of treatments in hybrid OR ensures the best results without multiple anesthesia or time waste, and avoids the risks of patient transport.[20)] Of course, in order to obtain the best results, we need adequate surgical plans and specialized personnel.

Clip reposition during surgery

We have no experience of performing intraoperative angiography after aneurysm clipping. However, routine intraoperative DSA use has been reported to reduce possible complications after aneurysm clipping.[4)5)] Clip reposition during surgery is most likely to occur in complex aneurysms, especially those with deep perforating branches not identified by ICGA,[21)] but guidance with intraoperative DSA can help improve the results. Xin et al. reported that promotion of intraoperative angiography should be considered in most aneurysms cases.[21)] In addition, Klopfenstein et al.[11)] reported that DSA use during surgery could further reduce the overall expenditures associated with patient care.[11)] We wanted to perform all aneurysm surgery in the hybrid OR, but there is a limit to the use time in elective surgery because various department such as thoracic surgery, general vascular surgery and transplant surgery have access to the hybrid OR.

Surgery for rescue after endovascular procedures

We performed eight craniotomies (including craniectomy) and 40 frameless stereotactic procedures after endovascular ones, eliminating the unnecessary processes of transferring the patient after the endovascular procedure, CT, and transferring the patients to the conven-

tional OR. Although a more direct comparative study is needed, we think the quality of patient care could be improved by eliminating unnecessary intermediary steps.

Spine surgery in hybrid OR

We performed one spine surgery in a patient with bow hunter syndrome in hybrid OR. There are several reports on usefulness or technical note of spinal surgery performed in hybrid OR.[2)7)8)17)19)] These reports are about feasibility and accuracy in pedicle screw placement using a real-time navigation system or intraoperative DSA system for various spine levels. These papers reported that the surgery could be performed accurately and effectively. There is also a report of a case of surgery performed using intraoperative DSA in hybrid OR for bow hunter syndrome.[6)15)]

Multi-axis robotic arm DSA system

Since the Zeego DSA system is a monoplane DSA, it has the disadvantage of needing longer for endovascular procedures and higher contrast doses than biplane DSA. However, it also has the advantage of a wider working angle by using a multi-axis robotic arm. Biplane DSA is more useful and feasible than monoplane DSA for simple endovascular procedures and diagnostic angiography. However, in terms of space utilization in the hybrid OR, monoplanes can be located in less space. Murayamaet al. reported that a multi-axis robotic DSA system is faster in switching from surgery to endovascular procedure and is advantageous in space utilization compared to the conventional DSA system.[14)] There are reports on various uses of the multi-axis robotic DSA system in cerebrovascular surgery and spine surgery, as on safety and accuracy.[14)17)18)] In our experience, going on for the last four years, the safety and accuracy of the multi-axis robotic DSA system are more than satisfactory.

Suggestion for hybrid OR development

Hybrid OR is pioneering a new era in treatment strategies for cerebrovascular disease, but there are points to be aware of. First, the hybrid OR requires sufficient radiation shielding. Choi et al. emphasized that the radiation dose should be monitored and shielded to the maximum level for all persons participating in surgeries performed in hybrid ORs.[5)] Second, the movements of patients, surgeons, and surgical assistants must be efficiently structured. Incorrect movements or misalignment of instruments consume unnecessary time and sometimes lead to difficult situations. Expensive and sensitive equipment such as microscopes, DSA machines, and anesthesia machines should be configured so that they are free to move and do not interfere with each other. Third, various surgical situations, such as conversion to open surgery and endovascular procedures, should be considered. This must be performed under strict control, and the attending surgeon should be able to control all situations. Finally, radiologists and nurses should also be skilled and specialized.

CONCLUSIONS

Hybrid OR with a fully equipped DSA system could provide safe and precise treatment in neurosurgical procedures. In particular, the combination of surgery and endovascular procedures to treat complex cerebrovascular disease in a hybrid OR in one-stage was less time consuming and safer for patients than independent surgery or endovascular procedures. A combined endovascular and surgical procedure performed in a hybrid OR is a safe and useful strategy for complex cerebrovascular disease. In hybrid OR, using the multi-axis robotic DSA system, various neurosurgical procedures can be performed safely and conveniently. Hybrid OR will pioneer a new era in neurosurgical procedures.

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Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or findings specified in this paper.

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